Advanced Fibre Bragg Gratings:
Application to Dispersion Compensation

by

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This thesis presents the design and fabrication issues related to advanced fibre Bragg gratings with particular emphasis on realising novel devices with application to dispersion compensation. Developments of fabrication techniques presented herein resulted in the first demonstration of continuously-written metre-long chirped gratings. Subsequent development led to the realisation of gratings with deliberate spectral shaping (without affecting the group delay response) and the first demonstration of gratings designed to compensate both 2\textsuperscript{nd} and 3\textsuperscript{rd} order dispersion of dispersion-shifted fibre. Transfer of this fabrication technology to a commercial fabrication facility resulted in several successful system trials. Results are presented of the first demonstration of chirped FBGs with the application of dispersion-managed soliton transmission. Error-free transmission was obtained over 1000 km of non-dispersion shifted fibre. Application of a new reverse-engineering grating design concept has allowed the fabrication of gratings designed to meet the needs of DWDM dispersion compensation on a 50 GHz grid. The first experimental result of devices designed by this technique are presented, and have sufficient bandwidth utilisation for application in long-haul transmission and optically-transparent networks.
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CONTENTS

I INTRODUCTION

1 THESIS OVERVIEW ................................................................. 2
  1.1 WWW. FIBRE BRAgg GRATING .................................................. 2
  1.2 MOTIVATION ............................................................................ 3
  1.3 MAIN ACHIEVEMENTS .......................................................... 3
  1.4 SUMMARY OF CONTENT ......................................................... 4

2 INTRODUCTION TO FIBRE BRAgg GRATINGS ......................... 6
  2.1 PHASE MATCHING IN OPTICAL FIBRES ..................................... 6
    2.1.1 Modes in Optical Fibres ....................................................... 6
    2.1.2 Gratings in Optical Fibres .................................................... 8
      2.1.2.1 Short-Period Fibre Gratings ................................................. 8
      2.1.2.2 Long-Period Fibre Gratings ............................................... 9
    2.1.3 Mathematical Descriptions of Fibre Bragg Gratings ............. 10
      2.1.3.1 Coupled Mode Theory ...................................................... 10
      2.1.3.2 Transfer Matrix Approach ............................................... 13
      2.1.3.3 The Band Gap ................................................................. 14
  2.2 COMMON TYPES OF FIBRE BRAgg GRATING ......................... 15
    2.2.1 Uniform Fibre Bragg Gratings .............................................. 16
    2.2.2 Apodised Fibre Bragg Gratings ............................................ 17
      2.2.2.1 Side-Lobe Suppression .................................................... 17
      2.2.2.2 Effective Coupling Length of Apodised FBGs .................... 18
    2.2.3 Chirped Fibre Bragg Gratings ............................................... 19
      2.2.3.1 Differential Group Delay ................................................ 19
      2.2.3.2 Apodised Chirped Gratings ............................................. 21
    2.2.4 Superstructure Fibre Bragg Gratings ................................. 21
      2.2.4.1 Multi-Channel Superstructure Gratings ............................ 21
      2.2.4.2 Superstructures for Idealised Spectral Response ............. 21
4 THE CONTINUOUS GRATING FABRICATION TECHNIQUE

4.1 DESCRIPTION OF THE CONTINUOUS GRATING FABRICATION TECHNIQUE

4.1.1 Principle of Operation

4.1.1.1 Distinguishing Features of the Continuous Grating Fabrication Method

4.1.2 Reducing the Effects of Errors

4.1.2.1 Central Limit Theorem

4.1.2.2 The Effect of Beam Size

4.1.3 Experimental Arrangement for the Continuous Grating Fabrication System

4.1.3.1 UV Exposure

4.1.3.2 Fibre Tracking

4.1.3.3 Fibre Translation and Position Measurement

4.1.3.4 Beam Modulation Control

4.1.3.5 Control Software

4.2 WAVELENGTH DETUNING & CHIRP

4.2.1 Basic Detuning Limits

4.2.1.1 The Refractive Index Pattern Induced with Constant Dephasing Between Exposures

4.2.1.2 The Effect of Beam Size on Fringe Contrast

4.2.1.3 Equality of Spectral Range to the Response of a Short FBG

4.2.1.4 Limits to Small-Beam Detuning Range

4.2.1.5 The Effects of Beam Profile on Chirped Fibre Bragg Gratings

4.2.2 Increasing Detuning with Tuneable Interference Patterns

4.2.2.1 Chirped Phase Masks

4.2.2.2 Interferometer-Based Solutions for Tuneable Interference Patterns

4.2.3 Ultimate Limitations to Chirp Rate by Beam Size

4.2.3.1 Expression for Maximum Beam Size when using a Chirped Phase Mask

4.2.3.2 Expression for Maximum Beam Size with Tuneable Interference Patterns

4.3 BEAM MODULATION DUTY CYCLE

4.3.1 Ratio of Refractive Index Contrast to Induced Background Index Due to Duty Cycle
4.3.1.1 Expression for Induced Refractive Index .............................................. 55
4.3.1.2 Expressions for Fringe Depth and Induced Background Index........... 56
4.3.1.3 Expression for the Ratio of Fringe Depth to Induced
Background Index .............................................................................................. 56
4.3.2 Overall Ratio of Modulation Depth to Induced Background Index . 57
4.3.2.1 Restriction of Duty Cycle for Apodisation ............................................. 57
4.4 APODISATION ................................................................................... 58
4.4.1 Dephasing Pairs of Exposures to Achieve Apodisation..................... 58
4.4.1.1 Relationship of Phase Separation to Refractive Index Modulation
Contrast...................................................................................................... 58
4.4.2 Decomposition of Apodisation Profiles .............................................. 59
4.4.2.1 Considering Apodisation as Two Interlaced Gratings ....................... 59
4.4.2.2 Maximum Rate of Change of Apodisation Phase ............................. 60
4.4.2.3 Examples of Apodised Gratings ............................................................. 61
4.5 SUMMARY ......................................................................................... 62

5 MEASUREMENT OF GRATING FRINGES AND THE EFFECTS OF
PHASE MASK INTERFERENCE PATTERNS ........................................... 65
5.1 RESOLUTION OF GRATING FRINGE PATTERNS............................... 66
5.1.1 Fluorescence Bleaching/Loss Associated with Induced Refractive
Index Changes.................................................................................................. 66
5.1.1.1 Guided Fluorescence of UV Exposure .............................................. 66
5.1.1.2 The Effect of Fibre Type on Absorption ............................................. 67
5.1.2 Description of Grating Fringe Measurement System....................... 67
5.1.2.1 Correlation between Induced Loss Pattern and UV Interference
Pattern ....................................................................................................... 68
5.1.2.2 Experimental Arrangement ......................................................... 69
5.1.2.3 Software for High-Speed Data Logging ........................................... 69
5.1.2.4 Advantages Compared to Other Techniques .................................... 70
5.1.2.5 Limitations of the Technique ............................................................. 70
5.2 GRATINGS FORMED BY PHASE MASK EXPOSURE .............................. 70
5.2.1 Phase Mask Interference Patterns..................................................... 71
5.2.1.1 Mathematical Description of Three Beam Interference .................. 71
5.2.1.2 The Effect of Zeroth-Order Diffraction from Phase Masks .......... 72
5.2.2 Grating Structures Resulting from Phase Mask Exposure .............. 74
5.2.2.1 The Effect of Incomplete Suppression of Zeroth-Order Diffraction.... 75
5.2.2.2 The Effect of Phase Mask-to-Fibre Separation Distance................. 76
5.2.2.3 The Effect of Multiple Periodic Components of Refractive Index Modulation on the response of Fibre Bragg Gratings

5.3 GRATINGS FORMED BY THE CONTINUOUS GRATING FABRICATION TECHNIQUE

5.3.1 Gratings Made by Exposures Separated by a Single Fringe

5.3.1.1 Theoretically Expected Fringe Pattern

5.3.1.2 Experimentally Measured Fringe Pattern

5.3.1.3 Useful Refractive Index Modulation Depth

5.3.1.4 The Effect of Fibre-to-Phase Mask Separation

5.3.1.5 Gratings Made with Exposures Separated by an Even Number of Fringes

5.3.2 The Effect of Non-Sinusoidal Interference Patterns on Apodisation

5.3.2.1 Incomplete Destructive Interference

5.3.2.2 Modification of Apodisation Technique to give Near-Sinusoidal Response

5.3.2.3 Evaluation of Apodisation Techniques

5.3.2.4 The Effect of Incomplete Apodisation

5.3.2.5 The Importance of Suppressing Sub-Harmonic Spatial Periods for UV Post-Exposure Enhancement of Index Modulation

5.4 SUMMARY

6 THE CAUSES AND EFFECTS OF NOISE IN CHIRPED FBGS

6.1 STRUCTURAL NOISE AND CHIRPED FBGS

6.1.1 Description of Chirped FBGs

6.1.1.1 The Band Gap of a Chirped FBG

6.1.1.2 Reflected-Mode Power Evolution in Chirped FBGs

6.1.1.3 Apodisation and Chirped FBGs

6.1.2 The Effect of Short-Period Random Noise on Chirped FBGs

6.1.2.1 Chirped Gratings with Random Noise

6.1.2.2 The Consequence of Position on the Effect of Random Noise

6.1.3 The Effect of Long-Period Noise on Chirped FBGs

6.1.3.1 Chirped Gratings with Long-Period Noise

6.1.3.2 The Local Effect of Long-Period Noise on Spectral Characteristics

6.1.4 Definition of Long and Short Period Noise in Chirped FBGs

6.1.4.1 The Physical Extent of the Band Gap in Chirped FBGs

6.1.4.2 The Effect of Long and Short-Period Noise
7.2 Dispersion Compensation Schemes ............................................. 124
  7.2.1 Dispersion Compensating Fibre ............................................. 125
  7.2.2 Mid-point Spectral Inversion ................................................... 125
  7.2.3 Chirped Fibre Bragg Gratings ................................................. 126

7.3 Chirped FBGs for Dispersion Compensation .............................. 128
  7.3.1 Single-Channel Dispersion Compensation .................................. 128
  7.3.2 Broadband Dispersion Compensation ....................................... 130
  7.3.3 Multi-Channel Superstructure Dispersion Compensation ........... 131

7.4 Summary .................................................................................... 131

8 Long Chirped FBGs for Dispersion Compensation ......................... 133
  8.1 The Need for Long Fibre Bragg Gratings .................................... 134
    8.1.1 Transmission System Requirement for Broadband Dispersion
        Compensation ........................................................................... 134
      8.1.1.1 Transmitter Wavelength Drift .............................................. 134
      8.1.1.2 Thermal Drift of Grating Wavelength .................................. 134
    8.1.2 When a Chirped FBG Becomes Long .................................... 135
      8.1.2.1 Bandwidth of Chirped FBGs ............................................ 135
      8.1.2.2 Minimum Bandwidth for Chirped FBGs .............................. 136

  8.2 Design of Long Chirped FBGs ................................................ 137
    8.2.1 Historical Development of Apodisation Profiles ...................... 137
    8.2.2 The Effect of Apodisation on Bandwidth Utilisation for Long
        Chirped FBGs ........................................................................... 139
      8.2.2.1 Apodisation Effects on 1 m Long Chirped FBGs .................. 139
      8.2.2.2 Design Rule for 1 m Long Chirped FBGs ......................... 140
      8.2.2.3 The Effect of Grating Dispersion .................................... 140
    8.2.3 The Effect of Apodisation on the Group Delay Characteristic of
        Long Chirped FBGs ................................................................ 142

  8.3 Fabrication of Long Chirped Gratings ...................................... 143
    8.3.1 First 1 m Long Continuously-Chirped FBGs ........................... 143
      8.3.1.1 Previous Long Gratings .................................................... 143
      8.3.1.2 Fabrication Details ............................................................ 144
      8.3.1.3 Experimental Results ....................................................... 144
      8.3.1.4 Short Wavelength Loss .................................................... 145
    8.3.2 Spectral Equalisation of Cladding-Mode Losses ..................... 147
      8.3.2.1 Short Wavelength Cladding-Mode Loss in Broadband Chirped FBGs 147
8.3.2.2 Spectral Equalisation of Cladding-Mode Loss ..................................... 147
8.3.2.3 Design of Gratings to Compensate for Cladding-Mode Losses .... 148
8.3.2.4 Experimental Results ........................................................................... 149
8.3.2.5 High NA Fibres for Suppression of Cladding-Mode Coupling .... 149
8.3.3 Non-Linearly Chirped FBGs for Combined 2nd and 3rd-Order Dispersion Compensation .......................................................... 150
  8.3.3.1 Requirements for 3rd-order Dispersion Compensation.................. 150
8.3.3.2 Non-Linearly Chirped Fibre Bragg Gratings ...................................... 151
8.3.3.3 Experimental Results ........................................................................... 152
8.3.4 System Trials .......................................................................................... 153
8.4 SUMMARY ............................................................................................ 154

9 CHIRPED FBGS FOR DISPERSION-MANAGED SOLITON TRANSMISSION .................................................. 156
9.1 DISPERSION MANAGED SOLITONS .................................................. 156
  9.1.1 Problems with Soliton Transmission .................................................. 157
9.1.2 Partial Soliton/Dispersion Managed Soliton Transmission ............ 157
    9.1.2.1 Reduced Timing Jitter .......................................................................... 158
    9.1.2.2 Pulse Shape ........................................................................................... 158
9.2 1000 KM TRANSMISSION WITH CHIRPED FBGS FOR PARTIAL DISPERSION COMPENSATION .......................................................... 158
  9.2.1 Description of the Test System ........................................................ 158
    9.2.1.1 Chirped FBG Dispersion Compensators .............................................. 159
    9.2.1.2 Dispersion Map ..................................................................................... 159
  9.2.2 Results of Transmission over 1000 km ............................................ 160
    9.2.2.1 Variation of Dispersion Compensation................................................ 161
    9.2.2.2 Effects of Grating PMD ........................................................................ 161
  9.2.3 Follow-Up Experiments .................................................................... 162
9.3 SUMMARY ............................................................................................ 163

10 COMPLEX FBGS FOR DWDM DISPERSION COMPENSATION .................................................. 164
10.1 REQUIREMENTS FOR DWDM DISPERSION COMPENSATION ............... 165
  10.1.1 Bandwidth Utilisation of Long Chirped FBGs ................................. 165
    10.1.1.1 Temperature Drift .............................................................................. 165
    10.1.1.2 Channel Coverage ............................................................................. 166
10.1.2 Bandwidth Utilisation of Short Chirped FBGs

10.1.2.1 Single-Channel Characteristics

10.1.2.2 Temperature Drift

10.1.3 Transparency in Optical Networks

10.1.3.1 100 GHz-Bandwidth Apodised Gratings for 50 GHz-spaced Channels

10.1.3.2 50 GHz Apodised Gratings

10.1.3.3 Ideal Designs

10.2 DESIGN & REALISATION OF DWDM DISPERSION COMPENSATING CHIRPED FBGS

10.2.1 Characteristics of the Inverse-Scattering, Layer-Peeling Technique for the Exact Synthesis of FBG Structures

10.2.2 Design of the DWDM Device

10.2.2.1 Device Characteristics

10.2.2.2 Length Constraint

10.2.2.3 Dependence on Refractive Index Modulation Depth

10.2.2.4 Optical Transparency

10.2.3 Fabrication and Experimental Results

10.2.3.1 Bandwidth Utilisation Factor

10.2.3.2 Group Delay Characteristics

10.2.3.3 Filtering of Out-of-band Noise

10.3 SUMMARY

IV SUMMARY

11 SUMMARY OF THESIS

11.1 FIBRE BRAGG GRATING FABRICATION

11.2 CHIRPED FBGS FOR DISPERSION COMPENSATION

11.3 AVENUES FOR FUTURE WORK

REFERENCES

BIBLIOGRAPHY

LIST OF PUBLICATIONS
INTRODUCTION
1.1 **WWW. FIBRE BRAGG GRATING**

Uncontrollable offspring of military strategy, affordable personal computing, Net-escape, and optical fibre telecommunication, the internet is mercilessly refashioning human culture. An unprecedented revolution of commercial and social opportunity with universal appeal (e-mail, global business for all, home shopping, entertainment-on-demand), the internet’s parasitic addiction for bandwidth provides both the financial means and the technological goals that drive telecommunications research world-wide. All-powerful and all-knowing, the internet demands to be everywhere: but on its highways, bandwidth rage is already apparent. Optical amplifiers allow the transmission of data channels encoded with light of different wavelengths. Wavelength-division multiplexing, as this is known, dramatically increases the throughput of optical fibres, and means that data channels have the potential to be routed around a global network of fibres according to their wavelength. With the imminent development of metropolitan optical networks, the challenge for photonics is to realise all-optical signal processing devices. Filters must not disrupt adjacent wavelength channels; the pulse-burring effects of fibre transmission must be overcome: efficiently; cheaply; optically. Virtual traffic jams need to be avoided since there are no police in cyberspace.

The fibre Bragg grating is a device that, when tamed, can provide exacting control of both the amplitude and phase characteristics of optical signals. Offering the potential for almost-ideal filter characteristics and the possibility for refocusing short optical pulses blurred by the effects of fibre dispersion, the fibre Bragg grating is an extremely attractive technology. First generation fibre Bragg gratings, based on simple designs, have already found huge application in commercial tele-
communications systems. Optical telecommunications does not rest on its laurels, however, and future transmission systems and network architectures will require the development of no-compromise high-specification optical devices. Accordingly, in order that fibre Bragg gratings fulfil the potential of their early promise, new levels of understanding and technological innovation have been demanded.

1.2 MOTIVATION

The motivation of this research has been to develop advanced fibre Bragg grating fabrication technology, and to realise new and novel devices that may be implemented in optical transmission systems and networks to postpone the onset of data grid-lock. A mission statement for this thesis might be:

- to develop personal engineering, software, and research skills
to develop understanding of the design and fabrication issues relating to advanced fibre Bragg grating structures
to develop world-leading fibre Bragg grating fabrication technology capable of producing high-quality long gratings and complex filter designs
to understand current technology limitations of fabrication technology and how they may be overcome
to understand issues of dispersion compensation, and to develop and fabricate innovative, high-quality gratings to meet the need of current and future transmission systems

1.3 MAIN ACHIEVEMENTS

The initial drive of this work was the development of fabrication technology to produce the world’s-first continuously-written metre-long gratings and complex grating superstructures. From this followed the first gratings for combined management of 2nd and 3rd-order fibre dispersion (and for NZDSF), and the first demonstration of broad-band dispersion compensating gratings with deliberate spectral equalisation (shown to have no effect on group delay characteristics). Such devices were subsequently used in an experiment that that proved the application of chirped Fibre Bragg gratings in dispersion-managed soliton transmission systems.
More recently, the grating fabrication technology has been turned to address the possibilities of devices designed by a new reverse-engineering method. The first results of gratings fabricated to such designs are presented. These 50 GHz dispersion-compensating gratings have a much improved group delay linearity compared to similar devices designed by traditional methods: the bandwidth utilisation sufficient for operation in multi-span DWDM transmission systems.

A novel interrogation technique was developed that is capable of resolving grating microstructure—useful information about grating formation process was obtained, leading to subsequent improvements in some areas of fabrication technology. Additionally, significant effort has been made into understanding of causes and effects of noise in the fabrication process.

During the time span of this PhD I have also fabricated numerous gratings for use both internally in other University research projects, and for several external contracts for commercial prototype devices. Much of the technological work presented has been transferred to the commercial fabrication facility of my sponsors, Pirelli. This technology has subsequently been used to produce devices with successful application in transmission system trials. Over the course of this thesis, I have spent considerable time developing numerically-efficient software for modelling the characteristics of fibre Bragg gratings. This was subsequently licensed to Virtual Photonics, for integration in a optical network-modelling environment that is fast becoming the industry standard.

1.4 SUMMARY OF CONTENT

The following chapter gives an introduction to the characteristics and properties of fibre Bragg gratings, and a brief overview of numerical techniques that may be used to describe the spectral response of FBGs. The main body of the thesis is split into two sections: one covering aspects of grating fabrication, the second covering the application of chirped FBGs to dispersion compensation.

Section II starts with a review of fibre Bragg grating fabrication techniques, and discusses their relative merits (chapter 3). The technique for fabrication of long and complex gratings is presented here, before a thorough discussion in the following chapter (chapter 4). A method developed to interrogate the fringe pattern of fibre Bragg gratings is presented in chapter 5, with a study of the effects of phase mask characteristics on the microstructure of the gratings subsequently
formed. A comparison is made between gratings fabricated by traditional methods, and by the technique developed at the ORC. The results of this investigation led to a re-appraisal of certain aspects of the fabrication technology, giving a significant increase in the dynamic range of the system. Chapter 6 introduces the problems caused by imperfections in the structure of fibre Bragg gratings, before assessing the causes of such problems in fabrication systems, and discussing the steps that may be taken to minimise their effects.

Section III starts with a review of the need for dispersion compensation, the main technologies that have been used to approach this goal, and then introduces the requirements of chirped FBGs for dispersion compensation (chapter 7). Chapter 8 introduces the rationale and design requirements for long, broadband chirped FBGs for dispersion compensation. The first result of continuously-written chirped FBGs with metre-length are presented, with subsequent developments made to increase the functionality and application of these devices. These devices are free from the large glitches seen in previously reported long chirped gratings. In chapter 9, the first results of using chirped FBGs for dispersion-managed soliton transmission are presented; error-free operation was achieved over 1000 km of standard fibre at 10 Gb/s. Consideration of grating requirements for DWDM systems is made in chapter 10, along with the first experimental results of gratings designed by a new reverse-engineering grating design process developed at the ORC. These gratings have significantly improved characteristics over conventional grating designs, and could provide an attractive and scalable solution for dispersion management in DWDM systems.

The final section of this thesis summarises the developments and results presented in this thesis, before suggesting avenues for future work.
INTRODUCTION TO
FIBRE BRAGG GRATINGS

The aim of this chapter is to provide a background to the fundamental principles of Bragg reflection in optical fibres. The different possibilities for phase-matching and power transfer between mode of an optical fibre are presented, before an overview of the mathematics that may be used to numerically describe the spectral characteristics of short-period, fibre Bragg gratings. Common types of fibre Bragg grating are presented and identified by their key characteristics. The chapter concludes with a short historical summary of photo-induced grating formation in optical fibres.

2.1 PHASE MATCHING IN OPTICAL FIBRES

This section describes the different types of modes supported by an optical fibre, and how period structures can lead to power transfer between the modes.

2.1.1 Modes in Optical Fibres

The typical structure of a silica-based optical fibre comprises a core of refractive index \( n_c \), surrounded by a cladding of lower refractive index \( n_e \); the increase in core refractive index is usually achieved by using germanosilicate glass. A simple step-index fibre, of this sort, can be usefully described by two parameters: numerical aperture, \( NA \); and the V-number, such that:
where \( a \) is the core radius and \( \lambda \) is the wavelength of light measured in a vacuum [Buck, 1995: chapter 3]. The core-cladding interface provides the condition for total internal reflection and consequently light launched into the core at an angle less than the critical angle remains confined in, and propagates along the core; this critical angle is related to the numerical aperture. A step index fibre will support a single core-guided mode for wavelengths above that defined by the cut-off condition:

\[
V = V_c = 2.405
\]

\[
\lambda_c = \frac{2\pi}{V_c} a \cdot NA
\]

Optical fibres are usually coated with an acrylate layer to provide mechanical strength. The refractive index of the coating is chosen to closely match that of the cladding to simulate an infinite cladding and thus minimise the possibility of guided modes being supported in the cladding of the fibre due to the silica/air interface. In the fabrication of fibre gratings, however, the acrylate coating is usually removed; this means that as well as core-guided modes, the bare-fibre that plays host to the grating also supports a number of cladding-guided modes. These modes may be characterised by an effective refractive index, \( n_{\text{eff}} \), which relates the propagation constant, \( \beta \), to the vacuum wavelength by:

\[
\beta = \frac{2\pi}{\lambda} n_{\text{eff}}
\]

For a single-moded optical fibre the core-guided mode has a propagation constant \( \beta_{co} \), given by:

\[
\beta_{co} = \frac{2\pi}{\lambda} n_{co}
\]

whilst the cladding guided modes have propagation constants in the range:

\[
\frac{2\pi}{\lambda} < \beta_{cl} < \frac{2\pi}{\lambda} n_{cl}
\]
Additionally the fibre will support radiation modes (non-guided modes) with propagation constants given by:

$$0 < \beta_{rad} < \frac{2\pi}{\lambda}$$  \hspace{1cm} (2.8)

These modes are shown schematically in figure 2.1. Note that a negative propagation constant signifies propagation in the reverse direction.

### 2.1.2 Gratings in Optical Fibres

Fibre gratings comprise a (quasi) periodic perturbation to the waveguiding structure of an optical fibre: typically this is a photo-induced refractive index change. The effect of such an index feature is to provide phase matching, and subsequent transfer of power, between different modes of the optical fibre. Fibre gratings are classified according to the refractive index modulation period and the modes between which cross-coupling occurs.

#### 2.1.2.1 Short-Period Fibre Gratings

The short period fibre grating (more commonly known as a fibre Bragg grating-FBG) has a refractive index structure of period $\Lambda_0$ that provides phase matching between counter propagating core-guiding modes [Erdogan, 1997] at the Bragg wavelength, $\lambda_{Br}$, such that:

$$\frac{\pi}{\Lambda_0} + \beta_{co}^- = \beta_{co}^+$$  \hspace{1cm} (2.9)
where:
\[
\beta_{co}^{+} = \frac{\pi}{\Lambda_0} = 2n_{eff}\Lambda_0
\]  

so:
\[
\Lambda_B = 2n_{eff}\Lambda_0
\]  

This is shown schematically in figure 2.2. Note that the period of this type of grating is usually a factor of approximately three less than the wavelength of the light since \(n_{eff}\) is typically around 1.45 (hence: short period grating).

Short period gratings can also provide phase matching between a core-guided mode and a counter propagating cladding-guided mode according to:

\[
\Lambda + = \lambda_{eff} n_{co} + \lambda_{eff} n_{cl}
\]

The coupling of power between the core-guided mode and a cladding-guided mode, whilst much less that that of the primary Bragg reflection, can lead to a set of significant losses visible on the short-wavelength side of Bragg resonance if the fundamental reflection is high (see chapter 8).

It is the fabrication of devices based on this category of gratings that has been the driving force for the work presented in this thesis. Fibre Bragg gratings are particularly useful since the fundamental Bragg condition provides reflection into a core-guided mode: this means that the reflected signal can be simply connected with other single-moded fibre spans, or components. Fabrication issues of advanced grating structures are presented in section II; the application of fibre Bragg gratings to dispersion compensation is covered in section III.

2.1.2.2 Long-Period Fibre Gratings

Long period gratings (also known as transmission gratings) are distinct from fibre Bragg gratings since they provide phase matching between co-propagating modes. Normally the purpose of a long period grating (LPG) is to couple power from the
core-guided mode into cladding modes (see figure 2.3). The phase matching
wavelengths of an LPG are thus given by:

\[
\lambda = \left[n_{\text{eff,co}} - n_{\text{eff,cl}}\right] \Lambda_0
\] 

(2.13)

The grating period necessary to provide phase matching between co-propagating
modes is much larger than that required for coupling between counter-propagating
modes. Since the power transfer of light is to cladding-guided mode, these grat-
tings effectively act as a loss filter when they are spliced to fibre with an acrylate
coating.

2.1.3 Mathematical Descriptions of Fibre Bragg Gratings

The theoretical background to fibre Bragg gratings is well understood and exten-
sively documented. A brief overview of the mathematics typically used to predict
the spectra of fibre Bragg gratings is presented in this section. Readers interested
in learning more are referred to [Erdogan, 1997] for a good general review, and
also to [Kashyap, 1999] and [Othonos and Kalli, 1999].

2.1.3.1 Coupled Mode Theory

Fibre gratings are devices that lead to power transfer between modes of an optical
fibre. Coupled mode theory is thus well suited to describing the evolution of
power in the counter-propagating modes along the length of a fibre Bragg grating
[Yariv, 1973] [Kogelnik, 1976] [Kogelnik, 1990]. The refractive index pattern of a
grating of period \( \Lambda_o \) with length \( l \) is usually expressed as:

\[
n = n_{\text{eff}} + \Delta n_{\text{eff}} \cos[2\beta_o z] \quad -l/2 < z < l/2
\] 

(2.14)
where:

\[ \beta_0 = \frac{\pi}{\Lambda_0} \quad (2.15) \]

The quantities in the above expression are, in the general case, position dependent. The envelopes of the forward and backward propagating core guided modes, with electric fields \( A(z) \) and \( B(z) \) respectively, can be described in a grating by:

\[
U(z) = A(z) e^{-i\delta z} \\
V(z) = B(z) e^{i\delta z} \quad (2.16)
\]

The coupled differential equations used to relate the power transfer between these modes (shown schematically in figure 2.4) can be written as:

\[
\frac{dU}{dz} = -i \left[ \delta(z) U(z) + \kappa(z) V(z) \right] \\
\frac{dV}{dz} = i \left[ \delta(z) V(z) + \kappa^*(z) U(z) \right] \quad (2.17)
\]

where the coupling constant \( \kappa \), and the detuning parameter \( \delta \), are defined as:

\[ \kappa(z) = \kappa^*(z) = \frac{\pi}{\lambda} \Delta n_{eff}(z) \quad (2.18) \]

\[ \delta(z) = \beta - \beta_0(z) \quad (2.19) \]

The differential equations (2.17) can be solved analytically in the case where \( \Delta n_{eff} \) and \( \beta_0 \) are not position dependent (referred to as a uniform grating), using the boundary condition that the backward-propagating mode, \( V(z) \), does not exist beyond the far end of the grating. The amplitude reflection coefficient, \( r(\lambda) \), and the reflectivity, \( R(\lambda) \), can be evaluated at the input of the grating [Yariv, 1973] [Kogelnik, 1990] such that:

\[ r(\lambda) = \frac{V(\lambda, -l/2)}{U(\lambda, -l/2)} \quad (2.20) \]
Introduction to Fibre Bragg Gratings

\[ r(\lambda) = \frac{-\kappa \sinh[\gamma l]}{\delta \sinh[\gamma l] + i\gamma \cosh[\gamma l]} \] (2.21)

\[ R(\lambda) = \frac{\sinh^2[\gamma l]}{\cosh^2[\gamma l] - \frac{\delta^2}{\kappa^2}} \] (2.22)

where:

\[ \gamma = \sqrt{\kappa^2 - \delta^2} \] (2.23)

The calculated reflectivity and group delay of a uniform FBG with length 20 mm, and \( \Delta n_{\text{eff}} = 10^{-4} \) are shown in figure 2.5; the grating has a peak reflectivity of 99.9 %. It is possible to define the peak reflectivity of a uniform grating (\( \delta = 0 \)) from equation (2.22), as in [Kogelnik, 1976] by:

\[ R_{\text{max}} = \tanh^2[\kappa l] \] (2.24)

Note also that the first nulls of the spectral response can be used to define a bandwidth for the uniform grating, \( \Delta \lambda \), where, from (2.22):
The coupled mode equations (2.17), can be integrated numerically\(^1\) in the case where the grating structure is non-uniform, and no analytical solution exists. Such an approach is unnecessarily time consuming, however, and a more straightforward method exists.

### 2.1.3.2 Transfer Matrix Approach

The overall filtering effect of a FBG may be defined in terms of a scattering matrix [Yamada and Sakuda, 1987] relating the output fields to the input fields at either end of the grating (see figure 2.6). Alternatively a transfer matrix may be defined, which relates both the input and output fields at one end of the grating to those at the other. These matrices take the form:

\[
\begin{bmatrix}
V_1(\lambda) \\
U_2(\lambda)
\end{bmatrix} = S(\lambda) \begin{bmatrix} U_1(\lambda) \\
V_2(\lambda)
\end{bmatrix}
\]

\[
\begin{bmatrix}
U_2(\lambda) \\
V_2(\lambda)
\end{bmatrix} = T(\lambda) \begin{bmatrix} U_1(\lambda) \\
V_1(\lambda)
\end{bmatrix}
\]

Exact analytical solutions of the coupled mode equations may be used to define the transfer matrix of a uniform grating, with elements given by:

\[
T_{\text{nn}} = T_{\text{bb}} = \cosh[\gamma l] - i \frac{\delta}{\gamma} \sin[\gamma l]
\]

\[\text{Figure 2.6: schematic diagram of how the forward and backward-propagating modes at the input and output of a fibre Bragg grating may be related by a single scattering matrix or a transfer matrix} \]

\[\Delta \lambda = \Delta n_{\text{eff}} \frac{\lambda}{n_{\text{eff}}} \left(1 + \left[\frac{\lambda}{\Delta n_{\text{eff}} l}\right]^2\right) \]

\[\text{(2.25)}\]
\[
T_{ab}^{*} = T_{ba}^{*} = -i \frac{\kappa}{\gamma} \sinh(\gamma \ell)
\]  

(2.29)

The attractive feature of transfer matrices (by way of their unity determinant) is that the response of many uniform grating sections may be cascaded simply as:

\[
T_{\text{tot}} = T_{m} \cdots T_{2} \cdot T_{1}
\]  

(2.30)

Any grating structure can thus be digitised, and its overall response calculated, by the cascade of appropriate transfer matrices. The total scattering matrix for a general FBG can then be determined in terms of the total transfer matrix as:

\[
S_{aa} = -\frac{T_{bb}}{T_{aa}}
\]

\[
S_{ab} = S_{ba} = \frac{1}{T_{bb}}
\]

\[
S_{bb} = \frac{T_{ab}}{T_{bb}}
\]  

(2.31)

This approach to modelling the spectral response of FBGs is offers huge gains in speed over the direct evaluation of coupled mode equations. The numerical modelling presented in this thesis are the output of carefully optimised algorithms, developed by the author. This code was licensed to Virtual Photonics Incorporated for use in their commercial optical network simulation package (Photonics Transmission Design Suite – PTDS).

2.1.3.3 The Band Gap

The parameter \( \gamma \), defined in (2.23), has significant physical consequences. When the detuning factor is smaller than the local coupling coefficient of the grating, \( \gamma \) is real. This condition defines an optical ‘band gap’, where, in an analogy with solid-state physics, the modes evolve in the grating with either exponential growth or decay (the modes are evanescent). Conversely, when the detuning parameter is larger than the coupling coefficient, \( \gamma \) is imaginary and the modes evolve in a sinusoidal fashion along the grating (this can be seen by using the trigonometric equalities that \( \sinh[i \ell] = \sin[\ell] \), and \( \cosh[i \ell] = \cos[\ell] \) in (2.28)). The power in the reflected mode of a uniform FBG is shown against wavelength in figure 2.7 cut away at various values of \( \gamma \). The side lobes in the spectral response of a uniform grating are thus occur for values of \( \gamma \) (outside the band gap) where the envelope of
the back-reflected mode has an incomplete number of modulation cycles along the length of the grating.

2.2 **Common Types of Fibre Bragg Grating**

The characteristics of the refractive index structure comprising an FBG need not be constant along its length: by accurately varying the amplitude and period of the structure along its length it is possible to tailor of the reflective and dispersive response to almost any desired characteristic. The range of functionality and application for FBGs explodes when the fabrication system employed is capable of realising the complexities and nuances of elegant grating designs. Described in this

---

**Figure 2.7**: calculated power in the reflected mode of a uniform fibre Bragg grating showing: *(top left)* exponential decay with distance at the Bragg wavelength *(top right)* a single oscillation in the mode power along the grating length, corresponding to the first spectral reflectivity null *(bottom left)* the first reflectivity side-lobe resulting from an incomplete number of oscillations of the modal power in the grating length *(bottom right)* modal power for the first four reflectivity side-lobes either side of the main Bragg resonance
section are the most common pigeon-hole categories for fibre Bragg gratings: uniform gratings; apodised gratings; chirped gratings; superstructure gratings.

2.2.1 Uniform Fibre Bragg Gratings

A uniform FBG comprises a region of constant-amplitude photo-induced refractive index modulation with a single spatial period (see figure 2.2). This type of grating, numerically described by equation (2.22), is typified by a narrow-band reflection peak at the Bragg wavelength where the structure provides exact phase matching into the counter-propagating core-guided mode. The main reflection band is surrounded by secondary reflection peaks (side-lobes) which have well-defined separation and extend over a large spectral window: the magnitude of these peaks reduces with increasing detuning from the main Bragg resonance. Shown in figure 2.8 are the calculated reflectivity and group delay of uniform 25 mm FBGs with different refractive index modulation depths. Note that as the coupling strength
increases, wavelengths away from the exact Bragg resonance, but within the band gap, are reflected predominantly from only the front part of the grating: the penetration depth is quite small (this is apparent from the group delay characteristic). It is also seen that the bandwidth of the grating increases significantly as the $\kappa l$ product becomes large. The plateau level in the group delay corresponds to the time taken for light to propagate half-way into the grating and back. The large peaks in the group delay occur in the regions of vanishingly-small reflectivity, and correspond to the case where light is trapped almost completely in the grating.

Conceptually the most simple structure, it is often assumed that the first generation of fibre Bragg gratings were uniform devices: whilst there may have been no deliberate attempt (or provision in the fabrication system) to generate a non-uniform structure, it is unlikely that these historic devices were, to any degree of certainty, truly uniform in nature. The application of uniform gratings is predominantly filtering. The usefulness of such devices is restricted, however, as the contrast between the level of reflection at the Bragg resonance and the secondary reflections of the side-lobes is small (the exact contrast is dependent on the specific details of the device).

### 2.2.2 Apodised Fibre Bragg Gratings

The high-specification, low-tolerance demands of telecommunications system designs, especially with the advent of wavelength division multiplexing (WDM), render the uniform FBG almost redundant. The cross-talk requirements for filtering WDM channels is ideally 60 dB (at least 30 dB): this specification cannot be met by a uniform FBG unless very wide channel separations are employed. Numerous other applications also benefit from a narrow-band filter/reflecter with side-lobe suppression far greater than can be achieved with a uniform grating.

#### 2.2.2.1 Side-Lobe Suppression

The seemingly restrictive problem of strong side-lobes associated with uniform fibre Bragg gratings can be essentially eliminated by tapering the amplitude of the refractive index modulation to zero at either end of the structure; this modification to the grating is known as apodisation [Matsuhara and Hill, 1974] [Cross and Kogelnik, 1977]. The smooth refractive index modulation envelope of an apodised grating has the effect of greatly suppressing the level of the side-lobes in the spectral response; depending on the exact apodisation profile used it is possible to reduce the level of the side-lobes by at least 60 dB (although this is realised more
Introduction to Fibre Bragg Gratings

easily in theory than practice). The spectral response of an apodised FBG is shown in figure 2.9, compared to an equivalent unapodised grating.

2.2.2.2 Effective Coupling Length of Apodised FBGs

It should be noted that the expression given in equation (2.23) predicts the strength for an unapodised grating for a give coupling parameter, $\kappa$. For an apodised grating, however, the coupling constant varies along the grating length; in order for equation (2.23) to be valid it is necessary to define an effective coupling parameter for an apodised grating, where [Kogelnik, 1976]:

$$ (\kappa l)_{\text{eff}} = \int_{-l/2}^{l/2} \kappa(z) \, dz $$

(2.32)

For a symmetrically apodised grating this can be expressed as:

$$ (\kappa l)_{\text{eff}} = \kappa_{\text{max}} l_{\text{eff}} $$

(2.33)
where \( l_{\text{eff}} \) is the full-width half-maximum of the apodisation profile. In figure 2.9 the grating is apodised with a Blackman profile defined by:

\[
\Delta n(z) = \Delta n_{\text{max}} \frac{1}{2.38} \left\{ 1 + 1.19 \cos(2\pi z) + 0.19 \cos(4\pi z) \right\}
\]  

(2.34)

Such a profile has a ratio of effective length to physical length of 0.42. Correspondingly, the length, or the maximum index modulation depth, must be increased by a factor of 1/0.42 to obtain a grating with the same reflectivity as its unapodised equivalent. It is for this reason that the Blackman apodised FBG of figure 2.9 has a length of 47.6 mm, compared to the 20 mm length of the unapodised FBG.

2.2.3 Chirped Fibre Bragg Gratings

The uniform and apodised FBG find their niche in filtering applications. Their wavelength-selective phase-matching is used to either redirect (when used in reflection) or attenuate (when used in transmission) optical signals and there is little application, or consideration, of their dispersive potential (although this may be short-sighted [Ibsen et al., 1998a]). Increasingly, though, researchers have been investigating the possibilities of using fibre Bragg gratings to modify the phase-relation between the different wavelengths comprising optical signals.

2.2.3.1 Differential Group Delay

By changing the period (chirping) of the refractive index modulation along the grating length it is possible to realise a device where the Bragg phase-matching wavelength is spatially dependent: the optical bandwidth of the main Bragg reflection is correspondingly broadened and different wavelengths within the main reflection band are effectively reflected from different depths into the grating (see figure 2.10). The wavelength-dependent position of the phase matching region leads to a differential group delay for wavelengths reflected by the grating. The total group delay offered by a chirped grating is determined by the time taken for
light to propagate all through the grating and back. If the grating is linearly chirped with a range of Bragg wavelengths $\lambda_1(z = 0)$ to $\lambda_2(z = l)$ defining a reflection bandwidth $\Delta \lambda$, then the dispersion, $D$, is (to the first approximation) given by:

$$D = \frac{2n_{\text{eff}}}{c l \Delta \lambda}$$

(2.35)

where $n_{\text{eff}}$ is the effective refractive index of the core-guided mode, and $c$ is the vacuum speed of light.

Applications of the extremely useful (and controllable) dispersive characteristic of linearly chirped fibre Bragg gratings have been prolific. Most notably chirped FBGs have been demonstrated as devices in optical transmission systems to compensate the dispersion of fibre links (see section III and, for example: [Ouellette, 1987] [Kashyap et al., 1996a,b] [Dong et al., 1997a] [Grudinin et al., 1997] [Gnauck et al., 1999]).
2.2.3.2  Apodised Chirped Gratings

The use of chirped FBGs usually demands a highly uniform dispersion characteristic (except for application in transmissive configurations, such as band-rejection or gain-shaping filters). Unapodised chirped FBGs exhibit undesirable non-uniformity in both the reflection and group delay response across the main reflection bandwidth. The use of apodisation with chirped gratings can dramatically reduce this problem, resulting in almost an uniform reflectivity and a highly-linear group delay profile across the reflection bandwidth (see figure 2.11). The example shown has a fringe contrast tapered with a raised cosine profile over 2 cm at either end.

2.2.4  Superstructure Fibre Bragg Gratings

The most complex class of fibre Bragg grating are often referred to as superstructures. They usually are distinguishable by a spatially-periodic (or quasi-periodic) modulation to the amplitude of the refractive index profile (sometimes known as a super-envelope) which is deliberately introduced during the fabrication process.

2.2.4.1  Multi-Channel Superstructure Gratings

A major application of superstructure fibre Bragg gratings to date has been to generate more than one Bragg reflection peak (multi-channel gratings). In this case the super-envelope is periodic: the length of the repeating section determines the spectral separation of the peaks, whilst the shape of the envelope in the repeating sections determines the spectral envelope that encompasses the various peaks. This can be understood from basic Fourier arguments, or alternatively by considering the overall refractive index pattern as the sum of several gratings with different wavelengths. Various approaches have been taken to superstructure gratings from a rudimentary binary modulations [Eggleton et al., 1994] [Ouellette et al., 1995] [Loh et al., 1999], to complex phase-shifted structures capable of generating an exact number of equal-strength Bragg reflections [Ibsen et al., 1998b,c].

2.2.4.2  Superstructures for Idealised Spectral Response

More recently complex superstructure gratings have been designed to give filters with very sharp edges and optimised in-band dispersion characteristics (see chapter 10). Of particular interest are the new grating designs developed by inverse-scattering methods [Feced et al., 1999a,b] that offer dispersion-less filters [Ibsen et al., 1998d], and linearised dispersion compensators with an extremely square
spectral response [Durkin et al., 2000]. These structures are likely to dominate the next generation of fibre Bragg gratings, requiring sophisticated fabrication systems, but offering significant gains in performance.

2.3 **Fibre Bragg Grating Formation**

The fibre Bragg grating, at the time of writing, is approaching the technologically-mature age of twenty-one. Despite increasingly widespread application and sophisticated fabrication schemes, there is still no definitive description of the physical mechanism responsible for photosensitivity in optical fibres; a good review of photosensitive mechanisms is given in [Othonos and Kalli, 1999]. The following section describes the landmark experiments in the history of fibre Bragg gratings.

2.3.1 Self-Organised Grating Formation

In a 1978 experiment at the Canadian Research Centre, a group of researchers, led by Hill, launched an intense beam from an Ar-ion laser into a germania-doped optical fibre [Hill et al., 1978] [Kawasaki, et al., 1978]. Over a period of minutes, an almost complete drop in power from the output of the fibre was observed; subsequent spectral analysis highlighted a narrow-band reflection at the wavelength of the laser radiation (488 nm). This marked the historical birth of fibre Bragg gratings via a process now referred to as self-organised grating formation [Hill and Meltz, 1997].

2.3.1.1 Initiation of Grating Formation

The end of the fibre had led initially to a partial back-reflection of the guided light. At the anti-nodes of the standing wave formed by the counter-propagating light the intensity of radiation was sufficient to initiate a previously unknown photosensitive reaction in the germanosilicate fibre core. The result: a permanent spatially-periodic increase in the refractive index of the fibre. The period of the refractive index modulation, being determined by the standing wave, was exactly equal to half the wavelength of the Ar-ion radiation: the self-consistency of this grating formation process gave rise to an increasingly strong Bragg phase matching, and hence back reflection, of the radiation that was responsible for the photosensitive reaction.
The process of self-organised grating formation, leading to 'Hill gratings', has limited application since the Bragg phase matching wavelength necessarily induces a photosensitive reaction in the optical fibre: this not only limits the choice of available wavelengths, but leads to a naturally unstable device. The field consequently lay dormant for some years before more detailed studies indicated that the photosensitivity observed at 488 nm was a two photon process, which could be much more efficiently initiated with ultra-violet single photons of wavelengths ~ 244 nm.

2.3.2 Grating Formation via Single-Photon Processes

The realisation of single-photon UV-induced photosensitivity in germanosilicate optical fibres had profound consequences: the concept of the fibre Bragg grating was no longer an academic curio, but had the very real potential to be developed into functional fibre devices. The photosensitive reaction was found to be orders of magnitude more efficient when initiated by a single photon process: in this case the refractive index of a fibre core can be significantly changed by exposing through the side of the fibre, rather than along its length.

2.3.2.1 Grating Formation by Side-Exposure

The interest in fibre Bragg gratings was rekindled when, in 1989, a group led by Meltz showed that a grating could be formed by intersecting two 244 nm beams at the fibre core [Meltz et al., 1989]: the grating period is determined by the period of the corresponding UV interference pattern (see figure 2.12). The Bragg phase matching wavelength of these side-written gratings is not constrained by the wavelength of the laser source used to initiate the photosensitive reaction, but
rather is determined by the angle between the intersecting beams. This increased the potential of the fibre Bragg grating enormously, leading directly to their subsequent application as precise wavelength filters in telecommunications systems, as narrow-band reflectors in the cavities of fibre-lasers and as both point and distributed reflectors in sensors applications [Hill and Meltz, 1997] [Giles, 1997].

2.3.3 Fibre Requirements for Fibre Bragg Gratings

2.3.3.1 Overlap of Mode Field and Grating

The effective refractive index modulation depth, as introduced in (2.14), is determined both by the induced refractive index change in the photosensitive region (usually the fibre core) and by the fraction of the mode power that geometrically overlaps the grating. The reader is referred to [Erdogan, 1997] for details of how this may be calculated for a given fibre geometry. The design of optical fibres has not been a research topic for this thesis, and is thus not covered. For the majority of the fibres used for this work, about 75% of the mode power overlaps with the induced refractive index grating, so $\Delta n_{\text{eff}} \sim 0.75\Delta n$.

2.3.3.2 Increasing Photosensitivity

A number of approaches have been made to increase the sensitivity of germanosilicate glasses to UV radiation. Again, this is not the subject of this thesis, so only a brief review of the available techniques is given. The most common technique is to keep the fibre in a high-pressure (50-200 bars) atmosphere of hydrogen or deuterium (the former exhibits loss at 1.55 $\mu$m due to the creation of a water-peak at $\sim 1.4 \mu$m). Co-dopants, such as boron and tin, are known to increase photosensitivity, in addition to localised heating prior to UV exposure by flame-brushing or CO$_2$ laser irradiation.

2.4 SUMMARY

Optical fibres support three distinct type of mode: core-guided mode(s); cladding-guided modes; non-guided radiation modes. Periodic perturbations to the guiding structure can lead to power transfer between different modes at certain wavelength. Short-period fibre Bragg gratings usefully provide coupling between counter-propagating core-guided modes; additionally, there is a certain degree of
power transfer from a core-guided mode to a counter-propagating cladding-guided mode. Long period gratings couple power between co-propagating modes. The spectral response of fibre gratings is well-described by coupled-mode equations, and, more efficiently, by cascading discrete transfer matrices. In the band-gap of a fibre Bragg grating (around the wavelength of exact Bragg reflection) the power in counter-propagating core-guided modes varies exponentially. Outside the band gap there is an oscillatory transfer of power to-and-fro between these modes. For wavelengths where there is an incomplete number of oscillations in the grating length there are side-lobes in the reflectivity response. Apodisation (tapering the fringe contrast to zero at the grating ends) minimises this effect and allows fibre Bragg gratings to be used as efficient narrow-band optical filters.

Gratings with a spatially-variant period (chirped gratings) can have a broad reflectivity and a highly dispersive response. The in-band reflectivity and group delay can be linearised by apodisation, making the chirped fibre Bragg grating an attractive option for compensating the dispersion encountered by short optical pulses during transmission through long fibre links. Fibre gratings can be designed and fabricated with complex refractive index profiles to give improved spectral characteristics, or multi-channel operation. It is envisaged that this will be an important avenue for research and development in the future.

Bragg reflection was first observed in optical fibres as a self-organised refractive index structure induced by two-photon absorption at the anti-nodes of a standing wave of 488 nm Ar-ion radiation. Realisation of single-photon photosensitivity at UV wavelengths led to gratings formed by side-exposure of an UV interference pattern. Fibre gratings made by this approach can be designed to reflect at any wavelength according to the details of the interference pattern. This has been of paramount importance in establishing their appeal for WDM telecommunication applications.
Fibre Bragg Grating Fabrication
This chapter provides a brief overview of the technology used to fabricate fibre Bragg gratings. The two methods of generating a period interference pattern (interferometers, and the $\pi$ phase mask) are introduced and their relative merits discussed. The historical development of fabrication methods is presented, with the rationale for development explained. The chapter ends by discussing the techniques developed to date to fabricate long gratings, an introduces the concept of the continuous grating fabrication technique, which is presented in detail in the following chapter.

3.1 **Generating Periodic Refractive Index Patterns**

The fundamental tool for generating fibre Bragg gratings is the optical arrangement used to create a periodic UV interference pattern. Current technology in this area is split between using the traditional two-beam interferometer approach and a transmissive optical diffraction element, known as a phase mask [Meltz et al., 1989] [Hill et al., 1993]. The following section introduces the two approaches and discusses their relative merits.
3.1.1 **Amplitude-Division Interferometry**

A traditional way of generating spatially-periodic intensity patterns is to split a monochromatic beam into two components which are then recombined with some angular separation. At the region of intersection there is a sinusoidal variation of intensity. The spatial-period of the intensity fringes, $\Lambda$, is dependent on both the wavelength of light used, $\lambda_{uv}$, and the angle of intersection, $\theta$, such that:

$$\Lambda = \frac{\lambda_{uv}}{2\sin(\theta/2)} \quad (3.1)$$

where $\lambda_{uv}$ and $\theta$ are both considered an air. The interferometric approach to generating interference fringes is inherently flexible since the fringe separation (and thus the period and Bragg wavelength of the UV-written fibre grating) can be changed simply by varying the angle of intersection.

3.1.1.1 **Drawbacks of an Interferometric Approach**

The interferometer looses favour, however, since it is highly reliant on the characteristics of the laser used and can be susceptible to both variations in environmental conditions and the quality of the optics used. In order to maximise the stability of the interferometer it is important to choose a balanced design where the two interfering beams have the same (or nearly the same) optical path length: specifically, the optical path lengths of the two arms should differ by significantly less than the coherence length of the laser to avoid jitter of interference fringes caused by stochastic shifts in the relative phase of the two beams. It is also preferable that one of the beams is not spatially inverted with respect to the other to avoid any problems associated with spatial coherence across the laser beam. The interference pattern quality is also compromised by any imperfections in non-common-path optics.

3.1.2 **The Phase Mask**

A phase mask is a transmissive diffracting optical element. Rather than the periodic variation in transmissivity of an amplitude mask, the phase mask has a periodically-etched surface relief pattern that induces changes in phase across an incident wavefront. A photo-resist film on a UV-transparent fused silica substrate is exposed to define a structure with the desired period; this fabrication step can be made either holographically, or by using a scanning electron beam. The surface-relief profile in the fused silica substrate is then generated by a processes such as
reactive ion etching, where the regions of exposure in the photo-resist film define the etch pattern.

3.1.2.1 Preferential Diffraction

The primary objective of the phase mask is to generate an interference pattern similar to that obtained by interferometric means: ideally the near-field interference pattern should comprise intensity fringes with a period and phase that does not vary with either distance from the phase mask or with position across the beam. The advantage of a phase mask over a traditional amplitude mask comes from the fact that, by carefully controlling the depth and profile of the surface relief pattern, it is possible to maximise the power in the ±1 diffracted orders (typically > 40% in each) and minimise the power in the zeroth order (~ 1% for a well-made phase mask).

The design for an ideal phase mask [Qiu and Sheng, 1999], where the incident radiation is normal to the surface, is that it should have a square relief pattern with duty cycle of 0.555 and a depth that leads to a phase change of 1.11\(\pi\) compared to the same distance of free-space propagation, for a desired wavelength of incident radiation; this leads to minimisation of the zeroth order power. An alternative configuration is based on equalising the power in the zeroth and first diffracted orders for a beam with non-normal incidence on the phase mask; in this case the interference pattern has the same period as the mask [Anderson et al., 1993]. The normal-incidence configuration is generally preferred in the fabrication of fibre Bragg gratings because alignment is more straightforward.
3.1.2.2 Near-Field Interference Pattern of a Phase Mask

The near-field interference pattern of a $\pi$ phase-mask thus approximates the case of two interfering beams in the region where the $\pm 1^\text{st}$ diffracted orders overlap (see figure 3.1). The period of the interference fringes, from this simple consideration, is equal to half that of the relief pattern itself. The angle subtended between the $\pm 1^\text{st}$ orders in the far-field and the normal to the phase mask, $\theta$, is:

$$\theta = \sin^{-1} \left( \frac{\lambda_{uv}}{\Lambda_{pm}} \right)$$

(3.2)

where: $\lambda_{uv}$ is the wavelength of the incident UV beam in air; $\Lambda_{pm}$ is the period of the surface relief pattern (typically $\theta$ is $\sim 13^\circ$ for Bragg wavelengths at 1550 nm in germanosilicate fibres). It follows that the extent of this region behind the phase mask is determined by the diameter of the UV writing beam and the angle between the primary diffraction orders, such that:

$$d_{\text{max}} = \frac{D}{2 \tan(\theta)}$$

(3.3)

where the diameter of the UV beam is $D$. Note also that the fraction of the $\pm 1^\text{st}$ orders contributing usefully to the interference pattern is given by:

$$\frac{P_{\text{fringe}}(x)}{P_{\text{tot}}} = 2E_1 \left[ \frac{d_{\text{max}} - x}{d_{\text{max}}} \right] \quad (0 \leq x \leq d_{\text{max}})$$

(3.4)

where: $P_{\text{fringe}}(x)$ is the UV power in the fringe region; $P_{\text{tot}}$ is the total UV; $E_1$ is the diffraction efficiency into the $\pm 1^\text{st}$ orders; $x$ is the distance from the phase mask.

The residual power in diffracted orders other than the $\pm 1^\text{st}$, however, leads to a more complex near-field interference effect first described by Talbot [Talbot, 1836]. Detailed theory and experimental evidence [Prohaska et al., 1994] [Dyer et al., 1995] shows that the interference pattern can contain a ‘self-imaged’ component that has the same spatial period as the mask in the transverse direction, but is also periodic in the direction normal to the phase mask surface. The purest interference pattern behind a phase mask is somewhere close to the transition region between the near-field and the far-field where all diffracted beams with orders greater than $\pm 1$ have stopped overlapping. This occurs at a distance given by (3.3) with the argument of the tangent equal to $2\theta$ (corresponding to the $\pm 2^\text{nd}$ diffracted orders); note that (3.4) predicts that the fractional contribution of the first diffracted orders to the interference pattern is only $\sim 42\%$ at this point, assuming 40% diffraction efficiency into each of the first orders. The presence of remnant
power in the zeroth order, whilst small, is not insignificant, however, since there is always interference between it and the $\pm 1^{st}$ orders. The effect of this is to give some modulation of the fringe pattern in the direction normal to the phase mask; this point, and its consequences, are discussed in chapter 5.

3.1.2.3 Advantages of Phase Masks

There is a huge gain in stability offered by the phase mask solution, compared to interferometry-based techniques, since the beam is not split until the phase mask. The only interferometric part comprises the path of the diffracted orders from the exit face of the phase mask to the core of the photosensitive optical fibre; this is typically in the order of 100 $\mu$m since the diameter of standard fibre (with the coating removed) is 125 $\mu$m. This largely common-path technique is also beneficial since it drastically reduces the coherence requirements of the radiation source: this allows excimer lasers to be used much more efficiently than is possible with an interferometer.

3.1.2.4 Disadvantages of Phase Masks

As with many things that benefit from being highly-stable, the main disadvantage of the phase mask is its inherent lack of tuneability: with no direct possibility for changing the angle of intersection between the $\pm 1^{st}$ diffracted orders, the strength of phase-mask based techniques is their optical simplicity, stability and repeatability. When fabricating a grating by using a phase mask it is necessary that the host fibre be within the near-field interference pattern. Such small separations between phase mask and fibre ($\sim 100 \mu$m) mean that any residue remaining on the fibre after the coating has been stripped is likely to be ablated by the high-power UV writing beam on to the phase mask. This effect can significantly change the efficiency of diffraction into different orders and hence change the form and contrast of the near-filed interference pattern. Additionally, phase masks do not offer flexibility in the design of chirp and apodisation profiles of FBGs without significant development of the fabrication technique (see the following section).

Phase masks fabricated by e-beam technology are made of small regions 'stitched' together. Errors in the phase continuity of the mask are directly translated into glitches in the grating that ultimately limit the device quality [Williams et al., 1997] [Liu et al., 1997] [Mihailov et al., 1998]. Phase masks fabricated by holographic means tend to have poor characteristics towards the edge of the mask (especially if it is several centimetres in length) as shown in chapter 6.
ings fabricated by phase mask-scanning may be repeatable, they are unfortunately, to some degree, repeatably flawed.

3.2 **FIBRE BRAGG GRATING FABRICATION SCHEMES**

This section describes the most noteworthy approaches to fabricating fibre Bragg gratings and the technology that has been used to increase their flexibility; chapters 3 and 4 deal extensively with the theoretical background and experimental requirements of the technique used throughout this thesis. For further reading excellent reviews are given elsewhere: [Russell et al., 1993] [Bennion et al., 1996] [Hill and Meltz, 1997] [Campbel and Kashyap, 1994] [Kashyap, 1999] [Othonons and Kalli, 1999].

3.2.1 **Stationary Holographic Exposure**

The first side-exposure FBGs were fabricated using a continuous wave (CW) frequency-doubled Ar-ion laser and an interferometer arrangement [Meltz et al., 1989]. Both fibre and interference pattern were stationary so the gratings were length-limited by the spot size of the beam (which was focused to 4 mm x 125 µm). A five minute exposure of 18.5 mW 244 nm UV caused index changes of ~ 3 x 10^-5 which is sufficient to observe Bragg reflection of ~ 5% (see previous chapter).

3.2.2 **Phase-Mask Scanning Techniques**

A simple method of fabricating FBGs is to scan the UV source beam across a phase mask behind which there is a stationary host fibre [Hill et al., 1993] (see figure 3.2): this effectively imprints the phase mask profile directly into the fibre core and the gratings are hence limited by the length and quality of available phase masks, [Williams et al., 1997] [Liu et al., 1997] [Mihailov et al., 1998]. This basic technique is well suited to the mass production of short gratings with identical profiles but is inherently inflexible.

3.2.2.1 **Moving Fibre/Phase Mask Technique**

The phase-mask scanning approach may be extended by introducing a relative axial motion between the fibre and phase mask [Cole et al., 1995]. By translating the
fibre with a constant velocity relative to the phase mask it is possible to write gratings detuned from the fundamental phase mask wavelength; a constant acceleration allows chirped structures to be fabricated (this effect is similar to a Doppler shift). Rapidly dithering the fibre during writing makes it possible to control the local fringe contrast and hence apodise the grating without inducing a change in the background index. The informatively titled ‘moving fibre/phase mask-scanning beam technique’ was the first to implement these extensions and has been successful in allowing gratings with a complex structure to be fabricated [Loh et al., 1995a].

The range of wavelength-detuning achievable, however, remains limited by the beam-diameter: the maximum detuning approximately corresponds to the case where the phase of the grating changes by $\pi$ over a length equal to the extent of the UV fringes [Cole et al., 1995] (smaller beams allow larger detuning). The maximum wavelength shift is thus determined by the minimum permissible depth of interference pattern (see section 4.1.2): a realistic Bragg detuning range in the order of 10-15 nm may be achieved.

3.2.2.2 Increasing Flexibility with Tuneable Interferometers

There have been several recent schemes presented that allow tuning of the UV fringe period without requiring either chirped phase masks or direct reliance on the moving fibre/scanning beam technique. These methods are based on remotely recombining the $\pm 1^{st}$ diffracted orders from the phase mask to be scanned, using an interferometer that can be controlled to change the angle subtended by the two beams at the remote point of intersection in the fibre. All techniques presented to date [Fonjallaz et al., 1997] [Cortès et al., 1998] [Yoffe et al., 1999] rely on the two $\pm 1$ order-beams scanning long mirrors. Not only is the quality of the grating thus
limited by imperfections in the phase mask, but also by the quality of the mirrors used; changes in the mirror flatness will lead to movement, and a probable change in the period, of the interference fringes.

3.2.2.3 A Problem of Length
The fabrication of gratings by direct UV scanning of a phase mask is highly attractive due to the fundamental optical simplicity of the technology involved; some of the enhancements described above, however, must increase the complexity and tolerances considerably. All of these techniques remain fundamentally limited, though, since the maximum length of the grating is determined by the size of the phase mask. Commercial phase masks are now available with 15 cm length, but the quality and uniformity of such devices is questionable. For applications such as multi-channel dispersion compensation (see section III) it is ideal to have gratings with lengths of the metre scale. The following sections describe approaches taken to fabricate gratings longer than the phase mask used to produce them.

3.2.3 Stitched Gratings
The length of gratings may be increased beyond that of the beam diameter or phase mask length if it is built up from a concatenation or overlap of sub-gratings. The fibre Bragg grating is highly sensitive to imperfections in the refractive index structure: attempting to join two or more grating sections is thus highly likely to give non-ideal characteristics unless extreme care is taken to make the grating structure as continuous as possible.

3.2.3.1 UV Phase-Trimming
The first approach to fabricating a quasi-continuous grating was based on butting together many short gratings (typically phase mask length sections) written separately in a single piece of fibre [Kashyap et al., 1996a,b]; the phase between each sub-section was controlled using UV post-processing of the refractive index in the joining regions (see figure 3.3) in order to trim the phase relationship between adjoining sections. Imperfections in this stitching lead to large glitches in the response of the grating, severely limiting the successful application of this technique. Differential ageing of stitching regions can lead to problems later in the life of the device.
3.2.3.2 Phase-Coherent Stitching of Grating Sections

More recent approaches to stitching have attempted to achieve a phase-sensitive alignment between the end of a previously written grating and the interference pattern of the phase mask used to write the subsequent section [Rourke et al., 1999]. The advantage of this approach is that, ideally at least, the grating structure should be inherently coherent and thus not require post-processing techniques, such as the UV phase-trimming described above. The basis of these techniques is to achieve alignment of the UV interference pattern with the periodic absorption/bleaching of a fluorescence mechanism associated with the photo-induced refractive index change (see figure 3.3).

3.2.4 Continuous Grating Fabrication Techniques

A more elegant solution to fabricating long gratings is to synthesise the structure with many short (beam-sized) exposures that are spatially separated by one, or several, grating periods. The following section describes the different technological routes, taken to date, that allow continuous gratings to be fabricated with lengths greater than the phase mask and UV spot-size used.
3.2.4.1 Modulating UV-beam Approach

The first, and to date most elegant, approach to this technique involves exposing a fibre to a sequence of spatially-separated, short (beam diameter sized) UV interference patterns such that the successive exposures are separated by a controlled phase and may overlap somewhat [Asseh et al., 1997]. The technique used throughout this project is a logical progression of the moving fibre/phase mask-scanning beam technique that results in an approach cosmetically similar to that of Asseh et al. The relative motion of the interference pattern and fibre is turned on its head, however, and the UV beam remains stationary on the phase mask whilst the fibre is translated [Cole, 1997]. In order not to completely wash out the periodic index change in the fibre core the UV beam is blocked when the fibre has moved by a fraction of one interference pattern and then unblocked when the fibre has moved by one whole fringe; successive exposures gradually build up the grating structure (see figure 3.4). The control of the sub-section phase relation on a fringe-by-fringe basis leads to a versatile technique offering a solution for fabricating gratings of, theoretically at least, arbitrary length. In practical terms it is preferable to trigger the UV exposures from interferometric position measurements of the fibre displacement: this limits the maximum length of gratings that can be fabricated in this manner to the translation range of an available linear motion stage.

3.2.4.2 Technique for Unlimited-Length Continuous Fibre Bragg Gratings

The first technique (in principle) capable of fabricating arbitrarily long FBGs uses a pulsed UV pattern to build up the grating as above, but the fibre is spooled, rather than translated, past the phase mask [Brennan III et al., 1999]. Whilst there is no longer the length restriction imposed by using a linear translation stage, this means that the pulses cannot be interferometrically controlled. Instead, the UV
beam is modulated with a constant frequency based on the assumption that the fibre is translating with a constant velocity. The quality of the gratings presented to date suggest that this is a very dangerous assumption to make.

3.2.4.3 Mechanical-Scanning Implementation

In another recent variation on the continuous grating fabrication technique, the fibre is translated continuously whilst a phase mask is mounted on a PZT stage driven with a saw-tooth motion [Yoffe et al., 1999]. For the majority of the PZT cycle the phase mask and fibre have no relative motion whilst they both translate by an integer-number of grating fringes; the PZT flies back rapidly at the end of the cycle its original position. The grating quality of this technique could be limited by the quality and accuracy of the PZT motion (especially since PZT stages are marred by hysteresis). The frequency response of PZT stages may also limit the accurate realisation of the saw-tooth drive motion.

3.3 SUMMARY

The period of fibre Bragg gratings is less than the spot size readily achievable with basic focusing optics; it is thus preferable to use an interference pattern to fabricate fibre Bragg gratings via a photo-induced refractive index change. Two basic methods exist for generating such interference patterns: amplitude-division interferometry, and the near-field interference effects behind a $\pi$ phase mask. Whilst interferometers offer natural tuneability of the fringe period, they are inherently sensitive to environmental perturbations and demand high levels of both temporal and spatial coherence from the light source used. Phase masks offer a very stable solution, since the beam is only non-common-path for several hundred microns. The fundamental lack of wavelength-tuneability, however, makes the phase mask an object of desire for repeatable production, rather than for flexible research. Issues with the complexity of the near-field interference pattern also raise questions as to the fundamental applicability of basic phase mask scanning techniques.

The development of side-exposure fabrication techniques increased the potential application of fibre Bragg gratings enormously. The first example using a stationary holographic exposure of UV laser radiation was quickly followed by phase-mask scanning techniques. The inflexibility of these later techniques was addressed by the Moving Fibre/Phase Mask technique that permitted accurate control over both the amplitude and phase of the refractive index structure com-
prising a grating. Similar methods have expanded on this technique by using a combination of a phase mask and two-beam interferometry to give more flexibility of the grating wavelength. All phase mask-scanning techniques, however, fundamentally fall foul to the issues of length (~10 – 15 cm) and quality (dubious, but improving) of readily available phase masks.

Two fundamental approaches exist that address the issues of phase mask-based length limitation: grating sections can be ‘stitched’ together, or the grating can comprise may thousands (or millions) of single-exposure sub-grating sections that overlap with a well controlled phase relation. Stitched gratings have been demonstrated whereby completely separate sections have their phase relation trimmed by UV-induced refractive index post-processing in the joining section; this clearly yields non-ideal results. More recently stitched gratings have been made where high levels of inter-section phase coherence are achieved by aligning the interference pattern used to inscribe a section with the existing refractive index structure (and associated periodic bleaching of a fluorescence mechanism). The most attractive approach to date for fabricating gratings longer than a phase mask is based on using many overlapping beam-sized grating sections generated by pulses of UV radiation that are typically triggered by interferometric measurement of the fibre host to the grating, such that successive exposures are separated by a well-controlled number of grating periods (or fractions thereof).
This chapter introduces the principles of the continuous grating fabrication technique and describes the experimental arrangement developed to allow the realisation of the first high-quality metre-long gratings, and novel complex grating superstructures. The operational characteristics of the method are discussed in detail, with particular emphasis on the limitations that will be encountered for various experimental arrangements. Methods for achieving broad wavelength detuning are discussed, and the basis for the extremely flexible apodisation technique discussed. Examples are shown of a high-quality apodised grating and a complex superstructure fabricated by the technique.

4.1 Description of the Continuous Grating Fabrication Technique

The continuous grating fabrication technique [Cole, 1997] was designed to make high-quality gratings of a length exceeding that of available phase masks. The method, conceived at the ORC in 1995 by Martin Cole, Dr. Richard Laming, and Professor Michalis Zervas, combines ideas from the Moving Fibre/Phase Mask technique [Cole et al., 1995], the essence of point-by-point long-period grating fabrication techniques, and builds on work of an unpublished step-and-repeat method [Cole, 1997]. A considerable amount of the author’s time has been spent in developing this technology to permit the reliable fabrication of metre-long gratings.
4.1.1 Principle of Operation

Turning the traditional idea of phase mask-based FBG fabrication upside-down, in this technique the UV beam does not scan the phase mask to imprint an interference pattern into a stationary fibre: rather, the beam and phase mask are (nominally) stationary, whilst the fibre translates continuously through the interference pattern. In order to generate a refractive index grating (rather than a uniform increase in refractive index) the UV beam is modulated such that successive exposures are separated by a single grating fringe (or a well-controlled fraction thereof). This concept is illustrated in figure 4.1.

A CW UV beam passed through a modulator and is incident on a \( \pi \) phase mask with a period double that of the desired grating structure. The near-field interference pattern of the phase mask exposes the photosensitive core of the optical fibre. The host fibre is translated by a linear translation stage. The position of the stage is measured (interferometrically) and used to trigger exposures of the UV beam when the stage has moved by a single grating period. There are many interference fringes within the extent of the UV beam, so each grating fringe is the result of many separate exposures.

4.1.1.1 Distinguishing Features of the Continuous Grating Fabrication Method

The continuous grating fabrication technique may be identified by the following characteristics:
The Continuous Grating Fabrication Technique

- a continuously translating host fibre
- a (nominally) stationary interference UV pattern
- a CW UV beam modulated every grating fringe
- multiple exposures of every point on the fibre

4.1.1.2 Advantages Over Other Fabrication Techniques

The continuous grating fabrication technique has several key advantages over other grating fabrication techniques:

- gratings can be much longer than available phase masks
- grating characteristics and designs are not limited by the characteristics of available phase masks
- Bragg wavelength and grating fringe depth can be controlled extremely accurately on a very localised level
- the grating quality is not ultimately limited by phase mask quality
- gratings are continuous in nature, and are free from the large phase glitches seen with stitched gratings
- a diverse range of structures can be made without the need for complicated optical arrangements
- the use of a modulated CW source avoids the problems of fibre damage and noise associated with high-power pulsed laser sources

4.1.2 Reducing the Effects of Errors

It may seem pessimistic to introduce the effect of errors so soon in the description of a fabrication technology, but reality bites (especially if your want is to fabricate metre-long optical structures requiring high-levels of phase coherence). The continuous grating fabrication technique naturally throws the rudiments of statistical error reduction at the problem of noise and circumvents many problems inherent to other grating fabrication techniques.

4.1.2.1 Central Limit Theorem

The Central Limit Theorem (CLT) of statistics describes the behaviour of variables that result from the sum of many others [Barlow, 1989: chapter 4]. It states that if $X$ represents the sum of $N$ independent variables $x$, each from a distribution with a
mean value \( m_i \) and variance \( V_i \) (or \( \sigma_i^2 \)), then the distribution for \( X \) has an expectation value of:

\[
\langle X \rangle = \sum m_i
\]

and a variance:

\[
V(X) = \sum V_i = \sum \sigma_i^2
\]

(additionally the distribution becomes Gaussian for large \( N \)). If the measured quantity is a constant, \( m \), then assuming the uncertainty in each of the \( N \) measurements is equal at \( \sigma \), then the expectation value of the sum is simply:

\[
\langle X \rangle = \sum m
\]

and:

\[
V(X) = N \sigma^2
\]

The average of \( X \), \( \bar{x} = X / N \), has a variance given by:

\[
V(\bar{x}) = \frac{V(X)}{N^2} = \frac{\sigma^2}{N} \]

The standard error of the averaged measurement from the measured quantity itself is subsequently \( \sigma / \sqrt{N} \).

### 4.1.2.2 The Effect of Beam Size

The Central Limit Theorem yields the result that if you need to measure something, measure it many times and the average of the measurements becomes increasingly accurate (with the square-root of the number of measurements made).

The continuous grating fabrication technique is based on overlapping many such exposures separated by a single grating fringe, \( \Lambda \) (for operation at 1.55 \( \mu \)m, \( \Lambda \sim 535 \) nm). A spot of diameter \( D \) incident on a phase mask of period \( 2\Lambda \) generates a near-field interference pattern of a dominant period \( \Lambda \), comprising \( N \) fringes where \( N = D / \Lambda \). The location of these exposures is obviously of paramount importance in determining the quality of the grating, but is inherently at the mercy of quantisation and noise on the measurement of position; accurate, high-resolution measurement, on the nanometre/sub-nanometre scale is difficult (see chapter 6). It is important to note, however, that every point in the fibre is the result of the
The continuous grating fabrication technique is significantly more complex than most grating fabrication techniques: a blend of no-compromise mechanical stability and real-time hardware control is required for successful realisation of this method. The development of the experimental arrangement has been made over a period of four years. The author played a major part in developing the fabrication system to allow the reliable fabrication of metre-long gratings (with fellow students Martin Cole, and Morten Ibsen). This was the world’s first grating facility capable of fabricating high-quality continuous (not joined) gratings of such length. The essence of the grating fabrication laboratory is shown diagrammatically in figure 4.2. Following this development, the technology of the metre-long grating fabrication facility was transferred to Pirelli Cavi for commercial production. The author spent time in Milan helping commission this facility.

4.1.3.1 UV Exposure

The UV laser source used is a Coherent FreD CW Ar-ion laser with intra-cavity frequency doubling from 488 nm to 244 nm using a Brewster-angled BBO crystal. The output power at 244 nm is ~ 100 mW ± 1%. The UV laser is directed through
a Brewster-angled fused-silica acousto-optic modulator (AOM). The AOM is aligned to give preferential diffraction into one of the first diffracted orders: about 80% efficiency can be achieved. It is possible to achieve virtually full modulation contrast on switching the device by using the first diffracted order. The state of the AOM is controlled by a TTL signal from the control electronics to toggle the beam state at the correct stage positions.

The first diffracted order is directed onto a phase mask designed to minimise the zeroth diffracted order at 244 nm. The phase mask is mounted on a three-axis position adjuster for alignment purposes, and on a motorised translation stage to allow accurate and repeatable setting of the phase mask-to-fibre separation (typically ~ 50 µm). The phase masks typically used are ~ 2 mm x 2 mm in size: these dimensions are defined to allow straightforward alignment of a beam with a width of several hundred microns. The near-field interference pattern of the phase mask generates the intensity pattern required to fabricate the grating.

4.1.3.2 Fibre Tracking

The UV beam is focused to approximately 25 µm in height by a lens of 25 mm focal length in order increase the level of fluence on the fibre. The fibre is held under
tension (approx. 0.1% strain) in V-grooves at either end of the 1.2 m span. Even under tension, it is difficult to completely remove the sag of the fibre due to its weight: for the ~ 0.1% strain used there is a sag of ~ 150 µm in the middle of the fibre. It is thus not possible to achieve a high level of UV fluence on the fibre without ensuring that the beam follows the vertical position of the horizontally translating fibre. It was proposed in [Komukai and Nakazawa, 1996] that monitoring the level of fluorescence upon UV exposure that is guided to the end of the fibre (see chapter 5) provides a good way of aligning the writing beam with the fibre core. The continuous grating fabrication technique uses an extension of this principle whereby a phase sensitive feedback control circuit is used to drive a 200 µm travel PZT stage, upon which the vertical focusing lens is mounted. The Melles-Griot PZT is dithered with a frequency of ~ 20 Hz to generate a tracking signal to ensure the beam follows the height of the fibre core according to the level of fluorescence detected.

4.1.3.3 Fibre Translation and Position Measurement

The fibre is mounted onto a 42″ aluminium bar with a cross section of ~ 1.5″ x 1.5″. This is in turn mounted onto an Anorad linear translation stage with 42″ travel. The primary purpose of this bar is to provide a direct mechanical connection between the fibre ends and to overcome the possibility problems associated with flexure of the translation stage carriage [Cole, 1997]. At one end of the aluminium bar is mounted a mirror with its surface normal to the axis of motion, providing the bounds for one arm of a He-Ne interferometer (Zygo ZMI-1000). This interferometer is based on a double-pass configuration giving a position resolution of 1.24 nm (λ/512). The interferometer has convenient A-Quad-B output which is incorporated into the translation stage control circuitry to give improved motion characteristics to using the coarse glass encoder. Additionally the interferometer has a 32-bit digital output of position which is updated at a rate of 2 MHz.

4.1.3.4 Beam Modulation Control

The positions of beam state modulation (nominally on-and-off once per grating fringe) are calculated by computer according to the desired spectral response. The data is stored as 32-bit numbers, quantised in 1.24 nm ‘Zygo units’, with the most-significant bit (MSB) used to define the beam state. The last bit is randomised to reduce the effects of quantisation noise and aliasing. The control computer outputs this data via a 32-bit digital in-out card (National Instruments PCI-DIO32HS), on request, to a 32-bit hardware comparator [Cole, 1997]. This compares the current datum with the position output from the interferometer: if the fibre position is
greater than, or equal to, the last position generated by the computer, then the
beam is modulated according to the state of the MSB of the data and the next item
of data is requested from the DIO card. Note that a metre long grating comprises
approximately two million beam modulation data (two per ~500 nm grating fringe).

4.1.3.5 Control Software
Aside from sound mechanical and optical design, the continuous grating fabrication
technique relies heavily on precise computational control of the beam modulation
hardware, since the grating is designed in an entirely digital manner, essentially
independent of the optical arrangement. A significant effort was made by the
author to develop the existing software [Cole, 1997], and to establish a sound base
to facilitate the reliable fabrication of current and future grating designs. The de-
velopments are summarised below:

- pre-calculation of beam-modulation positions to minimise computa-
tional overhead during grating fabrication
- provision for a wide range of superstructures, and for importing arbitrary chirp and apodisation profiles (including dispersion-less filters, DFB structures, combined 2nd & 3rd-order dispersion compensators, multi-channel superstructures, and inverse-scattering-based designs)
- development with 32-bit operating systems and direct-memory access
data output for minimised timing-jitter

This software has been used for all gratings fabricated at the ORC since 1997, and
was also transferred to the commercial production facility at Pirelli Cavi [Garrett et
al., 1998] [Robinson et al., 1998] [Gnauck et al., 1999].

4.2 WAVELENGTH DETUNING & CHIRP
Of key importance for a grating fabrication technique is the ability to fabricate
grating with periods away from that determined by a phase mask: using a different
phase mask for every wavelength is a very expensive (and cumbersome) approach.
Additionally there must be some provision for fabricating chirped gratings where
the period of the structure varies with position.
4.2.1 Basic Detuning Limits

This fabrication technique allows gratings to be written at detuned wavelengths by simply changing the phase between successive exposures (a linear change of phase implies a change of wavelength). The issue of how much dephasing can be tolerated is discussed below.

4.2.1.1 The Refractive Index Pattern Induced with Constant Dephasing Between Exposures

In the case where there is no dephasing from the fundamental Bragg wavelength, the fringes of successive exposures overlap exactly and the interference between them is entirely constructive. At wavelengths away from the Bragg resonance the phase difference between each exposure is given by:

\[
\Delta \theta = 2\pi \left[ \frac{\Lambda'}{\Lambda} - 1 \right]
\]

where:

\[
\Lambda' = \Lambda + \Delta \Lambda
\]

so:

\[
\Delta \theta = 2\pi \frac{\Delta \Lambda}{\Lambda} \equiv \beta \Delta \Lambda
\]

If it is assumed that the UV interference pattern is sinusoidal in the region where the first diffracted orders overlap, then the UV intensity may be written as:

\[
l(z) = l_0 \{1 + \cos[2\beta z]\}
\]

where \(\beta = \pi/\Lambda\). The induced refractive index is assumed to be linear with intensity, and so the refractive index pattern resulting from \(m\) exposures with a UV beam of period \(\Lambda\) and width \(D\), may be written as:

\[
n_{\text{tot}}(z) \approx n_0 \sum_{m=1}^{m=D/\Lambda} 1 + \cos[2\beta z + m\Delta \theta]
\]

The integral form of (4.11), valid for large \(m\), may be written as:

\[
n_{\text{tot}}(z) \approx n_0 \int_{-D/2}^{D/2} 1 + \cos \left[ 2\beta z + \Delta \theta \frac{z}{\Lambda} \right] dz
\]

\[
n_{\text{tot}}(z) \sim n_0 D + \frac{n_0 \Lambda}{\Delta \theta} \left\{ \sin \left[ 2\beta z + \Delta \theta \frac{D}{2\Lambda} \right] - \sin \left[ 2\beta z - \Delta \theta \frac{D}{2\Lambda} \right] \right\}
\]
The fringe depth of the induced refractive index pattern is thus given by:

$$\Delta n_i (\theta, \omega) = n_{tot} (z = 0) - n_{tot} (z = \Lambda/2)$$

$$\sim \text{sinc} \left[ \frac{\Delta \theta D}{2\Lambda} \right] = \text{sinc} \left[ \frac{\pi \Delta \Lambda D}{\Lambda^2} \right]$$

(4.13)

### 4.2.1.2 The Effect of Beam Size on Fringe Contrast

Complete constructive interference between exposures is observed when $\Delta \Lambda = 0$ (or for small $D$). The contrast falls as either $\Delta \Lambda$ or $D$ increase until the case when there is a $\pi$ phase change between exposures at either extent of the beam. The limiting case for detuning is thus:

$$\Delta \Lambda = \pm \frac{\Lambda^2}{D}$$

$$\Rightarrow \Delta \lambda = \pm \frac{\lambda^2}{2n_{eff} D}$$

(4.14)

The useable detuning range for a given beam diameter, before the fringe depth is compromised too greatly, defines an approximate condition:

$$\Delta \lambda = \pm \frac{\lambda^2}{8n_{eff} D}$$

(4.15)

for $\Delta n_i = 0.9 \Delta n_i(\text{max})$. The effect of beam diameter on detuning range is illustrated graphically in figure 4.4. The measured effect of detuning is shown in figure 4.3: calculated reduction of the effects of random noise due to the effects of multiple-exposure averaging.
4.5 for a series of gratings made with wavelengths detuned from the Bragg wavelength defined by the phase mask; in this case, the beam diameter was \( \sim 500 \) µm.

### 4.2.1.3 Equality of Spectral Range to the Response of a Short FBG

It should be noted that the expression (4.14) is identical to the separation of the first reflectivity nulls from the Bragg wavelength of a weak unapodised, unchirped FBG with a length \( D \). Physically, this means that the spectral response of the weak grating formed by a single UV exposure ultimately determines the range of reflection wavelengths that may be realised in a grating comprising many overlapping, but dephased, sub-gratings. The effect of introducing constant dephasing between successive exposures is to preferentially enhance one of the spectral components available. A significant consequence of this is that the spectral range available from this simple pulse dephasing approach also depends on the beam profile: considering a weak grating of an appropriate length, but with an apodisation profile equal to the beam profile yields the spectral response available for a given beam.

### 4.2.1.4 Limits to Small-Beam Detuning Range

It seems from figure 4.4 that very large tuning of the Bragg wavelength may be achieved by using an appropriately small UV beam; for instance, a 20 µm beam will give something in the order of ±20 nm detuning range (sufficient to cover the EDFA bandwidth). There are two important factors, however, that limit the application of such an approach:
tight focusing reduces the depth (an subsequently the contrast) of the UV interference pattern

smaller beams mean less statistical reduction in noise and subsequently poor quality gratings

As described in section 3.1.2.2, the maximum depth of interference between the $\pm 1^{st}$ diffracted orders from a phase mask is given by:

$$d_{\text{max}} = \frac{D}{2\tan(\theta)}$$ (4.16)

where the UV beam width is $D$ and $\theta$ is typically 13°. The 125 $\mu$m diameter of a typical optical fibre means $d_{\text{max}}$ must be at least $\sim 65$ $\mu$m for there to be any interference pattern in the photosensitive fibre core; this means a minimum beam diameter of $\sim 30$ $\mu$m. Additionally, the fraction of the power usefully contributing to the interference pattern can be defined at a distance $x$ from the phase mask by:

$$\frac{P_{\text{fringe}}(x)}{P_{\text{tot}}} = 2E_1 \left[ \frac{d_{\text{max}} - x}{d_{\text{max}}} \right] \quad (0 \leq x \leq d_{\text{max}})$$ (4.17)

where: $P_{\text{fringe}}(x)$ is the UV power in the fringe region; $P_{\text{tot}}$ is the total transmitted UV; $E_1$ is the diffraction efficiency into the $\pm 1^{st}$ orders. The above expression is evaluated for $x=70$ $\mu$m, $E_1=0.4$, and shown in figure 4.6; this illustrates the fractional power in the interference pattern at the fibre core for a phase mask-to-fibre separation of $\sim 10$ $\mu$m (this is a realistic minimum for experimental cases). From
this consideration it is apparent that the contribution made to the interference pattern falls sharply for beam sizes less than ~100 µm. Note that the above discussion considers the interference pattern of a phase mask in a simple geometric manner, ignoring complex near-field effects; for a deeper insight, see chapter 5.

4.2.1.5 The Effects of Beam Profile on Chirped Fibre Bragg Gratings

Section 4.2.1.3 discusses how the detuning range available from a certain diameter beam corresponds to the reflection spectrum of a weak grating with a length equal to the beam diameter. A deeper consequence of this is that any noise in the beam profile will be translated directly into a minimum noise for the different spectral components of a chirped grating. The spectral components of linearly-chirped FBGs are distributed evenly along the length of the device. Since noise on the beam profile translates into spectral noise, there is a direct one-to-one mapping of beam intensity noise onto the apodisation profile of a chirped grating. The effect of noise in chirped gratings is considered thoroughly in chapters 6 and 11. This effect is not entirely obvious, however, since the grating should experience an equal amount of fluence as each point of the beam passes every point on the fibre. It is of important practical value, however, to realise this fact (especially when using excimer lasers or badly-tuned CW sources).
4.2.2 Increasing Detuning with Tuneable Interference Patterns

It should be appreciated that the limits to wavelength detuning and bandwidth described above are not fundamental characteristics of fibre Bragg gratings: nor are they an inherent reason why the continuous grating fabrication technique should be limited to devices of relatively small optical bandwidths. The key point here, is not any perceived limitation, but rather the fact that a significant degree of wavelength detuning can be achieved without the need for complex optical arrangements or dedicated phase masks. However, in many instances it is desirable to fabricate gratings with large optical bandwidths: especially since the bandwidth of erbium-doped optical amplifiers is 30 nm and gaining.

4.2.2.1 Chirped Phase Masks

Having said that the continuous grating fabrication technique in not reliant on scanning a phase mask, it can be useful to do so if the period of the phase mask is chirped. A larger detuning range can be achieved if the beam position on the phase mask is controlled in order to match the phase mask interference period with the desired grating fringe period at any point. For a detuning range of 30 nm the period of the phase mask should change by ~20 nm across the substrate. The advantage of this method is that it maintains the optical stability of the phase mask approach whilst allowing a wavelength detuning range much larger than otherwise available. The main disadvantage, however, is that variations in the zeroth-order transmission and non-linearity of chirp can strongly affect the characteristics of fabricated gratings. This point is discussed in chapter 6.

4.2.2.2 Interferometer-Based Solutions for Tuneable Interference Patterns

Many grating fabrication techniques, even those based primarily on phase mask technology, use some form of interferometer to control the period of the interference pattern [Fonjallaz et al., 1997] [Cortès et al., 1998] [Yoffe et al., 1999]. Of increasing popularity are methods whereby a phase mask is used to generate two diffracted orders, which are then remotely recombined via an optical arrangement that can controllably vary their relative angle of intersection (and thus the period of the interference pattern). These techniques have been shown to be flexible and benefit from having an interference pattern resulting from just two beams, rather than the complex near-field pattern of a phase mask. Additionally, they mean that there is not an (expensive) phase mask in close proximity to the fibre, with possible remnants of coating waiting to be ablated onto any near-by surface. The inevitable trade-off is the heightened sensitivity to mechanical and environmental perturbations that can plague interferometric methods.
4.2.3 Ultimate Limitations to Chirp Rate by Beam Size

Section 4.2.1.2 describes how the detuning of wavelength for a finite beam diameter results in a reduction in the refractive index contrast of a grating. It may be questioned, then, how far the chirp rate of a grating can be pushed for a given beam size before it starts to become self-apodised. For all practical circumstances, the dominant factor is that the wavelength change over a beam width should be less than the detuning range for that beam size, as given by equation (4.15) (note that if the period of the interference pattern is tuned, this does not limit the possible grating bandwidth). This typically represents a very large detuning range, unless a very wide UV beam is used, or the chirp of the phase mask across the beam is larger than the detuning range for the beam size used.

4.2.3.1 Expression for Maximum Beam Size when using a Chirped Phase Mask

For a phase mask with a chirp rate $\phi_{pm}$, defined by:

$$\phi_{pm} = \frac{d\Lambda_{pm}}{dz}$$

(4.18)

the preferred (largest) beam width is defined by equations (4.15) and (4.18):

$$n_{eff} \phi_{pm} D \leq \frac{\lambda^2}{8n_{eff} D}$$

$$\Rightarrow D_{max} = \frac{\lambda}{n_{eff}} \left[ \frac{1}{8\phi_{pm}} \right]^{1/2}$$

(4.19)

This expression is shown graphically in figure 4.7. For a phase mask covering 30 nm of the EDFA window, with a maximum length of 10 cm, it is shown that beam widths of up to $\sim 850$ µm can be used before self-apodisation effects begin to occur. Note that from equation (4.6), there is a large degree of noise reduction resulting from multiple-exposure averaging with this approach, and the fibre-to-phase mask separation distance is relaxed.

4.2.3.2 Expression for Maximum Beam Size with Tuneable Interference Patterns

Tuneable-period interference patterns generated by an interferometric approach are not limited by wavelength chirp across the beam. The maximum beam size useable before self-apodisation occurs is thus determined by the chirp rate of the grating structure, $\phi_{bg}$. This consideration yields the result:
This approach facilitates very large chirp rates indeed with large diameter beams (see figure 4.8).

\[ D_{\text{max}} = \frac{\lambda}{4n_{\text{eff}}} \left( \frac{1}{\phi_{\beta_g}} \right)^{1/2} \]  

(4.20)

This approach facilitates very large chirp rates indeed with large diameter beams (see figure 4.8).

4.3 BEAM MODULATION DUTY CYCLE

The continuous grating fabrication technique is based on making multiple UV exposures. It may seem initially that the ideal scenario is to have very short pulses so that there is no blurring of the stationary refractive index pattern as it exposes the moving fibre. This approach is not ideal, however, since high pulse energies are required in order to achieve a desired refractive index modulation if the pulse is short. Realistically this means using a pulsed UV source, such as a 248 nm excimer laser (such as [Asseh et al., 1997]), but the high powers required can damage the fibre (and phase mask) and pulsed lasers are notoriously noisy. For this reason it is preferable to use a lower-power, continuous-wave (CW) UV source, which is externally modulated such that each exposure covers a significant fraction of the grating period.
4.3.1 Ratio of Refractive Index Contrast to Induced Background Index Due to Duty Cycle

The minimal effect of fabricating a fibre Bragg grating is to raise the average (background) refractive index by half of the peak-to-peak amplitude of the induced refractive index modulation. When the grating is fabricated by a succession of finite-length exposures, as described above, there is a further addition to the background refractive index: the fibre is dragged through a stationary interference pattern for a fraction of a grating period, $\Delta \Lambda$, decreasing ratio of grating fringe depth to induced background from the ideal case.

4.3.1.1 Expression for Induced Refractive Index

The induced index pattern for a certain exposure duty cycle, $c$, can be deduced by integrating the induced index of a stationary exposure, over a distance $\delta z$, corresponding to the spatial length of the exposure ($\delta z = c \Lambda$). Assuming a linear change in refractive index with intensity means the induced refractive index pattern is of the form:

$$n_i(z, c) \propto \frac{n_0}{\Lambda} \int_{-\Lambda/2}^{\Lambda/2} \left[ 1 + \cos(2\beta z + 2\beta \delta c) \right] d\delta z$$

$$n_i(z, c) \sim n_0 c + \frac{1}{2\pi} \left( \sin[2\beta z + \pi c] - \sin[2\beta z - \pi c] \right)$$  \hspace{1cm} (4.21)
where $\Lambda$ is the period of the UV interference pattern, and $c = \Delta\Lambda/\Lambda$. This expression is presented graphically in figure 4.9, comparing the fringe depth, $\Delta n_i$, to the induced average background refractive index, $n_i$.

### 4.3.1.2 Expressions for Fringe Depth and Induced Background Index

The induced refractive index over one grating period is thus given by:

$$\bar{n}_i(c) = n_0 c$$  \hspace{1cm} (4.22)

whereas the peak-to-peak index change is:

$$\Delta n_i(c) = n_i(z = 0) - n_i(z = \Lambda/2)$$

$$= \frac{2}{\pi} n_0 \sin[\pi c]$$  \hspace{1cm} (4.23)

### 4.3.1.3 Expression for the Ratio of Fringe Depth to Induced Background Index

The ratio of the fringe depth to the induced background index is thus simply:
The largest difference between \( \Delta n_i \) and \( \overline{n_i} \) is observed for a duty cycle of 30 – 35%; at this point the modulation depth is \( \sim 1.6 \) times that of the induced background index. The effect of a finite duty cycle is thus to reduce the contrast of the fringe depth to the induced background index from the ideal 2:1 case.

### 4.3.2 Overall Ratio of Modulation Depth to Induced Background Index

The considerations of beam size shown that a further 25 – 50% of the power incident on the fibre does not contribute usefully to the refractive index pattern used to inscribe the grating. Additionally the fringe contrast may be reduced by the effect of wavelength detuning. A parameter \( \gamma \) can be defined reflecting the fraction of the beam power contributing to the UV interference pattern (before the effect of duty cycle is considered). The intensity patterns and corresponding induced refractive index are thus described as:

\[
I(z) = I_0 \left[ 1 + \gamma \cos(2\beta z) \right]
\]  
(4.25)

\[
n_i(z,c) \propto c + \frac{\gamma}{2\pi} \left\{ \sin(2\beta z + \pi c) - \sin(2\beta z - \pi c) \right\}
\]  
(4.26)

The expressions for fringe depth and ratio of fringe depth to induced background index are scaled by \( \gamma \). An example of this effect is to consider a grating fabricated with a 350 \( \mu \)m diameter beam (\( \gamma \sim 0.7 \) from equation (4.17)), and a duty cycle of 35% (giving \( \Delta n_i = 1.6 \overline{n_i} \)). The ratio of fringe depth to induced background index is now only a factor of 1.13. It should be noted that this is a maximum estimate since the useful power in the UV interference pattern may be significantly less than given by (4.17) as phase masks do not generate pure sinusoidal intensity patterns a single spatial period (see chapter 5 for in-depth discussion of this point).

#### 4.3.2.1 Restriction of Duty Cycle for Apodisation

Throughout the majority of the practical work described in later chapters a duty cycle of 35% was used. Although this gives a reasonable trade-off between fringe contrast and induced background index, it is apparent that larger index modulation depths could be achieved by using a 50% duty cycle. This is not desirable, though,
since the method used for apodisation in this fabrication technique is based on
dephasing pairs of exposures by as much as ±π, which would lead to a vanishingly-
small pulse separation and subsequent problems in pulse triggering.

4.4 APODISATION
A parameter of crucial importance in a grating structure is the magnitude of the
index modulation (or coupling constant). The modulation of UV fluence along the
length of the grating during fabrication certainly offers direct and localised control
over the induced index modulation, but it has the inevitable and unfortunate con-
sequence of also changing the local background refractive index leading to undesir-
able chirping effects. The technique of pure apodisation [Cole et al., 1995], [Asseh
et al., 1997] in contrast, permits control of the index modulation without inducing a
background index change, and hence the local Bragg wavelength is not unduly af-
fected.

4.4.1 Dephasing Pairs of Exposures to Achieve Apodisation
The control of dephasing between the sub-gratings in the continuous grating fabri-
cation scheme can also be applied to apodisation. If it is considered that the overall
structure is formed by related pairs of single-exposure gratings, then the overall
index change induced by such a doublet is simply the vector addition of the two
exposures. When both exposures of a pair are made to fall in phase then the effec-
tive depth of index modulation at the Bragg wavelength is maximised. Dephasing
of the exposures with equal magnitude but opposite direction means that the con-
trast of the index change at the Bragg wavelength may be reduced (see figure
4.10); the total induced index change of an exposure doublet remains constant re-
gardless of the dephasing condition. The effective index modulation depth at the
Bragg wavelength is zero when the exposures of the pair are out of phase by π.

4.4.1.1 Relationship of Phase Separation to Refractive Index Modulation Contrast
The apodisation envelope, $\alpha(z)$, is related to the dephasing parameter, $\phi_a(z)$, by:

$$\alpha(z) = \cos[\phi_a(z)]$$  \hspace{1cm} (4.27)

if it is assumed that the UV intensity pattern is sinusoidal. A simple and reasona-
bly effective apodisation profile thus may be incorporated into the structure by af-
fecting a linear variation of the dephasing magnitude, $\phi_a(z)$, between zero and $\pm \pi/2$; such a variation yields a cosinusoidal variation of effective index modulation depth at the Bragg wavelength (figure 4.11).

4.4.2 Decomposition of Apodisation Profiles

An interesting physical insight into this method of apodisation combined with the effect of multiple exposures, can be gained by considering the decomposition of a grating structure into two gratings, formed by alternate exposures. Bearing in mind that each exposure comprises typically a few hundred fringes it is reasonable to assume that a grating could be written by only illuminating the phase mask on either the first or the second component of each exposure pair; the result would be a grating with half the total index modulation depth and less averaging (although there are additional consequences discussed in chapter 6).

4.4.2.1 Considering Apodisation as Two Interlaced Gratings

If the exposures that form alternate pulses are dephased symmetrically by an amount, $\phi_a(z)$, as is the case for achieving apodisation, then the grating formed by the first pulses of each pair has a wavelength $\lambda_1$, whilst the grating formed by the second pulses will have a Bragg wavelengths $\lambda_2$, where:

$$\lambda_1 = \lambda_0 \frac{1}{q} \left[ q - \frac{\phi_a}{4\pi n_{eff}} \right]$$

$$\lambda_2 = \lambda_0 \frac{1}{q} \left[ q + \frac{\phi_a}{4\pi n_{eff}} \right]$$

(4.28)
where $\lambda_0$ is the fundamental Bragg wavelength and $q = l / \lambda_0$. Rather than directly tempering the index modulation at the fundamental Bragg wavelength, this apodisation process physically writes two interlaced gratings at different wavelengths with the result that there is an *effective* component at the fundamental Bragg wavelength modulated by an envelope governed by the beating effect between the two different frequency components (see figure 4.12). Simply, a linear dephasing of the two components from zero to $\pm \pi/2$ corresponds to one quarter of a Moiré structure; because the regions of apodisation at the end of a grating are typically a few centimetres the two wavelengths of the Moiré structure are very close to that of the resultant Bragg wavelength. Other apodisation profiles may be generated by a non-linear dephasing; in these structures the two wavelengths, whilst still symmetric about $\lambda_B$, are not constant along the apodised section.

4.4.2.2 Maximum Rate of Change of Apodisation Phase

The effect of apodising a fibre Bragg grating, then, is to generate spectral components away from the fundamental Bragg wavelength: the separation of these components from the Bragg wavelength is determined by the rate of change of the refractive index modulation depth. Section 4.2.1.2 describes the reduction in fringe contrast that may be expected for a given UV beam size when the grating is deliberately written with a period detuned from that of the interference pattern. From considering an apodised grating as two interleaved gratings of different wavelength, it thus follows that there is a maximum rate of change of the grating envelope that may be realised for a given UV beam size before the structure becomes self-apodised (that is, the wavelength detuning associated with apodisation fall outside the spectral range that may be achieved for the beam size used).

The deviation of wavelength from the fundamental period, $\lambda_{\phi}$, for a given rate of change of apodisation phase is given by the expression:

\[
\phi = \frac{\pi}{2}
\]
In order that the grating should not become self-apodised, equations (4.15) and (4.29) give the condition that:

\[
\frac{d\phi}{dz} < \frac{\lambda_0^2}{2\Delta n_{\text{eff}}} \leq \frac{\lambda_0^2}{8n_{\text{eff}}D}
\]

The essence of equation (4.30) is, quite reasonably, that the beam width should be less than the size of any feature in a grating structure that goes from a state of no apodisation to one of full apodisation in this manner (or vice-versa).

### 4.4.2.3 Examples of Apodised Gratings

Two examples of gratings with apodised structures are shown in figure 4.13 and figure 4.14. Designed for a low-cross talk wavelength-multiplexed sensor system, the grating shown in figure 4.13 has a Blackman apodisation profile and achieves channel isolation of ~50 dB (i.e. 0.001% cross-talk). The grating shown in figure 4.14 (designed by, and fabricated with Morten Ibsen) has a sinc-shaped apodisation.
profile with the aim of achieving a square spectral response with minimal in-band dispersion\(^2\) [Ibsen \textit{et al.}, 1998a,d].

4.5 \textbf{SUMMARY}

The continuous grating fabrication technique is used to write gratings by overlapping many beam-sized exposures: each exposure is separated by a single grating period. Since the induced refractive index at each point in the fibre is the result of many exposures, the effect of exposure position uncertainty are drastically reduced. The use of a modulated CW UV gives good pulse-to-pulse stability, but leads to a reduction in the contrast of the induced refractive index fringe contrast to the induced background refractive index.

Introducing a constant dephasing between exposures makes it is possible to fabricate gratings with Bragg wavelengths away from that defined naturally by the UV interference pattern; chirped gratings can be fabricated by varying the pulse-to-pulse phase in a linear manner along the grating length. The limit to this simple dephasing technique is when the sub-gratings formed by exposures sepa-

\(^2\) this is so since the Fourier transform of a square spectral response gives a sinc-refractive index profile. The Gaussian tapering is needed to reduce the effect Gibbs-phenomena, resulting from finite grating length
rated by a beam diameter are out-of-phase by $\pi$. This detuning range can also be identified as the bandwidth of a weak grating with a length and profile governed by the UV beam; correspondingly, poor beam-quality leads to noise on the spectral response of gratings fabricated. Gratings with 10 nm bandwidth can be fabricated by using a UV beam focused to $\sim 50 \mu$m, although the associated reduction in overlap of the $\pm 1^{st}$ diffracted orders from the phase mask leads to a smaller fringe contrast. It is possible to realise gratings with much broader bandwidths by scanning a chirped phase mask, or using a tuneable interferometer.

The control of individual exposure phase can be used to control the fringe contrast on a localised level, and thus realise complex apodisation profiles. The fringe contrast is maximised when successive exposures are in phase, and is minimised when they are made to be out-of-phase by $\pi$. The fringe envelope produced by this apodisation technique can be viewed as the result of beating between two interlaced gratings with different wavelengths. The rate of apodisation is thus also limited by the size of the beam diameter. Examples are given of a high-quality apodised unchirped grating with good side-lobe suppression, and a complex gratings designed to have a square spectral response and minimal in-band dispersion.
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This chapter presents the work obtained from an investigation into the micro-structure of fibre Bragg gratings. These results came from the development of a novel technique that allows resolution of grating fringes; the method is based on monitoring the level of fluorescence seen when a grating structure is scanned with a low-power UV interference pattern. This technique is capable of resolving both the large and small-scale structure of fibre Bragg gratings by probing the bleaching pattern of a fluorescence mechanism associated with the UV-induced formation of gratings in photosensitive fibre. An understanding of the fundamentals of a fabrication technique can be obtained by application of this method. Grating structures written both by a simple phase masks-canning technique and by the continuous grating fabrication technique are presented. The results obtained related to the physical differences between such systems, with particular emphasis on the contribution of a sub-harmonic component to the grating structure. This interrogation technique also led to a reappraisal of the apodisation technique for the continuous grating fabrication system, resulting in improved dynamic range.
5.1 RESOLUTION OF GRATING FRINGE PATTERNS

The results presented in this chapter gave the first reported resolution of grating fringe patterns [Zervas et al., 1999] simultaneously with [Fonjallaz and Börjel, 1999], and the first experimental evidence of the effects of non-ideal phase mask characteristics on the microscopic structure of fibre Bragg gratings. Additionally the consequences of grating inscription by the continuous grating fabrication technique are presented. The interrogation technique developed can give useful information into the characteristics of a grating that are difficult to extract from the spectral results alone, and can be used to assess the effect of non-ideal phase masks on the characteristics of fibre Bragg gratings made with different fabrication techniques.

5.1.1 Fluorescence Bleaching/Loss Associated with Induced Refractive Index Changes

The exposure of a germanosilicate glass to ultraviolet light results in fluorescent emission at a wavelength of ~400 nm [Williams et al., 1992]. It is observed that the level of this fluorescence falls with prolonged exposure [Gallager and Österberg, 1993]: this is caused both by a bleaching of the fluorescence mechanism, and by an increase in loss at short wavelengths caused by the photo-induced refractive index change. A consequence of fibre Bragg grating fabrication by UV exposure is thus a periodic bleaching/loss effect associated with the induced refractive index pattern. By interrogating the loss pattern it is possible to gain useful insight into the structure of a fibre Bragg grating on a microscopic level.

5.1.1.1 Guided Fluorescence of UV Exposure

A convenient side-effect of fabricating photo-induced gratings in core of a fibre (or waveguide) is that the fluorescence emitted is at least partially captured, and subsequently guided, by the fibre (see figure 5.1). Monitoring the level of fluorescence during grating fabrication gives a good way of aligning the UV writing beam with the photosensitive fibre core (see chapter 4 and [Komukai and Nakazawa, 1996]). The intensity of fluorescence is much reduced if a waveguide previously exposed to UV is subsequently re-exposed. Probing a photo-induced structure with a low-power UV beam allows the resolution of the loss pattern associated with the induced refractive index pattern. Detecting the effect of UV-induced loss by monitoring the level of guided fluorescence guided by the fibre gives offers reduced sensitivity to alignment over techniques that use free space detection.
5.1.1.2 The Effect of Fibre Type on Absorption

The level of detected fluorescence for a given UV fluence on a fibre is (inconveniently) influenced strongly both by the material composition of the photosensitive glass, and by the guiding structure of the fibre. Of particular importance is the fact that the process of D₂ (or H₂) loading of the fibre (in order to increase the levels of photosensitivity) leads to a huge loss at the wavelength of guided fluorescence: this makes it very difficult to resolve fine details (such as grating fringes) of a photo-induced structure by the UV probe-beam approach. Conversely, fibres with a boron co-doped core exhibit very high levels of fluorescence, even on re-exposure, whilst allowing strong refractive index features to be induced without the need for D₂ loading. For these reasons, a boron co-doped fibre with an NA of 0.13 was used for the purposes of this series of experiments.

5.1.2 Description of Grating Fringe Measurement System

The basic principle of the technique developed to resolve the UV-induced structures is thus based on simply scanning a grating with a UV probe beam and monitoring the level of guided fluorescence. A trial of the method was made with a long-period grating structure. The grating had a period of 500 µm and was formed by a pulsed UV beam focused to a waist of ~250 µm. The structure could be clearly seen by monitoring the level of guided fluorescence on scanning the structure with a lower power UV beam. It was ascertained that beam powers of ~ 5 mW result in levels of fluorescence sufficient to be detected, whilst not significantly modifying the refractive index structure.
The experimental arrangement for interrogating short-period FBGs is somewhat different since the spatial period of the refractive index structure (typically ~530 nm for gratings with a response in the EDFA bandwidth) is significantly smaller than the spot size that can be achieved without significant rearrangement of the optics used to inscribe the grating. The extension of this technique to FBGs thus requires the fabricated grating to be scanned with an interferometrically-generated interference pattern with a fringe separation closely matched to the period of the grating. There is no practical difficulty in achieving this criterion since the method for generating the UV fringes used to fabricate the grating provides the ideal UV footprint for subsequent interrogation of its structure. The only point to observe is that the system used to monitor the oscillations of the fluorescence during the interrogation must have a bandwidth/sample-rate sufficient to easily resolve the ~530 nm structure of the grating when it is scanned through the UV interference pattern (i.e. >>2 kHz for a scan speed of 1 mm/s).

5.1.2.1 Correlation between Induced Loss Pattern and UV Interference Pattern

The detected fluorescence level can be considered as an auto-correlation function of the intensity pattern in the case where the interference fringes and the induced-loss have the same form (as may be expected for a stationary phase mask exposure). The auto-correlation of a function comprising several oscillatory components is itself dominated by these components; the information of the phase relation between the oscillatory components, however, is not retained in the auto-correlation [Bracewell, 1978: chapter 3]. In the case where the induced loss pattern and the probe pattern are different, however, the detected fluorescence pattern is a cross-correlation.
5.1.2.2 Experimental Arrangement

The experimental arrangement of this technique is shown schematically in figure 5.2. The interrogation system used was based around a New Focus silicon photodetector with a bandwidth of 20 kHz and a National Instruments 16-bit PCI A/D data-acquisition card with a maximum sample rate of 100 kHz; the system can be used to extend the functionality of any grating fabrication system without any optical rearrangement. The 244 nm Coherent FreD laser was the UV source for both grating inscription and interrogation; the beam was passed through an AOM and the first diffracted order used as the probe beam in order that its power may be readily controlled; typically the probe beam had a power of ~5 mW and the fibre was scanned with a velocity of 250 µm/s giving detected fluorescence levels of –45 dBm to –50 dBm. The periodic intensity pattern was generated by the same phase mask used to fabricate the grating; the grating can be interrogated without removal from the fabrication system.

There are two main experimental points to be noted. Firstly, the detector used must have sufficient bandwidth to detect passing grating fringes. However, this leads to a reduction in the maximum gain available (for a certain gain-bandwidth product) which can make it difficult to apply this technique to fibre where the photo-induced loss is large. The grating fringes induced in the boron co-doped fibre used in this series of experiments were visible as a peak-to-peak voltage change of ~ 10 mV at the output of the New Focus detector for a 5 mW UV probe beam. For other types of fibres this signal is much less and it would be required to use phase-locked amplification methods to resolve the signal from noise. The second point of note is that in order to realise a dynamic range approaching the full 96 dB offered by the 16 bit DAC, it is important that a continuous cable screen be used between the output of the A/D card and the detector. Earth loops also present a problem for signals of this level, so care must be taken to avoid this possibility.

5.1.2.3 Software for High-Speed Data Logging

The National Instruments A/D card is similar to the DIO card used to trigger the UV exposures during grating fabrication. The use of direct memory access (DMA) and double-buffering data acquisition techniques (see chapter 4) allows other computational processes to be active whilst data is collected (timing jitter may otherwise be a problem). This is extremely useful since real-time display of data during acquisition is helpful to the user. A multi-threaded windows-based program was written in C++ to concurrently collect and display data.
5.1.2.4 Advantages Compared to Other Techniques
The main advantages of this grating interrogation technique are:

- straightforward application to any grating fabrication system without requiring any change in optical configuration
- resolution of microscopic features, rather than just the average level of refractive index change
- increased sensitivity compared to free-space detection methods
- fast rate of data collection
- (indirect) detection of features associated with small refractive index changes

The technique is also applicable to stitching grating sections in a phase-coherent manner.

5.1.2.5 Limitations of the Technique
The grating interrogation technique presented is limited by two main factors:

- the features detected are the average of all the features encompassed in the width of the prove beam
- compatibility problems with D₂ loaded fibres
- no direct measurement of induced refractive index

5.2 Gratings Formed by Phase Mask Exposure
The most common way to fabricate FBGs is by exposure through a phase mask (see chapter 3). It is often (incorrectly) assumed that the interference pattern of a phase mask optimised for zeroth-order suppression is sinusoidal in the direction parallel to the mask, and that it does not vary in form with distance normal to the mask. Recent studies, however, have highlighted that this is not the case. The purpose of the following series of experiments was to investigate the properties of FBGs formed by simple phase mask exposure, by interrogating the loss pattern associated with the induced refractive index structure.
5.2.1 Phase Mask Interference Patterns

Phase masks designed for use in fibre Bragg grating fabrication achieve strong diffraction into the $\pm 1^{st}$ orders (typically $\sim 40\%$ each). This is beneficial compared to diffraction from amplitude masks, but still 20% of the power is diffracted into other orders (typically phase masks used for fabricating gratings at 1550 nm with 244 nm light exhibit diffraction into 9 orders: -4 to +4). The desired effect is to use the interference pattern generated by the overlap of the $\pm 1^{st}$ diffracted orders, but interference between the (small) zeroth order component, and, to a lesser extent, higher diffracted orders leads to a more complex interference pattern. This section details the interference patterns that may be observed for a finite zeroth-order diffraction, in the region of overlap between the $\pm 1^{st}$ orders; the contribution of higher diffracted orders is not considered since this can be minimised by placing the fibre at a sufficient distance from the phase mask.

5.2.1.1 Mathematical Description of Three Beam Interference

The following mathematical description of the interference pattern behind a phase mask follows [Xiong et al., 1999] closely. This interpretation is a representation of multiple beam interference, but does not consider the characteristics of the phase mask directly; the reader is referred to [Qiu and Sheng, 1999] for a good description on how the details of the phase mask affect the amplitude and phase of the diffracted orders. Non-the-less, the multiple beam interference approach can give useful insight into the characteristics of the field distribution.

The diffraction angle of the $N^{th}$ diffracted order from a phase mask is:

$$\theta_N = \sin^{-1}\left( \frac{N\lambda}{\Lambda_{pm}} \right)$$  \hspace{1cm} (5.1)

where the incident light has a wavelength of $\lambda$, and the phase mask period is $\Lambda_{pm}$. The phase change of the electric field at a co-ordinate $(x, z)$ from the phase mask is thus given by the expression:

$$\phi_N = x\sin(\theta_N) + z\cos(\theta_N)$$  \hspace{1cm} (5.2)

where $x$ is parallel to the phase mask, but perpendicular to its grooves (nominally the fibre axis) and $z$ is the axis normal to the phase mask. The electric field distribution resulting from the interference of the $2N$ diffracted orders is given by:

$$E = \sum_{k=-N}^{N} C_k \exp[i2\pi k \phi_k / \lambda]$$  \hspace{1cm} (5.3)
where $C_N$ is the amplitude of the $N^\text{th}$ diffracted order. In the case where there is equal power diffracted symmetrically into the $\pm N^\text{th}$ orders, $C_N = C_{-N}$, and the amplitude of the zeroth order is $2C_0$. From (5.3) the intensity distribution, $EE^\ast$, is:

$$I = 4 \left\{ \sum_{k=0}^{N} C_k^2 \cos^2 \left( \frac{2\pi k x}{\Lambda_{\text{pm}}} \right) + \sum_{j \neq k} C_k C_j \cos \left( \frac{2\pi k x}{\Lambda_{\text{pm}}} \right) \cos \left( \frac{2\pi j x}{\Lambda_{\text{pm}}} \right) \right\} \cos \left( \frac{2\pi (\cos \theta_k - \cos \theta_j)}{\lambda} \right)$$

(5.4)

Finally, considering just interference between the zeroth order and the $\pm 1^\text{st}$ orders, the intensity pattern is given by [Xiong et al., 1999]:

$$I_{0,\pm 1}(x, z) = 4 \left\{ C_1^2 \cos^2 \left( \frac{2\pi x}{\Lambda_{\text{pm}}} \right) + C_0^2 + 2C_0 C_1 \cos \left( \frac{2\pi x}{\Lambda_{\text{pm}}} \right) \right\} \cos \left( \frac{2\pi z \left[ 1 - \sqrt{1 - \left( \frac{\lambda}{\Lambda_{\text{pm}}} \right)^2 } \right]}{\lambda} \right)$$

(5.5)

5.2.1.2 The Effect of Zeroth-Order Diffraction from Phase Masks

In the case where there is no power in the zeroth order, it is apparent that the intensity distribution is oscillatory in the $x$ direction with a spatial period of half the phase mask period, and that there is no variation of intensity in the $z$ direction. For finite zeroth-order diffraction, though, equation (5.5) yields the important result that the interference pattern is also oscillatory in the $z$ direction, with a period:

$$D_z = \frac{\lambda}{1 - \sqrt{1 - \left( \frac{\lambda}{\Lambda_{\text{pm}}} \right)^2 }}$$

(5.6)

The period of the interference pattern in the direction normal to the mask surface is 9.2 $\mu$m for a wavelength of 244 nm and a phase mask period of 1066 nm.

Intensity patterns of this three-beam interference case are shown in figure $\text{x}$, with a diffraction efficiency of 40% into the $\pm 1^\text{st}$ diffracted orders, for four values of zeroth-order diffraction efficiency: 0% (ideal); 1% (current practical minimum); 3% (still a good phase mask); 5% (could be better). It is clear that the interference pattern of a phase mask deviates significantly from the ideal case when even a small amount of power is diffracted into the zeroth order. Of significant importance is the lack of uniformity that will be observed if a grating is inscribed in a fibre by simple phase mask exposure, either when the fibre is not aligned exactly parallel to
the phase mask, or when the fibre-to-phase mask distance varies during fabrication, for some reason. It is also important that the amount of zeroth-order diffraction be consistent across the extent of a phase mask.

It is issues such as these that are beginning to tarnish the reputation of simple phase mask-scanning techniques for FBG fabrication: whilst these methods are undoubtedly stable and repeatable, it has to be questioned whether they are simply repeatably wrong. The following section describes the features of the grating structure observed with the UV-probing technique described in section 5.1.2 for gratings formed by simple phase mask exposure. The subsequent section describes how the continuous grating fabrication technique is well suited to overcoming these problems, and how consideration of the interference pattern is important for achieving the best results.
5.2.2 Grating Structures Resulting from Phase Mask Exposure

The aim of the first in this series of experiments was to compare the structures resolved by the UV-probing interrogation technique with what may be expected from phase mask interference patterns. Gratings were induced in a length of fibre by making a stationary UV exposure through a $\pi$ phase mask, with a quoted zeroth-order suppression of $< 5\%$ (not by any means ideal). The UV beam power was $\sim 30$ mW on the fibre and the exposure time was five seconds. The induced grating structure was then scanned past the UV probe-beam interference pattern ($\sim 5$ mw) at a rate of 250 $\mu$m/s.

A section of the collected data is shown in figure 5.4. The fringe pattern detected is clearly representative of the grating refractive index structure since the dominant period is half that of the phase mask ($\sim 530$ nm). There is a high signal-to-noise ratio and the 16 bit DAC gives a good resolution; also note that it is possible to take reading on a nanometre scale, if desired. The main causes of noise are fluctuations in the laser output power and possible vibrations of the fibre. Using the fibre tracking technique described in chapter 4 helps reduce this problem. The effect of laser output noise could be eliminated by using a differential detection technique, whereby the laser power is sampled concurrently with the fluorescence to give a reference. Note that since increasing loss corresponds to increasing refractive index, the refractive index pattern of the grating is inverted with respect to the fringe intensity shown.
5.2.2.1 The Effect of Incomplete Suppression of Zeroth-Order Diffraction

Equally apparent as the fundamental grating period, is the strong sub-harmonic component at the period of the phase mask. This effect can be explained as the effect of interference between the ±1st diffracted orders, and the small zeroth-order component, as described in section 5.2.1.2. The grating written, and the measurements taken, are effectively the result of the phase mask interference pattern integrated over the extent of the fibre core (assuming a cylindrical geometry). The size of the fibre core is not known exactly, but is assumed to be 5 µm: this figure is smaller than the 9 µm fluctuation period of the interference pattern, so even integration over the depth of the core is not sufficient to result in an averaged refractive index pattern that is solely periodic at half the phase mask period. The interference pattern for a phase mask of period 1066 nm, with a zeroth-order component of 5%, and diffraction efficiencies considered were 40% into each of the first orders, and 5% zeroth order.

![Comparison of calculated and experimental data](image)

Figure 5.5: Comparison of collected data to the calculated intensity pattern of a three beam interference pattern integrated over a 5 µm fibre core in the direction normal to the phase mask; diffraction efficiencies considered were 40% into each of the first orders, and 5% zeroth order.

These results suggest that the association of the UV-probed loss pattern to
the refractive index pattern of the grating (and the interference pattern of the phase mask) can be made with a high degree of confidence.

The interference patterns of similar phase masks have also recently been observed experimentally by scanning near-field optical microscope (SNOM) [Mills et al., 1998]. Additionally, the same effect has been reported with Bragg gratings that were photo-induced on polymer substrates and examined under an atomic-force microscope (AFM) [Xiong et al., 1999] [Dyer et al., 1995], although the results shown are not as clearly related to theory as those presented here. These results, to the author’s knowledge, are the first reported experimental evidence of the effect of zeroth-order diffraction from phase masks in fibre Bragg gratings [Zervas et al., 1999].

5.2.2.2 The Effect of Phase Mask-to-Fibre Separation Distance

The effect of fibre-to-phase mask separation was described in a simple manner in chapter 4: here, consideration was only given to how the reduction in overlap of the \( \pm 1^{st} \) diffracted orders with distance leads to a corresponding fall in the fringe contrast of the interference pattern. Equally as important, though, is the increasing effect of interference between the zeroth and \(+1\) order, and the zeroth and \(-1\) orders, which is responsible for the sub-harmonic component in the interference pattern at the period of the phase mask. At distances from the phase mask where the \( \pm 1^{st} \) orders only overlap slightly, the interference pattern modulates strongly in the \( z \) direction; the dominant contribution is from the sub-harmonic component. The calculated interference patterns for a phase mask of period 1066 nm, with 244
nm light and a zeroth order diffraction efficiency of 3%, are shown in figure 5.6 for 10% and 1% diffraction efficiencies in the ±1st orders.

To investigate this effect experimentally a series of gratings were made, under the same conditions as before, with different fibre-to-phase mask separations, from 50 µm to 950 µm. The gratings were then interrogated with the UV probe beam: the results are shown in figure 5.7 (note that the fringe depths have been normalised). It is clear from these results that the ratio of the component with the desired grating period (half that of the phase mask) to the sub-harmonic component (equal to that of the phase mask period) increases as the phase mask is withdrawn from the fibre.

A hypothesis was made that the results could be explained as the average across the beam diameter of an interference pattern with an effective first-order diffraction efficiency that decreases linearly with distance from the phase mask (corresponding to the reduction of overlap of the ±1st orders, discussed in chapter 3). The data of the 50 µm separation distance fits well with the theoretical results of 40% diffraction efficiency into the ±1st orders and 5% zeroth order (as in figure 5.5). The data acquired with a separation of 950 µm was found to fit the theory well for an effective diffraction efficiency of 2%. For the separations in between, the effective diffraction efficiency was calculated from a linear regression through these two points.

The theoretical data of the phase mask intensity pattern for these effective diffraction efficiencies, integrated over a 5 µm cylinder as before, is shown in figure 5.7 in comparison to the experimental data. A high degree of correlation between the experimental results and theory suggests that this hypothesis is well founded. It is important to note that the fibre-to-phase mask separation was the same for both grating formation and subsequent interrogation: this results in an auto-correlation of the UV intensity pattern with the loss fringes. Had the separation changed, the results would represent a cross-correlation between the loss fringes formed by an interference pattern at one separation with the UV intensity pattern at another.

5.2.2.3 The Effect of Multiple Periodic Components of Refractive Index Modulation on the response of Fibre Bragg Gratings

An induced refractive index modulation pattern with two, or more, spatial periods, will exhibit a Bragg reflection from each. In the case of the phase mask interference pattern (with a small zeroth-order diffraction) the induced refractive index pattern will have a spatial period both at the desired grating period, \( \Lambda \), at the period
of the phase mask (2A). Zeroth-order diffraction from phase masks introduces a sub-harmonic component which leads to two effects:

- Bragg reflection at a wavelength determined by the period of the sub-harmonic component
- reflection at harmonics of the Bragg wavelength for this period

The observed loss pattern (and inferred refractive index pattern) has a sub-harmonic pattern that has twice the period of the fundamental grating period. The harmonic reflection from this spatial period is thus at the same wavelength as the fundamental Bragg reflection from the fundamental grating period. The coupling parameter for reflection of the \( m^{th} \) harmonic from a refractive index modulation \( \Delta n \)
is proportional to $\Delta n^m$. The contribution to reflection at the fundamental Bragg wavelength of a grating by a sub-harmonic refractive index component is thus determined by the square of the index modulation depth of the sub-harmonic component. Additionally, the reflection at the primary Bragg wavelength caused by the sub-harmonic component is in anti-phase with the main component reflected from the fundamental grating period [Zervas et al., 1999]. For strong sub-harmonic components, the interplay between reflection from the two spatial period of the refractive index structure leads to a non-monotonic increase in reflectivity at the fundamental Bragg wavelength.

It was recently reported [Moffat et al., 1999] that a fringeless UV post-exposure of a fibre grating can enhance the refractive index modulation depth. The gratings were formed by exposure through a phase mask. The experimenters observed, by monitoring He-Ne diffraction through the grating), that an enhanced growth of the sub-harmonic component grating resulted in an initial increase of reflection at the primary Bragg wavelength, followed by a partial erasure. This is explainable in terms of the concepts summarised above, as discussed by [Zervas et al., 1999]. The data presented in this section provides the first direct experimental evidence of the effect of zeroth-order phase mask diffraction on the induced refractive index structure of fibre Bragg gratings.

### 5.3 Gratings Formed by the Continuous Grating Fabrication Technique

The previous sections have presented the theory of phase mask interference patterns, and has confirmed, by comparison of experiment to theory, that the technique developed to probe the loss structure of an FBG gives a good representation of the induced refractive index pattern. The main aim of this technique was to interrogate grating structures formed by the continuous grating fabrication technique: only by doing this is it possible to gain information about the microscopic details of the refractive index pattern formed. The results obtained have subsequently led to a reappraisal of the apodisation technique described in section 4.1, giving the system an improved dynamic range.
5.3.1  Gratings Made by Exposures Separated by a Single Fringe

The continuous grating fabrication technique forms gratings by overlapping beam-sized gratings that are separated by one grating period; this distinguishes it from alternative techniques [Asseh et al., 1997] where a more generic integer-number of grating periods separate the exposures. The primary reason for this approach was to maximise the error reduction resulting from multiple exposures (see chapter 4). However, the recent results shown in the previous section indicate that this approach has further advantages.

5.3.1.1  Theoretically Expected Fringe Pattern

It is clear that the interference pattern of a phase mask has a significant sub-harmonic component in the (inevitable) presence of finite power in the zeroth diffracted order. A grating formed by many such exposures separated by a single grating period, however, should not exhibit this characteristic in their refractive index profiles. The data of the measured loss pattern from a single exposure (shown in figure 5.5) was used to calculate the expected refractive index pattern from two such exposures separated by a grating period (533 nm in this case); the results are shown graphically in figure 5.8. The resultant refractive index pattern is almost completely free of the sub-harmonic component.
5.3.1.2 Experimentally Measured Fringe Pattern

The fringe pattern detected by scanning a structure made by the continuous grating fabrication technique is shown in figure 5.9. The pattern closely resembles that predicted in the previous section and is much closer to the ideal sinusoidal refractive index pattern that is achievable with gratings formed by simple phase mask scanning techniques. The detected intensity characteristics in this case, corresponds to a cross-correlation between the UV interference pattern and the loss pattern associated with gratings formed with a predominantly single spatial period. The noise on the structure is more likely to be in the measurement than in the grating structure itself (since there is no multiple exposure averaging of noise in the measurement process).

The only technique presented to date that can overcome the problem of zeroth-order diffraction with phase mask-scanning techniques involves mounting the phase mask on a PZT stage that oscillates in the direction perpendicular to the mask so as to average out the effects of the interference pattern modulation. Whilst this is certainly a valid approach, the concept of deliberately vibrating a phase mask goes very much against the common-sense notion that the phase mask should be mounted in as stable a manner as possible. It can be appreciated that the continuous grating fabrication technique inherently offers a stable, non-mechanical solution to this problem and neatly circumvents the problems associated with finite power in the zeroth diffracted order of a phase mask.
5.3.1.3 Useful Refractive Index Modulation Depth

A significant benefit of this effect is that virtually all of the induced refractive index contributes to the fundamental spatial period of the grating: there is a minimal contribution to the sub-harmonic component with the phase mask period.

5.3.1.4 The Effect of Fibre-to-Phase Mask Separation

It has been shown that the ratio of the fundamental grating period to the sub-harmonic phase mask-period (and their relative phase) varies with the separation of the fibre and phase mask. A further advantage of the continuous grating fabrication technique is thus the inherent immunity to small variations in the distance of the fibre from the phase mask as it is translated: the alternate-fringe exposure means that the technique is not sensitive to the fluctuations in the interference pattern observed in the plane normal to the phase mask. It is important to note that this allows translations stages with relatively poor straightness of motion to be used without significantly compromising the quality of the grating; this may be a problem with similar techniques where exposures are separated by more than one grating fringe.

5.3.1.5 Gratings Made with Exposures Separated by an Even Number of Fringes

The effect of forming gratings by exposures separated by an even number of fringes was investigated to confirm the distinction between multiple exposure averaging and the suppression of sub-harmonic grating components by forming the grating by exposures separated by a single fringe. The UV-probing technique was
used to scan the structure of a grating formed by exposures separated by two fringes; the data is shown in figure 5.10. The re-emergence of a strong component with the period of the phase mask is seen, as expected. This result highlights the importance of the fringe-by-fringe exposure method of the continuous grating technique.

5.3.2 The Effect of Non-Sinusoidal Interference Patterns on Apodisation

Apodisation is achieved in the continuous grating fabrication technique (and in other techniques [Asseh et al., 1997]) by dephasing alternate exposures, as explained in chapter 4. There has been (until recently) an assumption made that the refractive index pattern induced by a single exposure is of a sinusoidal form (or at least, only has a single spatial-frequency component corresponding to the grating period). The results presented so far in this chapter have shown that this is not the case: the interference pattern from a phase mask can have a strong sub-harmonic component. The effect of this, and an alternative apodisation method to overcome such problems, are discussed in the following section.

5.3.2.1 Incomplete Destructive Interference

The effect of making two exposures separated by a complete fringe is to strongly suppress the sub-harmonic component in the induced refractive index change: the resultant structure is close to sinusoidal. In the case where two adjacent expo-
surfaces are dephased by one-half of the grating period, the overall refractive index modulation would be zero if the interference pattern were sinusoidal. In the case where the interference pattern of an exposure has sub-harmonic components, however, this is not the case and there will be some remnant index modulation induced. The experimental data collected for a grating formed by a single exposure was used to assess this effect. The sum of two such exposures separated by half a grating fringe is shown in figure 5.11. It is clear that there is a floor to the minimum refractive index modulation that may be achieved with this simple apodisation method.

An experimental investigation into the details of structures formed by the dephased-exposure apodisation technique was made by fabricating short gratings
designed with a linear spatial variation of index modulation depth. These gratings were then interrogated with the UV probing technique to examine the microscopic effect of this apodisation method. The fringe intensity data at three points along such a grating are shown in figure 5.12 (unapodised, partially apodised, almost fully-apodised). The unapodised section has a nearly sinusoidal form, as expected (top graph). As the level of apodisation is increased (middle graph) the sub-harmonic spatial frequency becomes increasingly prominent. When the exposures are dephased by half a grating fringe (bottom graph) there is a strong attenuation of the fundamental grating period, but a large component remaining at the phase mask period. These results suggested that perhaps the apodisation technique used with the continuous grating could give improved results if it was redesigned around the natural interference pattern of a phase mask.

5.3.2.2 Modification of Apodisation Technique to give Near-Sinusoidal Response
There were two options for improving the quality of the continuous grating apodisation technique:

- determine the level of dephasing required for a given fringe depth at the grating period directly from the phase mask interference pattern
- ensure that the induced refractive index modulation is close to a sinusoidal form before it is dephased to achieve apodisation
The second course of action was chosen as, if achievable, it is not phase-mask specific. It is apparent from section 5.3.1.1, that it should be possible to generate a near-sinusoidal refractive index pattern by having two exposures separated by a single grating fringe. The extension of this concept to that of apodisation is thus simply to form an apodised grating by having two pairs of exposures, in which the pulses are separated by a single grating fringe, with dephasing introduced between the pairs, rather than between individual pulse, as before. This concept is shown schematically in figure 5.13; shown are the original apodisation method, the variation described above, and an extension of this method whereby the apodisation is achieved by dephasing set of four grating exposures. It may be appreciated that

![Figure 5.14: Recorded intensity patterns of a grating with different levels of apodisation achieved by dephasing the pulses between pairs of exposures (top) no dephasing (middle) π/2 dephasing (bottom) π dephasing. Note that the grating pattern remains largely sinusoidal when this alternative apodisation technique is employed.](image-url)
the best apodisation could be achieved by using sets of $N$ exposures, where the interference pattern of the phase mask has sub-harmonic components with $N$-times the period of the grating (for instance, if the small contribution of the $\pm 2^{nd}$ diffracted orders are considered then there may be further sub-harmonic component to the interference pattern). For practical reasons, such as the finite size of the UV writing beam, $N$ should be restricted to a values of four, or less.

The linearly-apodised grating experiment of section 5.2.2.1 was repeated for the new apodisation technique (with $N=2$), and again the structure was interrogated with the UV-probing method. The results from three sections of the grating with different degrees of apodisation are shown in figure 5.14. In comparison to figure 5.12, it is apparent that this alternative apodisation technique maintains a refractive index pattern with virtually no sub-harmonic component (the longer scale drift probably results from slight fibre misalignment during measurement). Additionally there is much higher extinction seen when the pairs of exposures are dephased by one-half of a grating fringe.

5.3.2.3 Evaluation of Apodisation Techniques

The effect of different apodisation techniques has been clearly resolved with the UV-probing technique. In order to assess the fringe extinction achievable with various grating techniques a series of gratings were made designed to be completely apodised; ideally there should be no Bragg reflection whatsoever. From previous
experimental results it is known that the basic apodisation technique, whilst not perfect, it is certainly capable of generating very high-quality gratings. For this reason the gratings fabricated were 25 cm in length and unchirped: an unapodised uniform grating of this length would be very strong (> -60 dB transmission loss) so even very small levels of index contrast will lead to a readily-measurable spectral response. The typical spectral responses of gratings fabricated with the three apodisation methods are shown in figure 5.15. Using the basic apodisation technique there is a small Bragg reflection of approximately –15 dB (3%) in magnitude for such a grating, even when it is completely apodised. This figure falls to approximately –27 dB (0.2%) when apodisation is based on pairs of pulses, and is just –38 dB (0.016%) when sets of four pulses are used. The effective refractive index modulation depths are correspondingly: 3.3x10^{-7}; 8x10^{-7}; 2.5x10^{-7}. The effective index depth for the basic apodisation technique represents about 1% of the index change that would be induced in this fibre if the grating was unapodised.

The development of the UV-probing technique, and subsequent interrogation of grating structures, has thus resulted in an important realisation of how the apodisation method used in the continuous grating fabrication technique may be improved in a practical sense.
5.3.2.4 The Effect of Incomplete Apodisation

The effect of a minimum fringe contrast level was evaluated numerically for un-chirped gratings designed for a 50 GHz grid with a transmission loss of \(-30\) dB. The grating length is 20 mm, the effective refractive index modulation depth is \(25 \times 10^{-5}\), and a Blackman apodisation profile was used. The spectral characteristics were considered for ideal apodisation, for a minimum of 1% fringe contrast (corresponding to the original apodisation method), and a minimum of 0.25% fringe contrast (corresponding to that achieved with dephased pairs of exposures). The results are shown in figure 5.16. It is apparent that just 1% minimum fringe contrast is sufficient to compromise the reflection side-lobe suppression of such a grating by 10-15 dB. A noticeable improvement is seen when this level is 0.25%, corresponding to the newer apodisation technique. Whilst this effect is not currently the limiting factor in grating fabrication (see the following chapter), it may be soon, so it is important that the route to improvement has been identified.

5.3.2.5 The Importance of Suppressing Sub-Harmonic Spatial Periods for UV Post-Exposure Enhancement of Index Modulation

It was described by [Moffat et al., 1999] that the dynamics of grating index patterns when enhanced by fringeless UV post-exposure is determined by the ratio of the fundamental and sub-harmonic grating periods. The new apodisation techniques described above maintain suppression of the sub-harmonic grating component under all apodisation conditions. Not only does this increase the maximum suppression of Bragg reflection, but it also means that the ratio of the fundamental to sub-harmonic spatial periods in the induced refractive index pattern are constant along the length of a grating with any apodisation function (the sub-harmonic component remains minimal at all times). In the case where there is a remnant sub-harmonic component to the refractive index pattern, the growth-dynamics of an apodised grating upon fringeless UV post-exposure will be dependent on the local degree of apodisation in the grating structure: the shape of the grating envelope may thus change, compromising the effectiveness of the desired apodisation profile. Using the new apodisation techniques, however, it is thus expected that fringeless UV post-exposure of such gratings will result in similar growth dynamics along the grating length. This may be of significant importance for future grating manufacture, although there are no experimental results to confirm this at present.
5.4 SUMMARY

The exposure of a germanosilicate glass to UV radiation results in fluorescence at a wavelength of 400 nm. When the germanosilicate core of an optical fibre is exposed to UV, some of this fluorescence is guided to the end of the fibre. Prolonged exposure results in bleaching of the fluorescence mechanism, and an increase in loss at this wavelength. When a grating is formed in an optical fibre by a UV interference pattern the induced refractive index fringes are accompanied by similarly-periodic bleaching/loss effects. By scanning a UV-written grating with a low-power UV interference pattern (typically the same as used to inscribe the grating) it is possible to infer information about the grating fringe pattern by monitoring the level of 400 nm fluorescence guided to the end of the fibre. The results may be interpreted as an auto-correlation between the probe pattern and the grating fringes if the patterns are similar; if the patterns are different, the results are a cross-correlation.

The contribution of zeroth-order diffraction to the near-field interference pattern of a phase mask is to make the amplitude of adjacent fringes resulting from interference between the ±1st orders vary in an oscillatory fashion with distance from the phase mask. When this effect is considered across the extent of a fibre core, the result is a sub-harmonic spatial frequency at the period of the phase mask. The effects of this on the pattern of a grating formed by UV exposure through a phase mask is observed, for the first time, using the UV-probing technique. The measured profile is in good qualitative agreement with that predicted by a simple three-beam interference pattern model. Bragg reflection from the fundamental period and the sub-harmonic period combine in anti-phase to give a non-monotonic increase if refractive index modulation depth with exposure time. Additionally there are consequences of zeroth-order phase mask diffraction on the dynamics of grating growth resulting from fringeless UV post-exposure. The effect of phase mask-to-fibre separation is also presented; again, the results can be matched with a simple theory. The fringe pattern of gratings formed by the continuous grating fabrication technique is observed to be free of the sub-harmonic component when exposures are made every fringe.

An investigation into the effectiveness of the basic continuous grating apodisation technique is presented: it was found that the dynamic range of the system is limited so some extent by the effect of zeroth-order phase mask diffraction. By re-evaluating the apodisation technique to overcome this effect it was possible to achieve much greater annihilation of the fringe contrast. The significance of this result with respect to suppression of spectral side-lobes has been discussed.
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6

THE CAUSES AND EFFECTS OF NOISE IN CHIRPED FBGS

Affecting both the quality and reproducibility of FBG devices, sources of imperfection caused by the fabrication process need to be identified and understood, so that in future generation systems they may be minimised. This chapter introduces the effect of structural noise on the characteristics from two distinct standpoints: short-period stochastic noise, and long-period systematic noise. An attempt is made to visualise the localised effect of noise by considering the transfer of power between counter-propagating modes within the grating. The effects of short and long period noise are identified, and a scale defined for their distinction. The sources of noise in the current version of the continuous grating fabrication systems are evaluated.

6.1 STRUCTURAL NOISE AND CHIRPED FBGS

One of the key criticisms of chirped FBGs for dispersion compensation is the fact that imperfections in the structure lead to a ripple in the group delay response (see: [Enns et al., 1997] [Ouellette, 1997] [Enns et al., 1998a] [Durkin et al., 1998] [Garthe et al., 1998] [Scheerer et al., 1999] [Caponi et al., 1999] [Nielsen et al., 1999]). The following section addresses this issue, and attempts to give an insight into how noise on the refractive index structure affects the characteristics of chirped FBGs. The effect of both high-frequency stochastic noise and longer-period perturbations are considered and their significance discussed.
6.1.1 Description of Chirped FBGs

To understand the effect of imperfections in chirped fibre Bragg gratings, it is important to have a good mental image of exactly how such a device functions. The following section attempts to paint a useful picture to form the basis of discussion.

6.1.1.1 The Band Gap of a Chirped FBG

The band gap of a fibre grating was introduced in chapter 2 as the region in which the amplitudes of the forward- and backward-propagating modes vary exponentially with position. In the case of an unchirped grating the band gap is centred around a single wavelength throughout the length of the device. Chirped gratings, however, have a position-dependent Bragg wavelength, and thus the centre wavelength of the band gap varies along the length of the device; the band gap of an apodised chirped grating is shown schematically in figure 6.1. It is important to realise that fibre Bragg gratings of any type are truly distributed feedback devices: that is, all points in a grating contribute to the spectral response in someway. The only point in the grating at which the reflected field is zero is the furthest boundary of the grating. The idea that because the period of a chirped grating may very linearly with position means that a certain wavelength is reflected from a corresponding position in the grating is a simple first-order approximation (and a misleading one at that). If this were so there would be no problems with group delay linearity.

A more realistic interpretation is to view the region of the band gap as predominantly responsible for the reflection of a wavelength related directly to the local grating period, but also to appreciate that the region on the input side of the band edge itself makes a significant contribution to the power in the reflected mode. This contribution results from the same source as the spectral side-lobes of unchirped gratings: the sinusoidal variation of the mode power outside the band gap. Note that with chirped gratings the period of this modulation (for a certain wavelength) falls with distance along the grating from the band gap. The contribution of the portion of the grating beyond the band gap for a certain wavelength is dependent on the total coupling of power to the reflected mode in the band gap: the contribution is smaller when there is a strong coupling.
6.1.1.2 Reflected-Mode Power Evolution in Chirped FBGs

To calculate the effect of structural noise on the spectral characteristics of an FBG is essentially treating the grating as an optical ‘black box’. Examining (numerically) the evolution of the reflected mode inside such a black box can give a behind-the-scenes insight into the actual effects of imperfections. The reflected mode in an unapodised chirped grating is shown in figure 6.2a; the grating considered is 5 cm in length, has an index modulation depth of $7 \times 10^{-5}$ (reflectivity ~ 90%), and is designed to have a second-order dispersion of 1360 ps/nm (the optical bandwidth is 0.35 nm). It should be noted that the power in the reflected mode at the front face of the graph (wavelength axis) corresponds to the reflectivity of the device (i.e. the power in the reflected mode at the input of the device).

6.1.1.3 Apodisation and Chirped FBGs

Apodisation of unchirped gratings has the effect of making the many components coupled into the backward propagating mode along the grating length interfere in a destructive manner for wavelengths away from the Bragg condition. The only effect of apodisation at the Bragg wavelength, however, is to marginally reduce the level of coupling to the counter-propagating mode. The level of destructive interference for out-of-band wavelengths (side-lobe suppression) is determined by the exact profile of the refractive index modulation envelope.
Any imperfections in the apodisation profile result in undesirable changes of the local coupling strength and to errors in the phase relation between the multiplicity of back-scattered components that comprise the reflected mode. The net result of such errors is to compromise the effectiveness of the apodisation, with the effect that out-of-band wavelengths are not as efficiently suppressed as would be ideal. The same applies to apodised chirped FBGs, although it is slightly more difficult to visualise due to the spatial variation of the Bragg wavelength. The
reflected mode of a chirped grating, apodised with a raised-cosine profile over 25% of its length, is shown in figure 6.2b; the other details of the grating are as for the unapodised device.

6.1.2 The Effect of Short-Period Random Noise on Chirped FBGs

There are essentially two types of noise that may be introduced into fibre Bragg gratings during fabrication: stochastic, (quasi-) random noise, and systematic noise, with typically longer periods. The causes of these problems are distinct, and so are their effects. The following section is concerned with introducing the effects of stochastic noise on the optical behaviour of chirped FBGs.

6.1.2.1 Chirped Gratings with Random Noise

The reflected mode of a 5 cm grating with the same characteristics as that shown in figure 6.2b, but with gaussian noise ($\sigma = 5\%$) on the induced refractive index is considered; the results are shown in figure 6.3. It is apparent that the dominant effect of noise in this case is to reduce the effectiveness of apodisation for wave-
The Causes and Effects of Noise in Chirped FBGs

6.1.2.2 The Consequence of Position on the Effect of Random Noise

The previous section considered the case where the grating structure has an equal amount of noise throughout the structure: from such a grating it is difficult to appreciate whether the effect of the noise is localised, or not. For example, the period of a chirped grating varies linearly with position (for simple gratings), so it may be expected that for a Bragg wavelength related to the period by:

\[
\lambda(\Lambda_{\text{fg}}) = 2n_{\text{eff}} \Lambda_{\text{fg}}(z) \tag{6.1}
\]

that the noise at a position \( z \) will correspondingly affect the amplitude and phase wavelength \( \lambda \) given by (6.1). To investigate this effect, gratings were considered with a ‘burst’ of noise over a small region of the structure. Shown in figure 6.4 is the reflected mode power of a 10 cm grating, with a raised cosine apodisation profile over 20% of the length, with random refractive index noise (\( \sigma = 10\% \)) over the central 10 mm of the structure only. It is apparent that, rather than simply affecting the central wavelengths reflected from the band gap located in the noisy lengths outside the band gap. This leads to two effects: an increase of out-of-band noise, and an increase in group delay ripple.

![Figure 6.4: Power in the reflected mode of an apodised chirped FBG with a noisy section over the central 10% of the refractive index structure](image)
The Causes and Effects of Noise in Chirped FBGs

In the structure, the noise leads to a broad band effect with the predominant consequence being out-of-band noise. The effect of such noise bursts were considered for 20 cm-long gratings designed with a dispersion of –1360 ps/nm; regions of noise were located at 5 cm, 10 cm, and 15 cm with an extent of 2 cm and a standard deviation of 10% on the induced refractive index. The calculated results are shown in figure 6.5. The amplitude of the noise introduced on the spectral response is actually more apparent for wavelengths where the noise is outside the local band gap. The deviation from linear group delay is also not strongly affected by noise in the band gap region.

Figure 6.5: Calculated spectral characteristics of similar apodised chirped FBGs with short sections of short-period noise at various location in the structure.
The Causes and Effects of Noise in Chirped FBGs

99

dominant effect is an increase in group delay noise for wavelengths where the band gap is beyond the region of noise (there is a small effect on wavelength where the band gap is before the region of noise, but this is minimal for gratings with a reflectivity of more than 50%).

An important point to note is that this type of noise does not lead to a direct one-to-one correlation between the local noise at the position of exact Bragg phase matching and the reflectivity or group delay for a certain wavelength. The consequence of short-period random noise is the result of many ‘scattering-like’ events and has a broad-band effect. The effect of short-period random noise may thus be summarised as follows:

- the dominant effect, seen when the region of noise is outside the local band gap, is compromised out-of-band noise suppression and increased group delay noise
- group delay noise increases for wavelengths that are predominantly reflected from further into the grating than the noisy region
- the group delay ripple period falls with distance from the noisy region, suggesting a Fabry-Perot type cavity effect between the scattering of the noise region and the band gap
- there is little effect for wavelengths where the noisy region is within the local band gap

6.1.3 The Effect of Long-Period Noise on Chirped FBGs

Stochastic noise introduced during grating fabrication is only part of the story. Additionally much longer period perturbations to the induced refractive index profile may result from certain characteristics of the fabrication process. The following section considers the equally important effects of such imperfections.

6.1.3.1 Chirped Gratings with Long-Period Noise

The reflected-mode amplitude for a 10 cm long chirped grating, as before, is shown in figure 6.6; this time, a sinusoidal variation has been introduced on the induced refractive index profile, with a period of 1 cm and an amplitude of 10%. It is apparent that the predominant effect of this longer-period ‘noise’ is to change the local coupling strength in the band gap region; there is consequently a direct mapping of the noise level in the band gap to the reflectivity of a certain wavelength. It is also apparent that this longer-period perturbation has very little effect on the behaviour
of the grating in out-of-band regions. There is virtually no effect on the side-lobe suppression for wavelengths away from the main reflection band.

6.1.3.2 The Local Effect of Long-Period Noise on Spectral Characteristics

The effect of long period perturbations was considered on 20 cm long gratings with –1360 ps/nm dispersion. Shown in figure 6.7 are the calculated characteristics of two such gratings of 90% reflectivity, with a sinusoidal variation to the induced refractive index of amplitude of 5%, and periods of 4 cm and 1 cm. It is possible to directly associate the local perturbations of the index structure to the reflection and group delay characteristics of the grating. It should be noted that the amplitude of the reflectivity ripple decreases whilst the amplitude of the group delay noise increases as the period of the noise falls. The effect of long-period noise on the characteristics of a chirped FBG may be summarised as follows:

- longer period noise has little effect on the level of out-of-band noise, which remains well suppressed
- large scale ripples are introduced to both the reflection and group delay characteristics of the grating, that can be directly associated with the fluctuation of the induced refractive index inside the band gap

figure 6.6: power in the reflected mode of an apodised chirped FBG with a long-period sinusoidal perturbation to the refractive index structure (the amplitude of the perturbation is 5% of the induced index change, and there are five periods in the length of the grating)
there is no build-up of group delay noise for wavelengths reflected predominantly from regions deep into the grating (as is the case for short-period noise – see section 1.1.2)

6.1.4 Definition of Long and Short Period Noise in Chirped FBGs

The effects of long and short period noise are clearly distinguishable, not only in terms of scale, but also by their effect on the response of chirped FBGs. The following section describes why this is so.

6.1.4.1 The Physical Extent of the Band Gap in Chirped FBGs

The edge of the bang gap in a fibre Bragg grating is defined as the condition where the detuning of the propagation constant is equal to the coupling parameter. For a
The Causes and Effects of Noise in Chirped FBGs

grating with a local propagation constant \( \beta_o(z) = 2\pi \Lambda_o(z) \) and an effective refractive index modulation depth \( \Delta n_{\text{eff}} \), the optical wavelength at the band edge for a band gap centred at a wavelength \( \lambda_0 \) is expressed as:

\[
|\beta - \beta_o(z)| = \frac{\pi \Delta n_{\text{eff}}}{\lambda} \\
\Rightarrow 2\pi n_{\text{eff}} \left| \frac{\lambda - \lambda_0(z)}{\lambda_0(z)} \right| = \frac{\pi \Delta n_{\text{eff}}}{\lambda} \\
\therefore \lambda - \lambda_0(z) = \pm \frac{\Delta n_{\text{eff}}}{2n_{\text{eff}}} \lambda_0(z)
\]

The optical bandwidth of the band gap is thus simply:

\[
\Delta \lambda_{\text{BG}} = \frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} \lambda_0(z)
\]  

(6.3)

If a grating of length \( l_{\text{fg}} \) is linearly chirped with an optical bandwidth \( \Delta \lambda_{\text{fg}} \) over a length \( z_{\text{fg}} \), then the spatial extent of the band gap is given (from geometric consideration) by the expression:

\[
\Delta z_{\text{BG}} = \frac{\Delta \lambda_{\text{BG}}}{\Delta \lambda_{\text{fg}}} l_{\text{fg}} \\
= \frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} \frac{\lambda_0}{\Delta \lambda_{\text{fg}}} l_{\text{fg}}
\]

(6.4)

For the 20 cm gratings considered, with \( \Delta \lambda_{\text{fg}} = 0.71 \) nm, \( \Delta n_{\text{eff}} = 7 \times 10^{-5} \), \( n_{\text{eff}} = 1.450035 \), the extent of the band gap is thus \( \sim 2.1 \) cm: only 10% of the length (note that this is the general value for a dispersion compensating grating with a dispersion of \(-1360 \) ps/nm and a reflectivity of \( \sim 90\% \)). It is important to realise that whilst (6.4) describes the length over which the mode power varies exponentially, because the grating is chirped, the exact position of Bragg wavelength is only at the centre of the band-gap: the effective coupling constant thus varies over the extent of the band-gap. Consequently, it is not possible to use the expression for \( \Delta z_{\text{BG}} \) in the normal expression for grating reflectivity (2.23) assuming a value of \( \kappa \) based on the refractive index modulation depth [Hill, 1974]. It thus follows that ‘short period’ noise has a period \( \ll \Delta z_{\text{BG}} \), whilst noise may be considered as ‘long-period’ when its period is \( \geq \Delta z_{\text{BG}} \).

6.1.4.2 The Effect of Long and Short-Period Noise

Short-period noise leads to scattering-type behaviour for regions of the grating outside the band gap; long period noise leads to identifiable structure in the spec-
from considering the spatial extent of the band gap in chirped gratings, it is possible to draw the following conclusions:

- short-period random noise is ‘averaged’ over the short band gaps of chirped gratings (where the mode amplitude is decaying slowly), but is not averaged for out-of-band regions where the mode amplitude is oscillating rapidly (leading to scattering-like events)
- when the period of the noise is comparable, or larger than the depth of the band gap, noise can be identified in the spectrum from noise on the index profile: the perturbation is no longer averaged over the extent of the band gap, and also has a minimal effect outside the band gap

These considerations show that the effects associated with short-period noise are thus observed with perturbations at the sub-centimetre scale.

6.2 SOURCES OF SHORT-PERIOD RANDOM NOISE

This section discusses the identified sources of short-period stochastic noise in the grating fabrication process. As mentioned previously, it is effectively impossible to directly correlate measured noise with spectral characteristics due to the non-local effect of high-frequency noise in chirped FBGs: measurement limitations of both the grating spectral response and fabrication parameters limit this approach. It is also difficult to experimentally isolate one effect from the other sources of noise. Improvement of the grating fabrication with respect to such stochastic noise must therefore be made on a ‘seek-and-destroy’ basis.

6.2.1 Quantisation Effects & Measurement Noise

The previous chapter highlights the fact that the refractive index fringes induced by the continuous grating fabrication system are largely independent of the interference pattern used (assuming there is a significant component with the correct spatial period). The characteristics are ultimately determined by the accuracy to which the exposures can be made (both in terms of position and dosage).

6.2.1.1 Interferometer Position Quantisation & Measurement Noise

The ultimate limit to the quality of devices that may be realised with the continuous grating fabrication system is determined by the level of quantisation and noise of the beam modulation positions. Not only is the resolution of the position-
measuring interferometer important, but the effects of mechanical vibrations and environmental fluctuations can lead to significant measurement errors that will be translated to errors in the positioning of the UV exposures. The fabrication system is covered by an enclosure to minimise environmental effects (most notably from air drafts). The position of the fibre translation stage, when stationary with the motor disabled, was measured over a period of several hours (see figure 6.8). The measurement was made overnight, so the drift observed is likely to result from a change in ambient temperature. The drift recorded has a maximum rate of change of ~1 µm/hour. The time taken to fabricate a metre-long chirped grating is typically 8 – 16 mins (1 – 2 mm/s) so the drift represents a long term error of only 1/4x10^6.

More important is the short period variations that result from mechanical instability. Measurements made with a stationary stage and a sample frequency of 100 Hz highlighted that turbulence in the laser cooling water was leading to vibrations being coupled onto the optical bench (see figure 6.9). It was identified that the peak-to-peak noise was in the order of ± 50 nm when the laser cooling water was turned on (unfortunately a necessary requirement for operation of the UV laser); this is very significant compared to the ~ 530 nm exposure separation distance. The effects of this vibration were reduced by a factor of ~ 2.5 by installing a new optical table (24” thick, with tuned damping).

6.2.1.2 Reducing Phase Uncertainty with Multiple Exposures

The concept that the pulse-to-pulse noise could be reduced by forming a grating comprising many exposures was introduced in chapter 4. The blanket claim that
the level of phase noise is reduced by a factor of $N^{1/2}$ (where $N$ is the number of exposures for every grating fringe) is true for considering a gaussian distribution of measurement errors for the exposure locations. However, from the observations of the effects of vibration on the interferometer position measurement, it is apparent that the noise is not truly random and that its period is much longer than the time between exposures. It is expected, then, that the reduction in noise given by a UV beam of diameter $D$ is of the order $(fD/v)^{1/2}$ where $v$ is the translation velocity of the fibre and $f$ is the (temporal) frequency of the noise component (i.e. the square-root of the number of modulation periods in the beam diameter). The solid lines in figure 6.9 represent the average of the measured noise considering a beam diameter of 250 µm and a fibre translation speed of 2 mm/s.

figure 6.9: noise recorder on the Zygo interferometer with the Anorad translation stage stationary (top) old 8″-thick optical table (bottom) new 24″-thick optical table with tuned damping; the dominant source of noise is the turbulent flow in the laser cooling water.
6.2.1.3 Relationship of Apodisation Noise to Phase Noise

It should be appreciated that the degree of uncertainty of exposure position does not directly map to the level of noise on the envelope of the induced refractive index modulation. As discussed in the previous two chapters, the fringe contrast induced during fabrication is related to the cosine of the phase separation of consecutive pulse, as described in section 4.4. This means that the noise on the apodisation profile resulting from phase uncertainty depends not only on the amount of phase noise, but also on the relative phase between pulses required to achieve a desired apodisation level. The error in the apodisation envelope, $\Delta \alpha$, is thus:

$$\Delta \alpha = \alpha_{\text{noise}} - \alpha_{\text{ideal}} = \cos(\phi + \Delta \phi) - \cos(\phi)$$

where: $\alpha_{\text{noise}}$ is the apodisation level in the presence of noise; $\alpha_{\text{ideal}}$ is the desired apodisation level; $\phi$ is the relative phase of the exposures used to achieve apodisation; $\Delta \phi$ is the error in phase between the exposures. The effect of phase noise on the apodisation envelope error is illustrated graphically in figure 6.10. The effect of phase uncertainty is most apparent when the fringe contrast is minimised (pulses are nominally dephased by $\pm \pi/2$); in this case the apodisation noise is a factor of $\sim \pi$ greater than the phase noise. There is little effect when the grating is unapodised ($\phi = 0$).
6.2.2 Non-Uniform UV Exposure

It is quite straightforward to appreciate that non-uniformity in the UV dosage along the length of a grating will result directly in imperfections in the grating structure. The UV fluence delivered to any point in the grating is determined by two factors: the power of the UV beam incident on the fibre core; the length of the exposure. The causes and severity of these two factors is discussed below.

6.2.2.1 The Effect of Non-Uniform UV Exposure

As discussed in section 4.3.1 the minimum background index change induced during grating fabrication is half of the fringe depth; in reality this is an underestimate. The variation of UV fluence thus not only varies the fringe contrast, but also the background refractive index; the latter effect causes an undesirable detuning of the local Bragg wavelength for a given grating period. The effect of envelope noise and background index noise can be separated theoretically (as can pure phase noise) but it is difficult to visualise an experimental situation where they are not inextricably related.

6.2.2.2 UV Exposure

The power of the UV beam on the fibre core is determined by three key factors:

- UV laser power
- alignment of the UV beam with the fibre core (considering both fibre sag and vibration)
- contamination of fibre and optics (including remnants of coating left on the fibre surface)

The laser power was sampled using the measurement hardware developed for the work on grating fringe measurement. It is seen that there is ~ 2% noise on the output power of the laser. Spectral analysis of the data collected (see figure 6.11) shows that the output power variations are at frequencies associated with turbulence in the laser cooling water (resulting from vibrations of the laser cavity). Using the minimum possible cooling water flow (2.5 GPM for the Coherent FreD laser) gives the optimum performance (which is still not ideal). Since the tracking circuitry is based on detection of fluorescence resulting from the UV exposure, it is possible that the variations in fluence could be taken (incorrectly) as a movement of the fibre core. For this reason, it would be ideal to use a balanced receiver to distinguish the effects of laser output power fluctuation and fibre core movement (currently a low-pass filter is used to reject the high frequency laser noise). It is
also observed that certain types of fibre coating can be extremely difficult to remove efficiently if the fibre is kept in a high-pressure raised-temperature environment to increase its photosensitivity. Not only do small remnants of fibre coating result in a local ‘drop-out’ in the grating structure, but the following section is affected as the tracking circuitry attempts to recover from the perturbation.

6.2.2.3 Velocity Instability of Translation Stages

Aside from the intensity of the beam incident on the fibre core, the UV dose is also determined by the length of the exposure. Some contribution is made to uncertainty in this value by the noise in the position of exposures. The major effect here, however, is the velocity stability of the fibre translation stage (the exposure position is theoretically independent of velocity, since it is based on a position measurement).

The velocity of the Anorad translation stage was measured directly from the 32-bit position output of the Zygo interferometer, using the National Instruments DIO card. Measurements were triggered by the 2 MHz clock signal from the Zygo divided electronically by 256 with an eight-stage binary counter. It is important that the acquisition intervals be extremely accurate for determination of velocity from position measurement. The velocity non-uniformity was found to be quite consistent over a range of speeds from 250 µm/s to 2 mm/s. Additionally a strong periodic component was observed with a period of ~8 mm.

figure 6.11: spectral details of the noise on the output power of the frequency-doubled Ar-ion laser used for grating inscription; the amplitude of the power fluctuation is ~ 2%, and the dominant frequencies correspond to turbulent cooling water flow.
Shown in figure 6.12 is data collected on three separate occasions with a stage velocity of 2 mm/s; the spectral characteristic of the noise is also shown. The noise on the motion is clearly almost repeatable, and can largely be attributed to the size of the metallic strips on the commutator of the brushed linear motor drive (which are 8 mm in size). The data shown in figure 6.12 has been averaged with a sliding window to represent the averaging effects of a 250 µm UV beam diameter. Although only ~ 1% in amplitude, the velocity stability of the translation stage is another small contribution that leads to the ensemble effect of stochastic noise in the fabrication system.
6.3 SOURCES OF LONG-PERIOD NOISE

The sources of long period noise are more straightforward to identify since their effect on the grating structure can be readily determined from the spectral response of the grating. The following section highlights the two main causes of long period noise- phase mask imperfections and fibre diameter non-uniformity- both of which are also limiting in most other grating fabrication systems.

6.3.1 Phase Mask Imperfections

As shown in chapter 5, the interference pattern of a phase mask is determined by the balance of power in the diffracted orders. The problem of phase mask non-uniformity is apparent when different sections of a grating are formed by different regions of a phase mask. Although the continuous grating fabrication technique is not fundamentally reliant on scanning phase masks, it is often convenient to do so to realise broad bandwidth gratings (see section 4.2.2.1). Additionally, the need to follow the sag of the fibre leads to some vertical displacement of the UV writing beam on the phase mask during fabrication.
6.3.1.1 The Causes of Phase Mask-Based Imperfections

Imperfections in gratings may be caused by variation in the depth, duty cycle, shape, and period of the phase mask profile. Such variations lead to changes in the ratio of fringe contrast to background index induced in the fibre, resulting in changes in coupling strength and local Bragg wavelength of the fibre grating, as discussed in section 6.1. Additionally, stitching errors in phase masks fabricated by e-beam techniques, and chirp non-linearity in masks fabricated by holographic techniques present problems.

The characteristics of a 30 nm-bandwidth, 10 cm-long grating fabricated by the continuous grating fabrication technique where the UV writing beam was scanned over the full extent of a chirped phase mask are shown in figure 6.13. Clearly visible are the large imperfections in the grating response that can be attributed to the poor quality of the phase mask used. The same phase mask was used to fabricate a 30 cm grating with a 22 nm bandwidth (intended for phased-
array microwave applications). The spectral response, shown in figure 6.14, clearly echoes the characteristics of the phase mask apparent in figure 6.13: most notably the roll-off at long wavelengths caused by either chirp non-linearity, or variation in diffraction efficiency, of the phase mask.

6.3.1.2 Reducing the Effects of Phase Mask Imperfections
Phase mask technology is undoubtedly improving, and the fact that the continuous grating fabrication technique does not rely on state-of-the-art long phase masks is beneficial from this point of view. It has been shown [Loh et al., 1995b] that large-scale phase mask errors can be corrected for during fabrication (in this case the mounting of the phase mask under stress led to a large-scale chirp), but to overcome the small scale fluctuations is difficult, since any error in the correction process may enhance, rather than reduce, the problem. The problem is thus best tackled at source. The continuous grating fabrication technique, for reasons discussed in the previous two chapters, is less susceptible to the variations in fringe pattern than techniques that rely on direct scanning of phase masks to imprint gratings.

6.3.2 Fibre Non-Uniformity
The diameter of an optical fibre is controlled by a feedback loop during the drawing process (the fibre diameter is determined by the drawing tension). The time-constant of the feedback loop can lead to a resonance in the fibre draw tension that leads to variations of the fibre diameter, typically with a scale of 10-20 cm (this may be considered as long-period noise for chirped FBGs). Although has no serious implications for transmission fibres or amplifier fibres, the dependence of grating characteristics on the local waveguide geometry can lead to problems. Changes in fibre diameter lead to a variation in numerical aperture which leads to a change in overlap of the core-guided mode and the fibre core; subsequently this changes the effective refractive index of the fibre, and the coupling strength of the grating (if it is written only in the core). As with the effects of phase mask non-uniformity, this leads to large scale perturbations that may be resolved in the spectral characteristics of the grating (see section 6.1.3).

It is typically observed that the period of the fibre fluctuations is of the order of 10-20 cm. For short gratings (~ 10 cm) it is difficult to identify this problem as anything other than a random factor affecting the yield of the fabrication process. The effect of fibre non-uniformity on the characteristics and reproducibility of
chirped FBGs was first observed in late 1996 before the advent of the metre-long grating fabrication system. At the time the continuous grating fabrication system was in an version capable of realising 40 cm gratings.

6.3.2.1 The Effect of Fibre Diameter Variations

In order to investigate the suspected problems of fibre non-uniformity, pairs of gratings were overwritten in the same length of fibre (note that no chirped phase mask was used so errors are not attributable to this source). The spectral characteristics of one such pair is shown in figure 6.15. There are two noteworthy features: firstly, the characteristics of both gratings are similar, suggesting a systematic, rather than transient fabrication problem; secondly there is a small region of gratings with an increased reflectivity. The increase in reflectivity seen with non-uniform fibres is a result of the interplay between an increase in refractive index modulation depth and a change in chirp rate (due to the associated change in background index). A more striking example is shown in figure 6.16; this is the spectral response of a 1 m-long chirped FBG fabricated in a boron co-doped fibre. The group delay deviation seen in this grating, resulting from fibre diameter fluctuations, clearly limits the application of this device for dispersion compensation.
6.3.2.2 Reducing the Effects of Fibre Non-Uniformity

The ideal way to reduce the effects of fibre diameter fluctuations is optimise the fibre drawing conditions. Recent work by Morten Ibsen at the ORC has led to a set of criterion that help to minimise the effect of a given non-uniformity: fibres in which the mode field size is relatively intolerant to small diameter fluctuations will give the best performance [Ibsen and Laming, 1999].

6.4 SUMMARY

By considering the evolution of modal power along the length of chirped FBGs is has been possible to identify two types of imperfection: short-period noise, which leads to scattering-like events outside the local band gap, and long-period noise, which leads to a variation in the coupling strength within the local band gap. Short-period noise leads to increased out-of-band reflection noise and high-frequency group delay ripple with increasing amplitude and decreasing period for wavelengths dominantly reflected from deep into the grating. It is not possible to
directly identify the local effects of short-period noise as features on the spectral response. Conversely, the local effect of long-period noise can be directly observed on spectral characteristics. The reflectivity and group delay ripple associated with long-period perturbations are the result of balance between a local variation in coupling strength and a local variation of chirp rate. With decreasing noise period the reflectivity ripple falls whilst the group delay ripple increases in amplitude; no increase of group delay noise amplitude is observed with long-period noise. The differentiation between the two scales of perturbation may be based on the spatial extent of the local band gap. The sources of short-period noise in the fabrication system largely result from mechanical instability. Long-period perturbations are observed from phase mask imperfections and fibre non-uniformity.
CHIRPED FBGS FOR DISPERSION COMPENSATION
The prohibitive cost of laying new fibres has had researchers competing to find ways of maximising the huge bandwidth offered by existing fibre links. The EDFA has effectively alleviated the problems of loss in the 1.5 µm transmission window, but its widespread adoption has meant using existing fibre links at wavelengths well away from their dispersion zero at ~ 1.3 µm. In order for high data rate and broad-band systems to function correctly over long distances it is necessary to periodically undo the pulse-broadening effects of dispersion. An attractive technique for dispersion compensation is to use the dispersive properties of chirped fibre Bragg gratings to temporally re-focus the spectral components of short optical pulses. This chapter reviews the effect of dispersion in optical fibres, and gives a brief overview of its effect in optical transmission systems. The three main techniques that have been made to address the problem of dispersion are introduced, before the necessary requirement for dispersion-compensating chirped FBGs are discussed.

7.1 DISPERSION IN OPTICAL FIBRE LINKS

Dispersion expresses the wavelength dependence of refractive index. The dispersion of an optical fibre may be small, but the long interaction lengths of typical transmission links mean that there can be significant broadening of short optical pulses that (necessarily) comprise a large spread of wavelengths. Chromatic dispersion, along with loss and non-linear effects, is responsible for limiting the maximum transmission length in an optical fibre. The variance of effective refractive index with wavelength means that the spectral components comprising a short
optical pulse travel with a distribution of group velocities: over long distances the spectral components of pulses spread out. Ultimately so severe is the effect that spectral components from one pulse shift into the time window of adjacent pulses. This undesirable temporal overlap of pulses leads both to interference between adjacent pulses (inter-symbol interference – ISI) and to a reduction in contrast which degrades the signal-to-noise ratio (SNR); subsequently this results in significant problems in the decision-making electronics of an optical receiver making error-free transmission impossible.

To a transmission system, overcoming the problem of dispersion in fibre links is the equivalent of a making trip to the opticians: refocusing of spectral components regains the contrast needed for successful resolution of information over long distances. The following section reviews the sources and effects of dispersion in optical fibres.

7.1.1 Dispersion in Optical Fibres

Distinct contributions are made to the total dispersion of an optical fibre both by the physical character of the glasses used and by the optical geometry of the waveguide structure; respectively, these are referred to as material dispersion and waveguide dispersion. A good review of the causes and effects of dispersion in optical fibres is given by Buck [Buck, 1995: chapter 5].

7.1.1.1 Material Dispersion

The frequency (or wavelength) dependence of refractive index (material dispersion) is determined by the absorption characteristics of a material according to the Kramers-Kronig relations (see [Yariv, 1989: pp. 160-164] for example). Far from material resonances the refractive index variation is well approximated by the Sellmeier equation (see [Agrawal, 1997: section 2.3.2, pp. 41-42] for example). It is possible to define a dispersion parameter, $D(\lambda)$, which equates to the wavelength-dependence of group delay, such that:

$$D(\lambda) = \frac{1}{c} \frac{dn_g}{d\lambda}$$  \hspace{1cm} (7.1)

where the group index of the material, $n_g$, is related to the material index $n_{mat}$ by:

$$n_g = n_{mat} - \lambda \frac{dn_{mat}}{d\lambda}$$  \hspace{1cm} (7.2)
The inflection point of a material's group index curve defines the wavelength for zero dispersion. For wavelengths greater than this, the behaviour of group dispersion is said to be anomalous - that is to say that propagation speed decreases with wavelength. Traditional transmission fibres have a step-index profile with a germanosilicate core and silica cladding. Designed with a dispersion zero at 1.3 µm, such fibres thus exhibit anomalous dispersion in the 1.55 µm EDFA transmission window.

7.1.1.2 Waveguide Dispersion
The second component of fibre dispersion comes from the waveguide geometry. Field distributions for step index fibres can be described by Maxwell's equations with appropriate boundary conditions to reflect the geometry of the waveguide (again see, for example, [Buck, 1995: chapter 3]). Above the cut-off wavelength for a given fibre geometry the waveguide supports a single guided mode. In this single-mode regime there is a greater penetration of the mode field into the cladding at longer wavelengths. The effective index of the fibre is thus determined by the balance of power in the core and cladding regions since the material index of the cladding is lower than that of the core. The relative contribution of the core and cladding materials is weighted by the fractional modal power in each region. As a consequence there is a wavelength dependence of the effective fibre index that must be combined with the effects of material dispersion when calculating the overall group dispersion of the fibre. By careful design of the waveguide geometry it is possible both to move the zero-dispersion wavelength and to vary its slope.

7.1.1.3 Fibre Dispersion
It is common to describe the overall group index for the mode of an optical fibre: this encompasses the combined effects of material dispersion and waveguide dispersion. The dispersion parameter for an optical fibre is typically considered as:

$$D_f(\lambda) = \frac{1}{c} \frac{dn_f}{d\lambda}$$  \hspace{1cm} (7.3)

where $n_f$ is the effective refractive index of a fibre mode. The dispersion parameter is usually expressed in terms of ps/nm-km. Step index fibre designed for operation at 1.3 µm (the majority of the world’s currently installed fibre) have a typical dispersion of 16-17 ps/nm-km at wavelengths in the 1.55 µm EDFA transmission window.
7.1.2 Effects of Fibre Dispersion

The propagation of an optical pulse through a single-mode fibre waveguide has an almost direct analogy in the free-space propagation of monochromatic light. As a free-space beam propagates from a beam waist it diverges spatially and the wavefront curves; a corresponding phase variation is introduced. The guiding aspects of the fibre geometry mean that pulses in an optical fibre do not suffer spatial divergence, but the phenomenon of chromatic dispersion leads to a temporal divergence of the different optical frequencies. Whilst lenses or spherical mirrors can be used to change the wavefront profile of a diverging free-space beam, the temporal phase profile of a dispersing pulse in an optical fibre can be reshaped using a dispersive optical element, such as a chirped FBG.

The dispersion parameter described in equation (7.3) describes the wavelength dependence of group delay, $\tau_g$, where $\tau_g$ after a distance $z$ is given by:

$$\tau_g = z \frac{d\beta}{d\omega}$$

(7.4)

($\beta$ is the mode propagation constant, and $\omega$ the frequency). Typically it is assumed that $\beta$ has a smooth variation with frequency, so it may be expressed as a Taylor series expansion about the central frequency of the pulse, $\omega_0$, such that:

$$\beta(\omega) = \beta_0 + \left[ \omega - \omega_0 \right] \frac{d\beta}{d\omega} \bigg|_{\omega_0} + \left[ \omega - \omega_0 \right]^2 \frac{d^2\beta}{d\omega^2} \bigg|_{\omega_0} + \left[ \omega - \omega_0 \right]^3 \frac{d^3\beta}{d\omega^3} \bigg|_{\omega_0} + \cdots$$

$$= \beta_0 + \left[ \omega - \omega_0 \right] \beta_1 + \frac{1}{2} \left[ \omega - \omega_0 \right]^2 \beta_2 + \frac{1}{3} \left[ \omega - \omega_0 \right]^3 \beta_3$$

(7.5)

7.1.2.1 Quadratic (2nd-order) Dispersion Effects

By far the dominant contribution to fibre dispersion is the quadratic term (unless the pulse comprises wavelengths close to the dispersion zero). If only this 2nd-order dispersion term is considered, the temporal broadening of a pulse, $\Delta \tau$, is given by the product of its spectral width, $\Delta \lambda$, the fibre dispersion, $D_f$, and the propagation length, $l$:

$$\Delta \tau = D_f \Delta \lambda l$$

(7.6)

The dominant effect of fibre dispersion is thus to linearly chirp the pulse due to an approximately linear change in group delay with frequency.
7.1.2.2 Cubic (3rd-order) Dispersion Effects

The cubic component to fibre dispersion has typically less effect than the quadratic part—except for wavelengths close to the dispersion zero. The 3rd-order component describes the wavelength dependence of the dispersion parameter and largely has two consequences: that the effect of dispersion is not consistent across all the channels of a broad bandwidth WDM transmission system; that a pulse can be nonlinearly chirped during transmission. The former effect is of importance in designing effective dispersion compensation components, whilst the latter has increasing importance in high-bit rate systems (with broad pulse bandwidths) or at operation close to the dispersion zero. Third-order dispersion (TOD) leads to a pulse-reshaping effect caused by the interference between pairs of frequencies with equal group delays (see, for example, [Buck, 1995: pp. 139-141]).

7.1.3 Dispersion Limitations in Linear Transmission Systems

The effects of group dispersion in fibre transmission systems become striking at high bit rates. Standard step index non-dispersion shifted fibre (NDSF) has a fundamental dispersion of ~ 16-17 ps/nm⋅km at 1550 nm. Increasing the data rate has a two fold effect: pulses become both temporally shorter and spectrally wider (from Fourier theory). Since (if a narrow line-width laser source is used) the pulse bandwidth is directly proportional to the data bit rate, $B$, the temporal broadening of a pulse increases linearly with bit rate.

7.1.3.1 Inter-Symbol Interference

In terms of data transmission the problem of dispersion is manifest when temporally sequential pulses begin to overlap and the distinction between the high and low state is blurred: this is referred to as inter-symbol interference (ISI). Higher data rates imply not just shorter pulses, but also correspondingly shorter times between successive pulses. The effect of dispersion should not be considered as the total temporal broadening, but rather the fractional broadening of the pulse with respect to its time slot; this is given by the ratio of temporal dispersion, $\Delta \tau$, to the time slot length, $\tau$, and is proportional to the bit rate squared:

$$\frac{\Delta \tau}{\tau} = |D_f|\Delta\lambda B L \propto |D_f|B^2 L$$

(7.7)
A good approximation for dispersion-limited transmission length, $L_{db}$ is given when dispersion-induced broadening makes the pulse as long as the time slot (considering only the effects of 2nd-order dispersion). This defines the condition:

$$L_{db} = \frac{1}{B\left|\Delta\lambda\right|}$$  \hspace{1cm} (7.8)

This equality is plotted for data rate versus transmission length in figure 7.1 for a NDSF with a dispersion of 16 ps/nm/km. It can be seen that whilst 2.5 Gb/s pulses can travel significant distances before becoming unresolvable\(^3\), 10 Gb/s data cannot be successfully transmitted over a 100 km link without some form of dispersion compensation, and 40 Gb/s data can only travel $\sim$ 5 km.

### 7.1.3.2 Signal-to-Noise Ratio Reduction

The simple argument presented in the previous section sets the dispersion limited length as that which minimises ISI. It is important to note that, additionally, the dispersion-induced broadening lowers the peak power and hence degrades the signal-to-noise ratio (SNR) at the receiver [Agrawal, 1997: section 5.4.2, pp. 214-216]. For example, if the pulse has been broadened by a factor of two, then the signal power must be enhanced by 3 dB in order to achieve the same SNR at the receiver.

\(^3\) note that the effects of fibre non-linearities are not considered here
7.1.3.3 Dispersion-Shifted Fibre Links

Tailoring the waveguide properties of a fibre allows the dispersion zero to be shifted significantly from the natural material dispersion. Of increasing prevalence over recent years have been new transmission fibres, such as AT&T’s TrueWave, with a much reduced dispersion at 1.55 µm. It is desirable to maintain a small amount of dispersion to prevent four wave mixing (FWM) effects from occurring during transmission [Agrawal, 1997: section 2.6.3, pp. 63-64] [Georges and Favre, 1999], but high-bit rate (10 Gb/s and above) signals may be transmitted over much longer distances before becoming dispersion limited. These new fibres, known as non-zero-dispersion shifted fibres (NZDSF), have dispersion values ~1-4 ps/nm⋅km at 1.55 µm and are likely to form the basis for many future transmission systems.

Ultimately though, it is still preferable to use some form of dispersion management in such links (albeit with reduced levels of negative dispersion) so designers of dispersion compensating components are facing new challenges for the future. Due to the small 2nd-order component of dispersion, the effects of 3rd-order dispersion are of increasing importance: transmission systems based around this fibre are designed to have large operational bandwidths and long transmission lengths. For example, typical values for 3rd-order dispersion are ~ 0.09 ps/nm²⋅km, so the fibre dispersion could vary by more than 3 ps/nm⋅km over the 30 nm operational bandwidth of an EDFA. From figure 7.2 it is apparent that this variation is
sufficient to change the dispersion-limited transmission distance by a factor of almost two, for a given bit rate. This suggests a prerequisite for a successful dispersion management technique is broad bandwidth compensation of 2nd and 3rd order dispersion.

7.1.4 Dispersion-Managed Soliton Transmission Links

Optical transmission over long distances using systems based either on linear pulses or on solitons alone is difficult. Long interaction lengths lead to a build up of non-linear effects degrading the performance of linear systems after ~ 500 km [Grudinin et al., 1997]. The soliton-breaking effects of loss means that non-linear transmission systems require frequent amplification; after long propagation lengths pulse-to-pulse interactions and timing jitter also become problematic [Smith et al., 1996]. It has been shown recently that a more attractive approach is to use a hybrid non-linear/linear transmission system [Kubota et al., 1992] with periodic dispersion management. Employing dispersion compensation to recompress the loss-broadened soliton pulses makes it possible to extend the intra-amplifier span length and allows solitons to propagate for longer distances before breaking up [Grudinin et al., 1996]. A direct consequence of these improvements has led to significant recent research into the development and deployment of partial soliton systems [Doran, 1998] [Georges and Favre, 1999]. For successful implementation of this transmission scheme it is essential that the dispersion compensation scheme used should be compatible with the higher pulse powers used; that is, they should exhibit low optical non-linearities.

7.2 Dispersion Compensation Schemes

Three main schemes have been proposed and demonstrated to compensate the dispersion of fibre links: all have their own peculiar advantages and pitfalls; all are still actively being pursued. This discourse will necessarily concentrate on the use of chirped fibre Bragg gratings for dispersion compensation, but an overview of the other two main techniques will be presented first. For other examples see [Agrawal, 1997: chapter 9].
7.2.1 Dispersion Compensating Fibre

Possibly the most traditional approach to fibre dispersion management is to post-propagate the optical data through a length of fibre with a large negative dispersion; the dispersion-length product of the dispersion compensating fibre (DCF) must be exactly opposite to the corresponding parameter for the transmission link (figure 7.3). The dispersion profile for DCF is obtained by a suitable design of the optical geometry. By only weakly guiding the fundamental mode a small change in wavelength leads to a large change in mode field diameter. As a consequence the negative waveguide dispersion can be made to dominate over the positive material dispersion [Jopson and Gnauck, 1995].

Dispersion compensating fibre unfortunately exhibits a high value of absorption and, after propagation over a length suitable for dispersion compensation of a typical NDSF link, the loss of signal power is severe enough to warrant the addition of an amplification stage. The high non-linear effects observed in DCF are also undesirable in practical systems, especially those where higher power return-to-zero (RZ) modulation formats are used. An additional concern with DCF is its operational bandwidth. Whilst fibre inherently allows wavelength-continuous operation, it may be difficult to make a fibre with 2\textsuperscript{nd} and 3\textsuperscript{rd}-order dispersion characteristics that can be made to match exactly those of installed fibres over large bandwidth ranges.

7.2.2 Mid-point Spectral Inversion

Mid-point spectral inversion (MPSI) uses four-wave mixing (FWM) to achieve phase conjugation and reverse the spectral dispersion of a pulse. If such an inversion is made part way along a fibre link the spectral components of the pulse
should have the same temporal relation at the end of the link as at the input (figure 7.4). MPSI is attractive for its broad continuous bandwidth of operation and ability to undo some non-linear effects. Unfortunately this technique can only compensate even-ordered components of dispersion\(^4\) and introduces noise into the system due to poor efficiency; this ultimately means reliance on some other technique to provide 3\(^{rd}\)-order dispersion compensation. However, there have been successful demonstrations of MSSI in high bit-rate (40 Gb/s) transmission systems [Set et al., 1998] [Stephens et al., 1999].

7.2.3 Chirped Fibre Bragg Gratings

It is the strong dispersive characteristic of chirped fibre Bragg gratings used in reflection that makes them suitable for dispersion compensation; the fact that they are low-loss, compact and exhibit virtually no non-linear effects is a bonus. The rationale behind FBG dispersion compensation is to refocus the spectral components of an incident pulse directly by effectively reflecting the longest wavelengths at the start of the grating and shorter wavelengths at positions progressively deeper into the grating (for normal fibres); this is illustrated schematically in figure 7.5. The grating is placed after an optical circulator to divert the backwards propagating pulses into the next fibre span (or receiver). The dispersion of a linearly chirped FBG, \(D_{\text{FBG}}\), is given by the relation:

\[
D_{\text{FBG}} = \frac{2n_{\text{eff}} l}{c} \frac{1}{\Delta \lambda}
\]  

\(\text{(7.9)}\)

\(^4\) realistically this means only 2\(^{nd}\) order dispersion compensation since the 4\(^{th}\) order component of dispersion is, in current systems, insignificant
where \( n_{\text{eff}} \) is the effective refractive index of the core-guided mode, \( l \) is the physical grating length, \( c \) is the vacuum speed of light, and \( \Delta \lambda \) is the bandwidth of the grating. The total group delay available from a chirped FBG is thus:

\[
\tau_{\text{FBG}} = \frac{2n_{\text{eff}} l}{c} \tag{7.10}
\]

This group delay must be distributed across the desired optical bandwidth, so the dispersion-bandwidth product of a chirped FBG is determined entirely by its length. For example, an 80 km link of NDSF with a dispersion of 17 ps/nm·km has a dispersion of 1360 ps/nm, so approximately 7 cm of grating length is required for every nanometre of operational bandwidth.

The advancement of the continuous grating fabrication technique made during the course of these studies means that it is now possible to design and make gratings with a dispersion profile exactly matched to a fibre link. In this sense the chirped FBG can provide, over its bandwidth, exact (although currently passive) phase reconstruction of the pulse as it entered the preceding fibre link. Chirped fibre Bragg gratings additionally offer the possibility of tuneable dispersion. To date, this has been most successfully demonstrated by introducing a thermal gradient along the grating length to vary the chirp [Laming et al., 1996] [Eggleton et al., 1999]. Recent system trials have confirmed the compatibility of operation of such devices at data rates of 20 Gb/s.
7.3 CHIRPED FBGS FOR DISPERSION COMPENSATION

The idea of using linearly chirped fibre Bragg gratings for dispersion compensation was first proposed in a published form in 1987 [Ouellette, 1987]. Initial systems trials on this scheme [Garthe et al., 1994] [Loh et al., 1996] used short devices and so could only operate on a single wavelength channel. Recent developments in fibre grating technology have resulted in a number of options for multi-channel dispersion compensation [Ibsen et al., 1999b] [Loh et al., 1999] [Gnauck et al., 1999]. It is envisaged that a dispersion compensating unit may be included at each amplifier stage of a fibre link, and so the chirped FBG should be able to offer typically between 50 km and 200 km of dispersion compensation.

Wavelength drift of transmission sources, and the recent development of multi-channel WDM systems means that the grating should offer as much operation bandwidth as possible. For the case of a drifting source, in particular, it is important that there are no glitches across the useful wavelength range of the device. For WDM systems it is important to enable operation on all channels. The potential of a single dispersion compensating chirped FBG is essentially determined by its bandwidth utilisation: if the grating is only designed for single-channel operation then it is important that the useable bandwidth should be a large fraction of the channel spacing; if the grating is a multiple channel device then it is important that the number of channels that fall between the operational bandwidths of adjacent devices is minimised (shown schematically in figure 7.6). As well as reflection bandwidth constraints, there are also group delay bandwidth considerations. These issues are discussed more fully in the following chapters.

7.3.1 Single-Channel Dispersion Compensation

The typical method of fabricating chirped fibre Bragg gratings is to use a phase mask-scanning technique (see chapter 3) which subsequently limits the maximum length of the device to that of the phase mask (typically 10 – 15 cm). A 10 cm long chirped grating can thus provide 80 km of dispersion compensation of a fibre with a dispersion of 17 ps/nm/km over a bandwidth of ~0.7 nm (i.e. a single 100 GHz ITU channel only).

\[5\] this length range encompasses most land-based fibre links, and the loss-limited range of transmission possible with EDFAs
There have been many demonstrations of dispersion compensation using single-channel chirped gratings (see, for example: [Laming et al., 1997a,b] [Zervas et al., 1997] [Laming et al., 1998] and from one point of view this approach provides a scalable solution; also such devices may be athermally packaged. Basic apodised chirped fibre Bragg gratings of this length, however, can only realistically have a filling factor (e.g. -1 dB bandwidth c.f. -30 dB bandwidth) of 0.4 - 0.7 (depending on the bandwidth and dispersion – see chapter 10); a figure that can be further reduced if there is any wavelength misalignment between several such gratings in a transmission line (see chapter 10). This means that the tolerable drift of signal wavelength is fairly small before changes in power are observed.

A recent development of fibre Bragg grating design-theory, however, has made possible a new generation of advanced single-channel dispersion compensators. The design technique was used to develop a grating structure capable of providing a high bandwidth utilisation factor and a highly linear group delay response. The results of this work are presented in chapter 10. It is anticipated that this ap-
7.3.2 Broadband Dispersion Compensation

An attractive approach to dispersion compensation is to use a much longer chirped grating capable of broadband operation. From (7.9) however, it can be seen that a grating of length $\sim 4$ m is required to give the correct dispersion to compensate 80 km of NDSF over 30 nm of the EDFA bandwidth. It is unfortunately more difficult to fabricate gratings of this length than short, single-channel devices, although there are an increasing number of attempts being made to achieve this goal [Rourke et al., 1999] [Brennan III et al., 1999] [Yoffe et al., 1999]. Initially the drive towards long, broadband chirped FBGs came from the need to cater for transmitter wavelength drift. The appeal was then extended when more densely-packed WDM systems began to emerge, since it became possible to use a single long grating to provide dispersion compensation for multiple channels. As the channel spacing becomes increasingly dense, however, the wavelength stability of transmitters must be much greater and the goal of catering for wavelength drift is no longer the primary objective: rather it is important that all possible channels in a transmission system can be utilised.

To date there have been several reported transmission experiments with bit-rates of 10 Gb/s and above, with gratings of length $\sim 1$ m [Kashyap et al., 1996b] [Grudinin et al., 1997] [Garrett et al., 1998] [Robinson et al., 1998] [Gnauck et al., 1999]. The first realisation of high bit rate linear transmission over an appreciable length of NDSF using long chirped FBG dispersion compensation was reported by Dong et al at OFC '97 [Dong et al., 1997a]: transmission at 40 Gb/s was demonstrated over 109 km of NDSF with a bit error rate (BER) of $10^{-9}$. Whilst by today’s standards this BER is only just in the error-free regime, the demonstration served to show that the fruition of FBG technology makes these devices of immense practical value in existing telecommunications networks. The demonstration of chirped FBG compatibility with dispersion-managed soliton transmission (see chapter 9) also helped to ensure their future desirability. Increasingly the need for dispersion management of NZDSF fibre links with dispersion values $\sim 2$ps/nm-km mean that compensation of third-order dispersion is crucial as well.
7.3.3 Multi-Channel Superstructure Dispersion Compensation

It is possible to make a multi-channel dispersion compensator by using a chirped superstructure grating [Ouellette et al., 1995] [Ibsen et al., 1998b] [Ibsen et al., 1999b] [Loh et al., 1999], in the same way that multi-channel filters may be fabricated. Whilst this approach may be beneficial from a packaging perspective, these devices are significantly more difficult to fabricate and it is not-trivial to include functionality such as 3rd order dispersion compensation and gain flattening. The developments of the continuous grating fabrication system presented permit the fabrication of such devices, and indeed a system trial on a four-channel device has established their potential application [Ibsen et al., 1999c]. Another aspect to consider, though, is that such devices are still subject to the low bandwidth utilisation factors associated with normal, short chirped FBGs when designed to operate with DWDM 50 GHz grid spacing (although it is conceptually possible to design a multi-channel structure based on the new grating designs presented in chapter 10).

7.4 SUMMARY

The overall dispersion of an optical fibre is determined by a balance between the effects of material dispersion and waveguide dispersion. Fibres designed with a dispersion zero in the 1.3 \( \mu \)m transmission window exhibit anomalous dispersion in the 1.55 \( \mu \)m EDFA window- longer wavelengths travel more slowly. The effect of dispersion leads to temporal pulse broadening and subsequent reductions in signal-to-noise ratio at the receiver; additionally, as pulse begin to extend from their allocated time slot, they overlap and the resultant inter-symbol interference leads to power penalties. The effect of dispersion can limit the maximum transmission length in a fibre. The relatively high dispersion of standard non-dispersion shifted fibre (16-17 ps/nm-km) limits 10 Gb/s data transmission to \( \sim 60 \) km, and 40 Gb/s transmission to \( < 5 \)km. New dispersion-shifted fibres offer lower dispersion (\( \sim 2 \) ps/nm-km) but ultimately require compensation of dispersion slope. New dispersion-managed soliton transmission methods combine non-linear dispersion management with conventional dispersion management techniques to provide a stable solution to the problem of dispersion.

Dispersion management has been approached by three routes: dispersion-compensating fibre (lengths of negative dispersion fibre are used to minimise the net link dispersion); mid-span spectral inversion (relying on phase conjugation); chirped fibre Bragg gratings (different wavelengths are reflected from different
depths into the structure to temporally refocus the pulse). Of these, the chirped FBG approach is attractive because of its low loss, low non-linear effects, and tailorable dispersion. Chirped FBGs can either be long, broad band devices (to cater for source wavelength drift, or multiple WDM channels), or short single channel devices. Long gratings must be useable over the whole bandwidth, whilst short gratings must have a high bandwidth utilisation factor; group delay linearity is key for both devices. New developments in grating fabrication technology have led to significant steps towards realising long, broadband devices. Recently developed design techniques have offered a problem to the compatibility of single-channel devices with 50 GHz grid spacing.
LONG CHIRPED FBGS FOR
DISPERSSION COMPENSATION

The development of the fabrication technology described in chapter 4 was done with the aim of fabricating 1 m long chirped FBGs for dispersion compensation in WDM transmission systems. At the time (1997) WDM was in its infancy: channels were few and far between. The work presented in this chapter discusses the need for metre-long chirped FBGs, and the issues involved in designing such structures. The first reported results of continuously-written metre-long gratings are presented, before a technique capable of equalising the effects of cladding-mode losses in broadband chirped gratings is discussed; the results from this approach were the first example of deliberate spectral shaping in broadband chirped FBGs, made with no adverse effect on the group delay characteristics. The need for combined 2nd and 3rd-order dispersion compensation is then discussed before the design and realisation of such devices is presented. These gratings, designed for compatibility with dispersion-shifted fibres, were the first reported results of dispersion compensators capable of exactly matching the dispersion of a fibre link. Subsequent transfer of this technology to Pirelli Cavi, Milan, has led to successful systems trials of metre-long chirped FBG dispersion compensators.
8.1 **THE NEED FOR LONG FIBRE BRAgg GRATINGS**

### 8.1.1 Transmission System Requirement for Broadband Dispersion Compensation

The driving force for this work was to develop dispersion compensating gratings for use in a four-channel transmission system developed as a collaboration between Pirelli and MCI. The aim was to transmit 10 Gb/s NRZ data over a 220 km link of NDSF: in order to achieve this chirped FBGs were required to provide compensation for the fibre dispersion at the points of amplification. A channel spacing of 8 nm (1 THz) was employed (much larger than the 100 GHz grid of contemporary WDM systems). The optical bandwidth of 10 Gb/s NRZ pulses is ~ 10 GHz, so such an arrangement does not represent the ultimate in bandwidth efficiency. The rationale for such a configuration was based on the two fundamental issues discussed below.

#### 8.1.1.1 Transmitter Wavelength Drift

The source lasers used had a large degree of wavelength uncertainty and were subject to drift. Fundamentally this drift defined the channel spacing and also the requisite operational bandwidth of the dispersion-compensating FBGs. Catering for several nanometres wavelength drift presented a requirement for chirped FBGs with a bandwidth of 5 nm, capable of compensating for ~ 100 km of NDSF. These values define a grating length of ~1 m (from equation 7.9), explaining the development of the fabrication technology towards this goal. The dispersion of each channel in the transmission system was compensated for by a separate chirped FBG.

#### 8.1.1.2 Thermal Drift of Grating Wavelength

The temperature dependence of an optical fibre’s effective refractive index leads to a corresponding thermal drift of the grating Bragg wavelength. The typical operating temperature range for optical telecommunications components is -30 °C to +80 °C. A standard (fibre dependent) value of Bragg wavelength drift is ~5x10^-6 nm/°C, meaning that the grating bandwidth may move by ~ ±0.5 nm from its room-temperature value. It is possible to athermally package short FBGs by bonding the fibre, under tension, to a material (or combination of materials) with an suitable negative temperature expansion coefficient. The application of such a technique, however, is limited to relatively short (10-15 cm) gratings. An extrapolation of this technology to metre lengths would be difficult and highly-
cumbersome at best. It is generally acknowledged that gratings longer than 10-15 cm must have an excess of operational bandwidth to allow operation over a desired temperature range, unless active control of the device/ambient temperature is permissible. A worst-case scenario from this perspective is a grating of length \( \sim 20 \) cm with an operational bandwidth \( \sim 1 \)nm. Such a device would be just too long to package athermally and would have a vanishingly small fraction of its bandwidth useable over a large temperature range. The need for broad operational bandwidths was thus not only required to account for transmitter wavelength drift, but also to allow operation over a useful temperature range.

### 8.1.2 When a Chirped FBG Becomes Long

From a fabrication perspective a long grating is typically taken to be longer than a commercially available phase mask (\( \sim 10 – 15 \) cm); coincidentally this is similar to the length of grating that may be athermally packaged. An often overlooked point, however, is the nebulous physical distinction between short and long gratings.

#### 8.1.2.1 Bandwidth of Chirped FBGs

The bandwidth of an unapodised, linearly-chirped FBG of length \( l \), in a fibre of effective refractive index \( n_{\text{eff}} \), with a design dispersion, \( D_{\text{FBG}} \), is typically expressed as:

\[
\Delta \lambda = \frac{2n_{\text{eff}} l}{c} \frac{1}{D_{\text{FBG}}} \quad (8.1)
\]

This suggests that, for a certain dispersion the reflection bandwidth, \( \Delta \lambda \), will tend towards zero as the grating length is decreased. It is also well known, however, that the bandwidth of an unchirped grating is fundamentally determined by its length (see chapter 2). The bandwidth of an unchirped FBG (defined as the separation of the first nulls in the spectral response either side of the main Bragg peak) is given by the expression [Erdogan, 1997]:

\[
\Delta \lambda = \frac{\lambda n_{\text{eff}}}{n_{\text{eff}}} \left( 1 + \left( \frac{\lambda}{\Delta n_{\text{eff}} l} \right)^2 \right)^{1/2} \quad (8.2)
\]

The definition of bandwidth for a chirped FBG given by equation (8.1) holds true for the limit of \( l \) tending to infinity whilst (8.2) is correct in the limit of small \( l \).
8.1.2.2 Minimum Bandwidth for Chirped FBGs

It was found from numerical modelling that the actual spectral bandwidth of a chirped FBG is well approximated by the sum of equations (8.1) and (8.2). It is important to emphasise that when considering a grating of a certain reflectivity, \( R \), the refractive index modulation depth term in equation (8.2) is not constant with length, but varies as:

\[
\Delta n_{\text{eff}} = \frac{\lambda \tanh^{-1}\left(\frac{R^{1/2}}{\pi l}\right)}{\pi l} \tag{8.3}
\]

The length-dependence of spectral bandwidth for chirped gratings designed with three different chirp rates is shown in figure 8.1 for gratings with 90% reflectivity; the chirp rate is defined as:

\[
\frac{\Delta \Lambda}{l} = \frac{1}{c D_{\text{FBG}}} \tag{8.4}
\]

where \( \Delta \Lambda \) is the change in grating pitch along a length \( l \), and \( D_{\text{FBG}} \) is the desired dispersion.

The asymptotic behaviour towards the bandwidths described by equations (8.1) (feint lines) and (8.2) (solid line) naturally defines a minimum spectral bandwidth that a grating with a certain chirp rate may have. The evolution of spectral
response with grating length for a reflectivity of 90% and $D_{FBG} = 1700 \text{ ps/nm}$ is shown in figure 8.2. A physical definition of when a chirped FBG becomes long, is thus given by the condition:

$$\frac{2l}{cD_{FBG}} \gg \frac{\lambda}{\Delta n_{eff}} \left(1 + \left(\frac{\lambda}{\Delta n_{eff} l}\right)^2\right)^{1/2}$$

(8.5)

that is, where the spectral bandwidth of a chirped grating is well approximated by the simple relation of equation (8.1). From this consideration, for chirp characteristics of interest in dispersion compensation, the point at which a chirped grating become long is with lengths in the order of tens of centimetres: again, significantly more than is achievable by scanning commercially available phase masks.

8.2 DESIGN OF LONG CHIRPED FBGS

The performance goals for designing long, broadband, chirped FBGs are simply to achieve:

- a large bandwidth-utilisation factor
- a uniform in-band reflectivity
- a good group delay linearity
- a low insertion loss

The first three targets on this list are largely determined by a combination of the apodisation profile used and the quality of the fabrication system; these issues are discussed in the following section. The desire to achieve low insertion loss simply means increasing reflectivity; typically a reflectivity of 90-95% is used (insertion loss < 1 dB) to avoid fabrication issues with very large refractive index modulation depths.

8.2.1 Historical Development of Apodisation Profiles

The in-band characteristics of chirped FBGs can be linearised to a great extent by employing apodisation of the refractive index modulation. Much has been written on the design of apodisation profiles for chirped FBGs [Ennser et al., 1998b] [Pastor et al., 1996], but the emphasis has been firmly placed on short gratings, with
Long Chirped Fibre Bragg Gratings for Dispersion Compensation

lengths ~ 10 cm. The apodisation profiles described have largely been plucked from electrical filter design techniques [Madsen and Zhao, 1999: chapter 3] and for the most part, are modified versions of profiles used for unchirped gratings (see chapter 2). The state of fabrication technology at the time when most of these studies were made only permitted simple, smoothly varying refractive index modulation envelopes to be realised: the apodisation profiles studied reflect this.

The effect of apodisation is two-fold. On the one hand it is extremely effective at improving in-band spectral characteristics whilst minimising out-of-band

![Figure 8.2: Calculated reflectivity of FBGs with the same chirp rate, but different lengths; (top left) 5mm, (top centre) 10mm, (top right) 15mm; (middle left) 25mm, (middle centre) 35mm, (middle right) 45mm; (bottom left) 50mm, (bottom centre) 100mm, (bottom right) 1m. Note that the bandwidth is not a minimum for the shortest grating](image)
noise; on the other hand, however, apodisation carries with it the weight of reducing the useful bandwidth of a chirped grating. Recent developments in grating fabrication technology (see chapter 4) and progress in grating design theory [Feced et al., 1999a,b] have led to the realisation of chirped FBGs with long lengths and/or complex apodisation profiles, however. The issue of idealised apodisation profiles for short gratings is presented in chapter 10, whilst the following section presents the findings of investigations into design issues relevant to long, broad-band chirped FBGs.

8.2.2 The Effect of Apodisation on Bandwidth Utilisation for Long Chirped FBGs

Section 8.1.2 illustrates that the length of a chirped grating has significant implications on its spectral characteristics: for gratings of a given chirp rate it is clear that short, narrow-band gratings are closely related to unchirped gratings. It is not surprising, then, that the apodisation techniques described for short chirped gratings are very similar to those used with unchirped gratings. Long chirped FBGs intrinsically have a much squarer reflectivity profile (see figure 8.2), and so it is reasonable to expect the required apodisation profiles to be somewhat different. The aim of this section was to investigate apodisation designs suitable for linearise the spectral response with minimal bandwidth reduction.

8.2.2.1 Apodisation Effects on 1 m Long Chirped FBGs

The effect of different amounts of apodisation on 1 m long chirped FBGs with various chirp parameter values was modelled numerically to establish optimum designs for dispersion compensation of NDSF. The apodisation envelope considered was a raised-cosine profile, described by:

\[
\alpha = \frac{1}{2} \{1 + \cos(\pi \phi)\} \quad \left\{ \begin{array}{l}
-\frac{l}{2} \leq z < \left( l_a - \frac{l}{2} \right) \\
\left( \frac{l}{2} - l_a \right) < z < \frac{l}{2} \\
\left( l_a - \frac{l}{2} \right) < z < \left( \frac{l}{2} - l_a \right)
\end{array} \right. \\
\alpha = 1 \\
\text{where} \quad \phi = \frac{\left| z - \left[ \frac{l}{2} - l_a \right] \right|}{l_a}
\]

(8.6)

where \( l_a \) is the extent of the apodisation, and \( l \) is the grating length. Five different chirp parameter values were considered, representing the dispersion of 25, 50, 100, 200, and 400 km of NDSF with a 2\textsuperscript{nd}-order dispersion of 17 ps/nm-km. The goal of the apodisation design was to maximise the bandwidth utilisation factor,
which is defined as the ratio of bandwidths with a reflectivity of –1 dB and –30 dB. The results of the modelling are shown in figure 8.3. The effect of apodisation length on the spectral response of a 1 m long chirped FBG with a dispersion of 1700 ps/nm is shown in figure 8.4. Note that for just 1 cm apodisation length the out-of-band reflectivity level quickly falls to far below –30 dB.

8.2.2.2 Design Rule for 1 m Long Chirped FBGs

Two main features can be drawn from this investigation:

- higher bandwidth utilisation can be obtained for low-dispersion gratings
- less apodisation is required for low dispersion gratings in order to achieve the optimum bandwidth utilisation

From these curves a design rule is presented for maximising the bandwidth utilisation for 1 m long chirped FBGs:

\[ l_{a_{opt}} = 3.7 \times 10^{-4} \cdot D_{FBG} \text{ cm/(ps/nm)} \]  

(8.7)

where \( l_{a_{opt}} \) is the optimal length of apodisation for a raised-cosine profile, and \( D_{FBG} \) is the design dispersion of the grating.

8.2.2.3 The Effect of Grating Dispersion

It is again apparent that chirped FBGs with lower dispersion figures are closer to the ideal square reflectivity response. This is consistent with the findings of section 8.1.2, since for a given grating length, diminishing dispersion means greater
Long Chirped Fibre Bragg Gratings for Dispersion Compensation

distinction from the unchirped grating regime. Note that whilst low dispersion gratings can give a higher bandwidth utilisation factor, the excess bandwidth (from -1 dB to -30 dB) is actually greater than the figures seen for gratings with lower dispersion (see figure 8.6). The excess bandwidth of low dispersion gratings means that it is not possible to cover all channels in a WDM system due to the dead-space between gratings designed to cover adjacent spectral regions.
The Effect of Apodisation on the Group Delay Characteristic of Long Chirped FBGs

So far the effect of apodisation on long gratings has focused on the reflectivity bandwidth utilisation factor. Of equal importance for chirped dispersion compensating FBGs is the linearity of the group delay response. Gratings of metre length are far from the uniform grating regime for most chirp rates of interest for dispersion compensation. This is useful, since it means that the dispersion characteristics are largely linear (when apodised) and are not dominated by the non-linearities observed with short gratings (see chapter 10). It is important to minimise the intrinsic ripple of the group delay by the correct use of apodisation for dispersion compensation applications. A typical design goal is to achieve < 1 ps ripple (although whether this can be achieved in practice is questionable).

The effect of apodisation on the group delay characteristic of a 1 m long, chirped FBG designed with 1700 ps/nm dispersion is shown in figure 8.5. Even for very small values of apodisation the deviation from linear group delay quickly becomes less than 1 ps over the majority of the grating bandwidth (the deviation from linear group delay for the corresponding unapodised grating is ± 60 ps). For the apodisation giving optimum reflectivity bandwidth utilisation (2 – 3 cm) the group delay is essentially linear. Note also that useable bandwidth defined by the group delay linearity is similar to the optimum reflectivity bandwidth. The most efficient design for apodisation of 1 m long chirped FBGs is thus given by the maximum bandwidth utilisation criterion described in the previous section. This condition is quite different from any presented in the literature for short chirped gratings [Pastor et al., 1996] [Ennser et al., 1998].
8.3 Fabrication of Long Chirped Gratings

The continuous grating fabrication technique presented in chapter 4 was designed to make long gratings. The developments of technology and understanding discussed in section II were made over the course of three years, with the aim of fabricating high-quality FBGs with lengths up to 1 m. In the previous section the design issues of long chirped gratings were developed and presented. The reality of realising devices that approach the theoretical limits, however, is quite stark and requires much effort. To make an analogy, this is essentially the same as trying to make a 2 km long ruler, marked in millimetre intervals, with micron-scale accuracy: not trivial.

8.3.1 First 1m Long Continuously-Chirped FBGs

The following section draws together design principles and fabrication technology to present the first realisation of metre-long, continuously-written chirped fibre Bragg gratings. It should be noted that the fabrication technology at this stage was still under heavy development and these results do not represent the current state of the fabrication system. The first results of such devices were presented in February 1997 [Cole et al., 1997] [Dong et al., 1997a].

8.3.1.1 Previous Long Gratings

Prior to the realisation of gratings written in a continuous manner there had been several results presented of long chirped gratings essentially made by a concate-
nation of unchirped grating sections [Kashyap et al., 1996a]. Claims that high-quality chirped gratings can be made with just two uniform sections per millimetre, however, are made by either the misled or the misleading. Numerical modelling of apodised chirped gratings shows that an absolute minimum of 10 steps/mm are required for convergence of the group delay to the characteristics achievable with a truly continuous device for chirp rates of interest. Note that this is a best-case scenario which rapidly deteriorates in the presence of inter-section phase discontinuities.

8.3.1.2 Fabrication Details

The first 1m-long chirped FBGs were made in a step index germanosilicate fibre with an N.A. of 0.2. The fibre had been kept in an atmosphere of deuterium with a pressures of 45 bar for approximately two weeks in order to increase its photosensitivity. The CW frequency-doubled Ar-ion laser had an output power of 100 mW, and a power incident on the fibre of ~ 70mW. The level of wavelength detuning required to realise gratings with 5 nm and 10 nm bandwidths the beam was achieved by focusing the beam in the direction of the fibre axis, as discussed in section 4.2. The fibre was scanned at a rate of 1 mm/s during fabrication. The gratings were apodised over a length of 3 cm at either end.

8.3.1.3 Experimental Results

The first two good examples of metre-long chirped FBGs are shown in figure 8.7. In accordance with the transmission system requirements one of the gratings is designed to compensate for 100 km of NDSF with a dispersion of 17 ps/nm-km and thus has an operation bandwidth of ~ 5 nm. Gratings were additionally fabricated for 50 km dispersion compensation, but with twice the bandwidth; an alternative arrangement to using a single grating with the desired dispersion in conjunction with a three-port circulator is to use two, broader bandwidth gratings and a four-port circulator [Cole et al., 1996].

The spectral characteristics should be compared to those of obtained by numerical modelling, shown in figure 8.4. The shape of the grating reflectivity is very close to the theoretical case: there is some fluctuation of in-band reflectivity, but not a large amount. Out-of-band noise is well suppressed and these gratings are of much higher quality than any devices of comparable length reported previously [Kashyap et al., 1996b]. The group delay is predominantly linear, although there is a significant amount of noise present, for reasons discussed in chapter 6.
8.3.1.4 Short Wavelength Loss

It should be noted that the measurement of these gratings was made from the short wavelength end of the grating; this can be seen from the positive slope to the group delay characteristic. For compensation of standard transmission fibre with anomalous dispersion, however, it is necessary to use the grating to provide nega-
tive dispersion (light is launched into the long wavelength end). The reflection characteristics of an 8 nm 75 cm-long, chirped FBG are shown in figure 8.8. When the grating is measured in the negative dispersion sense there is a strong loss extending from the short wavelength edge of the operational bandwidth. The non-uniformity of in-band reflectivity is unacceptable for operation in a transmission system (operation in the region of loss will result in a degradation of the signal-to-noise ratio at the receiver). The subsequent aim was to realise broadband chirped FBGs with uniform in-band reflectivity suitable for use in the WDM transmission system. The following section describes the source of this loss, and the technological developments made to minimise its impact.

figure 8.8: the effects of coupling to cladding-guided modes are evident as the slope on the short-wavelength edge of this 8 nm 75 cm grating viewed in a negative dispersion sense
8.3.2 Spectral Equalisation of Cladding-Mode Losses

The structural period used to phase match between counter-propagating core-guided modes at the fundamental Bragg wavelength $\lambda_B$ also gives rise to phase matching between a core-guided mode and a cladding-guided mode at a set of discrete wavelengths shorter than $\lambda_B$. Propagation in cladding-guided modes is prone to high loss, and hence the spectrum of a uniform FBG, whilst dominated by the fundamental Bragg reflection, also comprises a set of short wavelength transmission losses. The variation of structural period along the length of a chirped grating not only leads to a spread of Bragg reflected wavelengths, but also to a corresponding spectral distribution of the phase matching conditions responsible for coupling from core- to cladding-guided modes.

8.3.2.1 Short Wavelength Cladding-Mode Loss in Broadband Chirped FBGs

When chirped gratings are used in the negative dispersion sense (required for compensation of positive fibre dispersion) light is launched into the long wavelength end of the structure. The quasi-integration of coupling conditions along the length of the grating leads to phase matching of the shorter wavelengths into cladding modes before they reach the part of the structure primarily responsible for Bragg reflection. As a result, chirped gratings with a bandwidth greater than the separation of the longest wavelength cladding-mode from the fundamental Bragg wavelength (determined by the fibre geometry) have a slope on the short wavelength side of the reflection spectrum. This slope extends to the position of the longest wavelength cladding mode associated with the longest structural period of the grating structure.

8.3.2.2 Spectral Equalisation of Cladding-Mode Loss

The strength of coupling to cladding modes is directly related to the fundamental Bragg coupling strength by the fibre geometry: reducing the reflectivity of the FBG leads to a corresponding decrease in cladding mode loss. If spectral uniformity is more important than insertion loss then it is possible to compensate for the effects of cladding mode losses by decreasing the (local) coupling constant of the grating at the longer wavelengths using apodisation. The flexibility of the fabrication technique discussed in chapter 4 allows exact computer control of the grating envelope with position, without changing the background refractive index (as would be the case if the UV power was varied to control the induced refractive index modulation depth). This is a prerequisite for shaping the spectrum of dispersion compensating gratings, since a change in background refractive index along the length of a chirped grating would adversely affect the group delay characteristics.
8.3.2.3 Design of Gratings to Compensate for Cladding-Mode Losses

The reflectivity of an apodisation-shaped FBG designed to counteract the lossy effects of cladding-modes may be expected to be some sort of inverse of a grating fabricated with a uniform coupling constant. It is possible to numerically calculate the characteristics of cladding-guided modes [Erdogan, 1997] necessary to generate a suitable apodisation profile for a given fibre, but practically, it is somewhat easier to obtain the results experimentally. The gratings fabricated in this set of experiments used an additional apodisation profile with a refractive index envelope described by:

\[
\alpha = \begin{cases} 
(1 - \gamma)(z - z_o)^2/z_o^2 + \gamma & z \leq z_o \\
\gamma & z > z_o 
\end{cases}
\]  

(8.8)

where \(z\) is the normalised distance along the grating from the short wavelength end, \(z_0\) is the location in the grating where the effect of cladding-mode loss first
becomes apparent \((z_0 = 0.6\) in this case), and \(\gamma\) is the relative strength of the grating in the region \(z > z_0\) (0.7 in this example). The values of \(z_0\) and \(\gamma\) are fibre dependent, but in general \(\gamma\) will be larger and \(z_0\) will be smaller for higher NA fibres where the coupling to lower order cladding-modes is both suppressed and shifted further from the Bragg wavelength [Dong et al., 1997b]. Indeed the specific shape of the apodisation function is also fibre dependent and the above function is the one found to be most successful for the test fibre.

8.3.2.4 Experimental Results

An example of using this custom apodisation profile to flatten the spectral response of a broadband 7.5 nm chirped FBG is shown in figure 8.9. Comparing this data to that of figure 8.8 shows that the apodisation profile is very successful in equalising the spectral response of the grating when used in a negative dispersion sense: it is clear that there is no perceivable slope on the short wavelength end of the grating when viewed from the long wavelength end (the shape of the reflection spectrum viewed from the short wavelength end illustrates the effect of the apodisation profile without the contribution of cladding-mode loss).

The fibre used in this experiment exhibited undesirably strong coupling to cladding-modes (see figure 8.8 top) and so the strength of the equalised grating (figure 8.8 middle) is less than would be ideal. However the complete removal of the \(~ 2.5\) dB short wavelength loss seen in the grating of figure 8.9 serves to emphasise both the power and the practicality of this technique. The time delay/wavelength characteristic of this FBG (shown in figure 8.9 bottom) illustrates that the use of a reflectivity-tailoring apodisation profile has no adverse effects of the dispersion (which was designed to be uniform in this case). Exercising control over the local coupling-constant using apodisation requires no changes to existing fibre design or experimental procedure, and adds an extra free parameter in the design of high-quality in-fibre Bragg devices used for dispersion compensation. These results were the first demonstration of deliberate spectral shaping across the bandwidth of a broad-band dispersion compensating chirped FBG using apodisation [Durkin et al., 1997b].

8.3.2.5 High NA Fibres for Suppression of Cladding-Mode Coupling

The fibres used during the fabrication of these gratings exhibited a separation of \(~ 3.5\) nm between the Bragg reflection in to the core-guided mode and the first cladding mode. It is possible both to suppress the strength of coupling to cladding modes and to increase this separation by using fibres with high numerical aper-
tures, depressed-cladding designs [Dong et al., 1997b], and photosensitive cladding [Dong et al., 1999]. The successful application of chirped FBGs to dispersion compensation applications is, however, highly reliant on fibres with good diameter control and low birefringence. It has been found that high N.A. fibres tend to exhibit increased birefringence (which is magnified into polarisation mode dispersion-PMD- by the dispersion of the grating). Additionally the effects of fibre diameter fluctuations are more severe in high N.A. fibres [Ibsen and Laming, 1999].

It seems probable, then, that whilst the fibre used in these experiments was not ideal for negative-dispersion broadband chirped FBGs, that it may not be ideal to simply use very high N.A. fibres for dispersion compensation applications. A realistic compromise between fibre design and the spectral equalisation technique are likely to give the best results.

8.3.3 Non-Linearily Chirped FBGs for Combined 2nd and 3rd-Order Dispersion Compensation
The potential exists with chirped FBGs for exact dispersion compensation of a fibre link by a suitable design of the grating structure. Transmission limited by the effects of 3rd order dispersion has been presented [Røysset and Laming, 1996]. An obvious extension of compensating the 2nd order component of fibre dispersion is to also take into account the wavelength dependence of this phenomena and thus also compensate the 3rd order dispersion as well. The following section describes the first results of gratings designed for combined 2nd and 3rd-order dispersion compensation [Durkin et al., 1997a], [Ibsen et al., 1997a].

8.3.3.1 Requirements for 3rd-order Dispersion Compensation
Compensation for the 3rd-order component of dispersion is of secondary concern when the transmission fibre has a high 2nd-order dispersion (such as 16-17 ps/nm-km for non-dispersion shifted fibres). For broad bandwidth operation and high bit-rate transmission, however, the wavelength dependence of the fibre dispersion can limit the maximum distance for penalty-free operation. Whilst the 3rd-order dispersion is typically small for NDSF, the typical values for the new non-

---

6 previous demonstrations had been made of gratings with a very small 2nd-order dispersion [Williams et al., 1996a,b], but none that provided 2nd and 3rd-order dispersion designed to match transmission fibres
zero dispersion shifted fibres are $\sim 0.08-0.09$ ps/nm$^2$·km (i.e. the 2\textsuperscript{nd}-order dispersion of $\sim 2$ ps/nm·km changes by 0.08-0.09 ps/nm·km every nanometre). The calculated limit to transmission length resulting from 3\textsuperscript{rd}-order dispersion alone is shown in figure 8.10 (effectively this shows the limit to wavelength detuning for a 2\textsuperscript{nd}-order dispersion compensated system before large penalties are observed). It can be seen that the limitations caused by 3\textsuperscript{rd}-order dispersion are not severe for 10 Gb/s transmission, except for large operational bandwidths and/or long-haul transmission. For 20 Gb/s transmission, the effects of 3\textsuperscript{rd}-order dispersion will play a limiting effect in practical transmission systems; for 40 Gb/s, the effects are severely limiting.

### 8.3.3.2 Non-Linearly Chirped Fibre Bragg Gratings

The temporal spreading of a pulse with spectral bandwidth $\Delta \lambda$ propagating through a dispersive fibre link of length $d$ is given by:

$$
\Delta \tau = D_2 \Delta \lambda d + \frac{D_3}{2} (\Delta \lambda)^2 d
$$

where $D_2$ is the 2\textsuperscript{nd} order dispersion, and $D_3$ is the 3\textsuperscript{rd} order dispersion. The total time delay generated by a chirped fibre grating of length $l$ is given by:

$$
\tau_g = \frac{2n_{\text{eff}} l}{c}
$$

where $n_{\text{eff}}$ is the effective index of the host fibre and $c$ is the vacuum speed of light. For a grating designed to compensate the fibre dispersion described by equation
(8.9) a Bragg phase matching wavelength $\lambda_B$ should be located at a position $z(\lambda_B)$ along the grating such that:

$$z(\lambda_B) = \frac{cd}{2n_{\text{eff}} l} \left[ D_2 \Delta\lambda' + \frac{D_3}{2} (\Delta\lambda')^2 \right]$$

(8.11)

where $\Delta\lambda' = \lambda_B - \lambda_0$ and $0 < z(\lambda_B) < 1$. By identifying two parameters, $\alpha$ and $\beta$, such that:

$$\alpha = \frac{cdD_3}{4n_{\text{eff}} l} \quad \beta = \frac{cdD_2}{2n_{\text{eff}} l} = \frac{1}{\Delta\lambda_{2nd}}$$

(8.12)

(where $\Delta\lambda_{2nd}$ is the bandwidth of a linearly chirped grating), then equation (8.10) can be rearranged to give the local Bragg phase matching wavelength $\lambda_B(z)$:

$$\lambda_B(z) = \frac{1}{2\alpha} \sqrt{\beta^2 + 4\alpha z - \beta} + \lambda_0$$

(8.13)

$$\lambda_B(z) = \frac{2n_{\text{eff}} l}{cdD_3} \left[ \left( \frac{cdD_3}{2n_{\text{eff}} l} \right)^2 + \frac{cdD_3 z}{n_{\text{eff}} l} - \frac{cdD_2}{2n_{\text{eff}} l} \right] + \lambda_0$$

(8.14)

where $D_2$ is the 2nd order dispersion at the short wavelength end. Note that a grating designed to compensate both 2nd and 3rd order dispersion has a bandwidth given by:

$$\Delta\lambda_g = \frac{2n_{\text{eff}} l}{cdD_3} \left[ \frac{1}{\left( \Delta\lambda_{2nd} \right)^2} + \frac{cdD_3}{n_{\text{eff}} l} - \frac{1}{\Delta\lambda_{2nd}} \right]$$

(8.15)

which is narrower than a grating of the same length with a 2nd order dispersion alone. The deviation from a linear time delay characteristic, $\Delta\tau$, at either edge of a bandwidth $\Delta\lambda$ is given by:

$$\Delta\tau = \left[ \frac{\Delta\lambda}{2} \right]^2 \frac{d}{2} D_3$$

(8.16)

### 8.3.3.3 Experimental Results

A series of gratings were written with the continuous grating fabrication technique with designs suitable for combined dispersion compensation of 2nd and 3rd-order dispersion. The gratings were designed to match the characteristics of a non-zero dispersion shifted fibre (NZDSF), such as Lucent’s TrueWave™. The dispersion characteristics were: $D_2 = 1.67$ ps/nm-km; $D_3 = 0.09$ ps/nm²-km. The gratings
were designed to have operational bandwidths of 5 nm and 10 nm, and 1 m length; the compensation lengths were 1060 km and 580 km respectively\footnote{the gratings were designed with bandwidth and length in mind, rather than any significant compensation length}. The results of two such gratings are shown in figure 8.11. The deviation from a linear group delay is close to quadratic, as predicted by (8.16). The wavelength detuning for these gratings was realised by using a chirped phase mask, as discussed in section 4.2.2.1. Imperfections in the grating profile can be largely attributed to poor phase mask quality (see section 6.3.1). A natural consequence of a non-uniform structural chirp is that the grating reflectivity is reduced somewhat when the chirp rate is high. This could be overcome by using the application of apodisation to spectral shaping described in the previous section.

As well as allowing high bit rates to be used over several channels in NDSF links, the addition of 3rd order dispersion compensation can also be used to ensure that dispersion shifted fibres maintain a constant, low, 2nd order dispersion across an operational bandwidth. Compensation of the 3rd order dispersion component of low-dispersion fibre may be of future importance in multi-channel non-linear transmission systems where it is ideal to have the same 2nd order dispersion in each channel; the 2nd order dispersion can then be balanced by non-linear effects (see following chapter).

8.3.4 System Trials
The amalgamation of grating design and fabrication techniques led to the first demonstration of metre-long chirped FBGs suitable for the systems application described in section 8.1. Many such gratings were subsequently fabricated in conjunction with engineers from Pirelli for evaluation in the transmission system with MCI. Additionally, the technology for fabricating combined 2nd and 3rd-order dispersion-compensating gratings was transferred to Pirelli Cavi, Milan, by the author. Subsequent successful system trials conducted by AT&T and Pirelli have shown that the metre-long grating technology developed is maturing well [Garret et al., 1998] [Robinson et al., 1998]. A recent demonstration of 16-channel transmission at 20 Gb/s using gratings for 2nd and 3rd order compensation shows significantly improved performance at the bandwidth edges compared to a DCF module with simple 2nd order dispersion compensation [Gnauck et al., 1999].
8.4 SUMMARY

The need for metre-long chirped FBGs in transmission systems, has evolved from a historical requirement to cater for transmitter wavelength drift, to the modern possibility of multi-channel operation. The design issues for long chirped gratings were discussed, before the first experimental examples of continuously-chirped metre-long chirped FBGs were presented. Significantly, these devices were free of
the large glitches seen in devices of similar length fabricated by more cured means. After the realisation that cladding mode losses are problematic for long, broadband chirped FBGs, results were presented of a technique capable of equalising the spectral response of chirped gratings using apodisation. The results presented were the first reported gratings capable of 80 km dispersion compensation, with 7 nm bandwidth and a flat in-band reflectivity. Additionally, this was the first example of spectral shaping on dispersion-compensating gratings, and was demonstrated to have no adverse effect on the group delay linearity.

The realisation of future transmission system limitation by 3rd-order dispersion was considered, and gratings were designed to compensate both 2nd and 3rd-order dispersion were designed. The devices realised were the first dispersion compensators reported capable of exactly matching the dispersion of a fibre link. To the author’s knowledge, no other technique has been shown capable of such control. Transfer of the metre-long grating technology to Pirelli Cavi, Milan, resulted in a number of successful systems trials on long gratings. The most recent report confirms improved system operation when using gratings for combined 2nd and 3rd-order dispersion at 20 Gb/s.

Acknowledgement

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This chapter presents the concepts of dispersion-managed soliton transmission systems, followed by the results of the first published transmission experiment using chirped FBGs. In contrast to most material on dispersion-managed soliton transmission which uses re-circulating loop configurations, this system trial, done in conjunction with Pirelli Cavi, Milan, used a straight-line 1000 km fibre link with ten fibre spans, ten amplifiers, ten chirped gratings, and achieved error-free transmission. Such an approach represents a real transmission system much more closely. Follow-up experiments using this technology (conducted by Pirelli) served to show good operation in an installed fibre link. This technology presents is a potentially-attractive solution both for future systems and for upgrades of existing fibre links. The use of fibre Bragg grating dispersion compensators is expected to give improved performance in multi-channel transmission systems where the high-powers in the non-linear regime may be problematic with dispersion compensating fibre.

9.1 Dispersion Managed Solitons

The initial driving force for dispersion compensation was to overcome the simple pulse-chirping effects of propagation, in the linear regime, through NDSF using
non-return-to-zero (NRZ) transmission formats. Simultaneous work on non-linear soliton propagation (with a return-to-zero, RZ, transmission scheme) was providing interesting alternatives to the problems of fibre non-linearity and dispersion.

9.1.1 Problems with Soliton Transmission

There are, however, some fundamental traits of soliton propagation that have, to date, prevented its widespread adoption as a practical (i.e. commercial) transmission scheme. The non-linear effects associated with high-power pulses are used to balance the effects of fibre dispersion: the power of the pulse required is determined by the dispersion of the fibre link. This raises two problems: if the dispersion is too low then the soliton power disappears; if the dispersion is too high (e.g. as is the case for NDSF at 1.55 µm) then the pulse powers become undesirably large. More fundamentally, noise introduced by amplification leads to pulse timing jitter, known as Gordon-Haus jitter [Doran, 1998].

The requirement of maintaining high pulse powers means the inter-amplifier distance is typically no more than 50 km: too short for application in existing transmission links. Operating in the presence of fibre loss, solitons eventually succumb to the effects of fibre dispersion, leading to temporal broadening and frequency chirping of pulses [Grudinin et al., 1996]. The subsequent effect is an fractional increase of non-soliton power, which ultimately leads to pulse break up.

9.1.2 Partial Soliton/Dispersion Managed Soliton Transmission

Of great importance for soliton communication has been the realisation of dispersion-managed soliton [Kubota et al., 1992] transmission (or partial soliton transmission). The effect of dispersion-induced pulse chirp can be overcome by using periodic dispersion compensation. This has several important advantages. Firstly, periodically compensating for loss-induced chirp allows the pulses to propagate for longer distances, in the presence of loss, before pulse break-up occurs: this means longer inter-amplifier spans can be used [Georges and Favre, 1999]. Secondly, periodic dispersion compensation leads to a low average link dispersion, but maintains the necessary local dispersion to allow the propagation of soliton-like pulses for at least part of an inter-amplifier span. Whilst the first part of each span operates in the non-linear regime, the second part uses dispersion compensation to undo the pulse-broadening effects associated with linear transmission.
9.1.2.1 Reduced Timing Jitter

The low average dispersion significantly reduces the effect of pulse jitter [Doran, 1998]. Timing jitter (Gordon-Haus jitter) accumulates as:

\[
Dl^3 \quad \text{for systems without inline filtering} \\
Dl \quad \text{for systems with inline filtering}
\]

(9.1)

where \(D\) is the (net) dispersion of the transmission link and \(l\) is its length. Periodic dispersion management reduces the net dispersion of the link to almost zero which is reflected in correspondingly diminished timing jitter.

9.1.2.2 Pulse Shape

The soliton pulses in periodically dispersion managed systems have a Gaussian-type profile, compared to the normal hyperbolic secant profile of solitons in fibre links with continuous dispersion profiles [Smith et al., 1996]. As a consequence higher mark-space ratios may be employed before pulse-to-pulse interactions become critical.

9.2 1000 KM TRANSMISSION WITH CHIRPED FBGS FOR PARTIAL DISPERSION COMPENSATION

Prior experiments in partial soliton transmission had all used fibre-based dispersion management techniques. Following theoretical demonstration that the used of chirped FBGs could be employed in a dispersion-managed soliton system [Grudinin et al., 1996] an experiment was co-ordinated by Dr. Anatoly Grudinin with Pirelli Cavi, in Milan, to evaluate the practicality of such a system in a laboratory test. Not only was this the first experimental verification of that chirped FBGs could be used in such a system [Grudinin et al., 1997], but it remained the longest 10 Gb/s transmission over NDSF using grating-based dispersion compensation for approximately two years.

9.2.1 Description of the Test System

A 1000 km link comprising ten spans of ~ 100 km of NDSF with an EDFA/chirped FBG combination after each link was set up to assess the practicality and performance of dispersion managed soliton transmission systems using chirped gratings for partial dispersion compensation (see figure 9.1). An actively mode-locked fibre
ring laser generating 30 ps bandwidth-limited pulses at 1549.5 nm with an average power of 14 dBm was used as the source. Pseudo-random data was encoded onto the pulse train using a Ti:LiNbO$_3$ modulator. The average power level after each amplifier, but before the grating, was $\sim$ 14 dBm. A pre-chirp of 126 ps/nm was induced using 2.1 km of DCF with a dispersion of $-60$ ps/nm$\cdot$km.

9.2.1.1 Chirped FBG Dispersion Compensators

Gratings of length 75 cm and 4.5 nm bandwidth were used to provide a nominal dispersion compensation of 1600 ps/nm (roughly 95% compensation for a 100 km link of fibre with a second order dispersion of 17 ps/nm/km); the dispersion variation between gratings was less than $\pm$ 20 ps/nm. The grating reflectivity was $\sim$ 90% giving an insertion loss of $\sim$ 4 dB in combination with a three-port circulator. The reflectivity data of the ten gratings used are shown in figure 9.2; note that the out-of-band noise floor is due to back reflection from the fibre ends.

9.2.1.2 Dispersion Map

The dispersion map of a transmission system describes how dispersion varies along the length of the transmission link. In a dispersion managed system the positive dispersion of each fibre link is compensated, to a certain degree, by a dispersion compensating element. The fraction of the link dispersion that needs to be compensated for is determined by the input power of the pulses at the start of each link.

The gratings were not designed specifically to match the dispersion of each link because the fibres were not characterised until after the experiment; as a consequence the gratings gave between 88.8% and 101.7% compensation with an overall compensation of 93.3% (see figure 9.4). The path-average dispersion is
thus just 1.14 ps/nm-km for each link. The power required for self-phase modulation effects to balance such a small chromatic dispersion in a basic fibre link is very low: the result would be a pulse that is essentially too feint to detect at the receiver. By balancing self-phase modulation against average dispersion, however, it is possible to achieve soliton-based transmission system, where there is sufficient energy per pulse to allow error-free detection (increased SNR), but with minimised Gordon-Haus jitter [Georges and Favre, 1999].

9.2.2 Results of Transmission over 1000 km

The measured bit error rate (BER) is shown in figure 9.3 for a back-to-back connection, and transmission over 500 km and 1000 km. There was no observed floor in the BER curves to below $10^{-11}$ although a power penalty of $\sim 3$dB was observed for transmission over 1000 km; this was largely attributed to a less-than-perfect extinction ratio of the modulator (evident as dark regions in the eye-diagram of figure 9.3) and a reduction in the signal-to-noise figure resulting from a build up of amplifier noise. It was noted that propagation over distances of more than 500 km incurred significant power penalties for lower input powers. This is a combined result of non-ideal balancing of self-phase modulation with chromatic dispersion,
and an increase in the severity of undesirable non-linear effects as the system begins to operate in the linear regime.

9.2.2.1 Variation of Dispersion Compensation

The variation of the dispersion map reflects a real transmission link quite well. This approach to transmission is quite stable to these relatively minor variation in dispersion, even in the tenth span which begins with negative pulse chirp due to overcompensation of dispersion in the ninth link. All previous demonstrations of partial soliton communication have been based on alternating spans of transmission fibre and dispersion compensating fibre. This not an ideal approach since the higher powers used in this transmission format (compared to traditional linear NRZ propagation) can lead to significant non-linear effects during propagation through the DCF.

9.2.2.2 Effects of Grating PMD

The strongly dispersive nature of chirped FBGs has the unfortunate effect of converting inherent fibre birefringence to polarisation mode dispersion (PMD). The PMD of the gratings used in this experiment was measured to be $\sim 7 \pm 3$ ps, but, interestingly, temporal variation of the pulse arrival time for different input polarisation states remained approximately constant at $10 \pm 5$ ps for up to 500 km transmission lengths; the power penalty for different polarisation states was negligible. After 1000 km the PMD was $\sim 20 \pm 5$ ps, and the power penalty, although
still small, had increased to 1 dB. The fact that the PMD after 1000 km was less than the sum of the individual grating PMD’s (713 ps) could imply the following:

- the PMD of gratings adds randomly (in quadrature) rather than linearly: this suggests a total PMD given by \((7^2 \times 10)^{1/2}\) ps (~22 ps) which is close to the observed value after 1000 km
- the non-linear region after each grating tends to recombine the dispersed polarisation eigenmodes into a soliton pulse

Further work is needed to assess the likelihood of these suggestions; a more accurate measurement technique is required and a comparison should be made to a similar linear transmission.

9.2.3 Follow-Up Experiments

An important feature of this experiment was the confirmation that improved performance to NRZ transmission can be achieved using partial soliton communication with long spans of NDSF, with characteristics comparable to the majority of the world’s currently installed fibre: this could provide a very attractive upgrade route to 10 Gb/s from 2.5 Gb/s.

A follow-up experiment to this technique was reported in a post-deadline paper at OFC ’98 by MCI/Pirelli [Robinson et al., 1998] using grating technology transferred from the ORC. The paper reports four-channel dispersion-managed soliton transmission over 450 km of installed NDSF links. Additionally 900 km
transmission was demonstrated in a single-channel send-and-return configuration over the 450 km of fibre. This demonstration using installed fibre strengthens the attractiveness of such an approach for long-haul fibre transmission.

9.3 SUMMARY

The results presented in this chapter of the first transmission experiment with chirped FBGs used for partial dispersion management. Error-free transmission over ten 100 km spans of standard NDSF was achieved with a transmission rate of 10 Gb/s. Subsequent system trials on installed fibre links have shown that this is a potentially attractive approach for future transmission systems and is compatible with the existing installed fibre network.

Acknowledgement

Dr. Anatoly Grudinin and Pierre-Luigi Franco are thanked for involving the author in the system trial. The gratings used were fabricated and characterised in conjunction with Morten Ibsen.
Since the four-channel transmission system that drove development of the initial metre-long gratings, the WDM rainbow has exploded. Both expanding in bandwidth and using ever-finer channel spacing, WDM has an important new prefix: D. Dense Wavelength-Division Multiplexing (DWDM) transmission systems may use up to 128 channels with just 50 GHz channel separation. A challenging combination of broad operating bandwidths and extremely low-tolerances, DWDM throws down a gauntlet to the entire photonics community. This chapter presents the problems faced by existing grating technology to provide dispersion compensation on a 50 GHz grid, and then discusses the ideal device characteristics required for such an application. After a brief overview of a new reverse-engineering design technique, the design and realisation of gratings designed for dispersion compensation of NDSF links on a 50 GHz grid is presented. The gratings shown are the first experimental devices to result from this design technique. Additionally, these devices are the first reported gratings capable of providing a scalable solution for 50 GHz grid DWDM dispersion compensation; the high level of optical transparency meets requirements for future optical networks.
10.1 Requirements for DWDM Dispersion Compensation

The increasing application of DWDM transmission schemes with bit rates of 10 Gb/s and 50 GHz channel spacing places a strict requirement on dispersion management for NDSF links. An ideal dispersion compensator should either provide continuous operation over the full bandwidth of a transmission system, or be capable of being closely packed with other such devices in order that every available DWDM channel can be transmitted. These criteria have, to date, been difficult to fulfil with grating technology: a single dispersion compensating grating with a bandwidth of >30nm needs to be several metres in length raising questions of fabrication practicality and packaging concerns; traditional short (<10cm) chirped gratings, which may be packaged athermally and are more straightforward to fabricate, have a low bandwidth filling-factor, and a non-linear group delay response.

The work presented in this chapter describes the application of a new FBG design method (developed by Ricardo Feced [Feced et al, 1999a,b]) to dispersion compensating FBGs. Not only are the experimental results presented the first confirmation of the power of the new design technique, but they are also the first realisation of dispersion compensators designed specifically for operation at a 50 GHz channel grid (also the devices are compatible with athermal packaging methods).

10.1.1 Bandwidth Utilisation of Long Chirped FBGs

The bandwidth utilisation factor of chirped FBGs with different lengths was investigated for different degrees of apodisation; all were designed to compensate 80 km of NDSF. As before, the bandwidth utilisation factor is defined as the ratio between the –1 dB and –30 dB bandwidths of a device. The apodisation profile considered was a raised cosine type. The results of this numerical modelling are shown in Figure 10.1. Gratings of length 50 cm or more, are well away from the short, unchirped regime (see chapter 8). As such, their bandwidth utilisation factor is extremely high.

10.1.1.1 Temperature Drift

Unlike the application of long, broad bandwidth gratings to cater for wavelength drift, the key of bandwidth utilisation with DWDM is that all possible channels should be useable. It was mentioned previously that it has not proven realistic to
package long gratings in an athermal manner: over a 100 °C operational temperature range, such gratings may be expected to drift in wavelength by ~ 1 nm. The high apparent bandwidth utilisation of metre-long chirped FBGs is thus tempered somewhat when this temperature drift is taken into account. The effect of such a bandwidth reduction is shown in figure 10.2 for a 92 cm grating designed to compensate 80 km of NDSF with a dispersion of 17 ps/nm·km.

10.1.1.2 Channel Coverage

The important consideration, then, is not specifically the percentage filling-factor of the grating (which, even accounting for drift, is high) that is important for DWDM, but rather the percentage of channels that may be covered. Six out of a possible eight channels (75%) can be covered by such a chirped FBG over a large temperature range. With a 50 GHz channel separation, only eleven of sixteen may be covered under all conditions, which drops the bandwidth utilisation to ~69%. More significantly, though, if metre-long gratings are employed in this manner a 30% channel redundancy must be accepted in a 50 GHz DWDM system (it is unlikely that this would be tolerated with the current addiction for bandwidth). It seems, then, that pending the development of ~ 4 m long chirped gratings of suitable quality, the future application of metre-long chirped FBGs will be to provide broad-band dispersion management for NZDSF links (see chapter 8 and [Gnauck, et al., 1999]).

figure 10.1: calculated bandwidth utilisation of gratings designed to compensate for 80 km of NDSF with different degrees of apodisation
10.1.2 Bandwidth Utilisation of Short Chirped FBGs

A significant reduction in the useable bandwidth of devices based on short, chirped FBGs is incurred in an attempt to linearise the group delay (see figure 10.1). The group delay response of short gratings remains non-linear, even with the application of apodisation, since they are not well distinguished from unchirped gratings (see chapter 8). This intrinsic trait is not desirable for practical dispersion compensation. It has been noted that asymmetrically apodised CFBGs can give improved performance [Zervas and Taverner, 1998] but the characteristics of such a device still fall significantly short of realising an ideal top-hat reflectivity profile and linear group delay.

10.1.2.1 Single-Channel Characteristics

The calculated spectral characteristics of two apodised CFBGs are shown in figure 10.4. Designed by standard methods to provide dispersion compensation for 80 km of non-dispersion shifted fibre (NDSF) with –30 dB bandwidths of 50 GHz and 100 GHz respectively, the gratings have a partial raised-cosine apodisation profile and a reflectivity of 90%. It is found that the group delay linearity of the 50 GHz grating is far from ideal with a large variation in dispersion across the device bandwidth. It is also questionable whether a grating such as this would be capable of supporting 10 Gb/s RZ pulses since the useable (-1 dB) bandwidth is just 0.17 nm.
The grating designed with a 100 GHz –30 dB bandwidth has a higher filling factor and the group delay linearity is significantly better in the centre of the reflection bandwidth. If such a device was used for 50 GHz channels spacing, however, two channels would sit close to the edge of the reflection bandwidth: there would be a significant variation in grating reflectivity across the bandwidth of a pulse, especially with RZ modulation. The group delay is also clearly non-linear for the higher-wavelength channel that is reflected predominantly from the front part of the grating.

10.1.2.2 Temperature Drift

An important consideration for narrow-band DWDM devices is their wavelength stability. Whilst there have been many demonstrations of nearly-athermal packaging there still remains some thermal drift over a desirable operating temperature range (e.g. –30 to +80°C) and uncertainty in central wavelength of the device, either due to fabrication or packaging. Assuming a wavelength uncertainty of ±20 pm (±2.5 GHz) gratings designed for single channel operation on 100 GHz and 50 GHz grids are considered. The grating designed with a 50 GHz – 30 dB bandwidth has a –1 dB bandwidth of 0.18 nm: this is correspondingly reduced to 0.14 nm in the presence of wavelength uncertainty. The 100 GHz grating has a –1 dB bandwidth of 0.54 nm: 0.5 nm including drift.
A key factor for future optical networks is the concept of optical transparency: that is, it should be possible to add a DWDM channel at any network node and retrieve it at any other. One of the reasons that metre-long gratings may be unacceptable for use in DWDM transmission systems is the difficulty in covering all available 50 GHz channel slots. The alternative problem, apparent with single-channel devices, is the effect of multiple passes through similar devices with non-ideal bandwidth utilisation factors. The spectra of the gratings designed by traditional apodisation methods for 100 GHz and 50 GHz grids (shown in figure 10.4) were used to determine the effect of non-ideal bandwidth filling after their application for dispersion compensation in ten similar links. The results of this numerical study are shown in figure 10.3 (the feint lines represent the bandwidth-narrowing effect of wavelength uncertainty and temperature drift).

10.1.3 Transparency in Optical Networks

The 100 GHz grating may suitable for use with 50 GHz-separated channels if the operational bandwidth is more than ~0.5 nm (for 10 Gb/s data). It is apparent that after just three fibre spans (240 km in this case) the operational bandwidth is too small to support two 50 GHz-spaced channels. If wavelength uncertainty is considered, then such an arrangement is only suitable for a single 80 km fibre link.
10.1.3.2 50 GHz Apodised Gratings

Gratings designed with traditional apodisation methods for 50 GHz channel spacing have a very low (< 50%) bandwidth utilisation. However, their application to 50 GHz channel grids may be more appropriate than the gratings with a design bandwidth of 100 GHz. Transmission of five spans may be possible for 10 Gb/s NRZ data (but a measly two if wavelength drift is considered). The possibility of using such gratings for 20 Gb/s data, or RZ modulation formats is non existent, though.

10.1.3.3 Ideal Designs

These considerations question the fundamental applicability of short chirped FBGs as dispersion compensators. It is necessary that gratings (or any other device) for application in DWDM systems should have a bandwidth utilisation factor exceeding that achievable with conventional apodisation designs. The following section presents the first realisation of dispersion compensators for 50 Ghz channel spacing with a suitably square spectral response and good group delay linearity.

10.2 Design & Realisation of DWDM Dispersion Compensating Chirped FBGs

The issue of grating design, until recently has been approached using standard apodisation techniques (as described previously). An ultimate design tool, though, is one that allows reverse-engineering of a grating structure from a desired spectral response. Several attempts had been made towards this goal- most notably those based on inverse scattering using the Gel’fan-Levitan-Marchenko (GLM) integral equations [Peral et al., 1996] [Skarr et al, 1998]- but none had succeeded in achieving exact reconstruction of the grating structure. A recently proposed take on the inverse scattering problem, developed by Ricardo Feced, uses recursive algorithms and causality arguments to reconstruct the grating structure layer-by-layer, according to a desired impulse response function [Feced et al., 1999a,b]. Offering the first exact recreation of a grating refractive index structure, coupled with high computational efficiency, this method opens the flood gates for new grating designs, placing strict demands on the accuracy of grating fabrication techniques.
10.2.1 Characteristics of the Inverse-Scattering, Layer-Peeling Technique for the Exact Synthesis of FBG Structures

It is possible to generate the required grating structure for a given spectral response using Fourier transform relations for gratings of low reflectivity (50%, or less). For gratings of high reflectivity, however, the Fourier transform approach fails since the amplitude of the forward propagating mode decays quickly with depth into the structure; this means that the discrete representation of the grating is incorrectly weighted. The layer-peeling technique works by acknowledging the fact that the reflected electric field a time $\tau$ can be represented as the sum of all possible paths through the grating (including multiple scattering) up to a depth that can be reached in a time $\tau/2$. By starting at the input end of the grating, and progressing backwards in discrete sections, it is thus possible to determine the characteristics of the grating layer-by-layer that are required to generate the impulse response function of a filter characteristic.

10.2.2 Design of the DWDM Device

The aim of this work was to design and fabricate short, chirped FBGs suitable for dispersion compensation on a 50 GHz channel grid. From the previous arguments, this naturally means realising a nearly-square reflection band and a highly-linear group delay response.

10.2.2.1 Device Characteristics

Using the inverse-scattering technique a grating structure was designed (by Ricardo Feced) with the following characteristics: –1dB bandwidth of 0.3 nm; –30 dB bandwidth of 0.4 nm; 90% reflectivity; dispersion compensation for 80 km of NDSF with a dispersion of 17 ps/nm/km. The apodisation profile of the grating and the variation of the grating period with position is shown in figure 10.5. Clearly the structure deviates significantly from the traditional dispersion compensation ethos of linear chirp and analytical apodisation functions.

10.2.2.2 Length Constraint

An important practical consideration was to restrict the grating length to 10 cm, so that it should be compatible with existing packaging technologies. Gratings of 10 cm length could be fabricated by using a phase mask-scanning approach, such as the Moving Fibre/Phase Mask technique [Cole et al, 1995]. Whilst this of no real consequence here, it increases the appeal of such devices to the wider reaches of
the gratings fabrication community, who largely use this approach. The consequence of imposing this length restriction is to compromise slightly the achievable bandwidth utilisation factor. However, as highlighted in section 10.1, it is of less use to have a slightly more square spectral response if the gains in bandwidth are less than the wavelength-drift encountered with gratings that are too long to package athermally.

10.2.2.3 Dependence on Refractive Index Modulation Depth
Gratings designed with high-reflectivity by the layer-peeling method are critically dependent on using the correct refractive index modulation depth. Such designs balance the contribution of many different scattering paths, so it is vitally important that the correct amount of power is reflected from the correct penetration depth. A numerical study was made in order to assess the sensitivity of this design to fabrication tolerances in refractive index modulation depth. To illustrate the results figure 10.6 shows the calculated spectral response and deviation from linear group delay for different peak values of effective refractive index.
The design reflectivity was 90% (solid line). For significantly different values of reflectivity it is apparent that the overall spectral response changes somewhat, and that the group delay linearity is compromised as the careful balance of Bragg phase matching along the grating is disrupted. This type of grating is not so sensitive to refractive index modulation depth that serious problems are encountered during fabrication. Such issues are only of strong concern for gratings with design reflectivities approaching 100%; in this case the penetration depths of different spectral components becomes are dominantly determined by localised regions of strong Bragg reflection, rather by equal contributions distributed throughout the structure as a whole.

10.2.2.4 Optical Transparency

One of the key goals in this work was to increase the bandwidth of gratings designed for a 50 GHz grid in order to realise devices that may be used practically in transmission systems. The spectrum of the grating designed by the layer-peeling method (shown in figure 10.5) was used to compare its suitability for use in multi-

figure 10.6: calculated spectral response of the 50 GHz grating with different values of effective refractive index modulation depth
span links to the results shown for the basic chirped FBGs shown in figure 10.3. The results are shown in figure 10.7.

In terms of the fractional bandwidth utilisation factor, the 50 GHz grating designed by the layer-peeling method remains over 65%, even after reflection from ten similar devices: this is a factor of five better than the 50 GHz chirped FBG with standard apodisation, and about 10% better than the 100 GHz design. In terms of the −1 dB bandwidth, the new design is sufficient to support 20 Gb/s NRZ or 10 Gb/s RZ data for a very large number of links.
10.2.3 Fabrication and Experimental Results

The nature of the layer-peeling technique for grating design is that the resulting structures are digitised. The software developed, as discussed in chapter 4, allows arbitrary apodisation and chirp profiles to be imported for this type of application. The calculated structure had 10,000 data points from which the profile of the grating was interpolated by the fabrication software. It is important to have small sampling distances to minimise the possibility of generating secondary reflection peaks due to the addition of a strong spatial period to the structure.

The germanosilicate fibre used has an NA of 0.2 and was loaded with deuterium at room temperature under a pressure of 145 bars for 10 days. A set of gratings were fabricated in two 1 m lengths of fibre at a speed of 1.5 mm/s with \( \sim 70 \) mW power incident on the fibre (25 mW after the 35% duty-cycle modulation). The spectral measurement was made using a tuneable laser modulated at 200 MHz in conjunction with a network analyser; the wavelength steps were 5 pm.

10.2.3.1 Bandwidth Utilisation Factor

The characteristics of the one of the devices is shown in figure 10.8. The reflection and the group delay measurements closely match the theoretical response obtained from using the profile shown in figure 2. Notably the bandwidth utilisation factor (\(-1\) dB bandwidth / \(-30\) dB bandwidth) of the experimental grating is 70%: this is significantly greater than the 41% theoretical value for the linearly-chirped grating designed using conventional apodisation. This grating offers a \(-1\) dB bandwidth of 0.29 nm for a full (-30 dB) bandwidth of 0.41 nm. The out-of-band noise level, whilst not ideal, is less than \(-35\) dB; this figure is \(-40\) dB at \(\pm 50\) GHz.

The spectral characteristics of six experimental gratings are overlaid and shown in figure 10.9. The purpose of this is two-fold. Firstly it is to show that the fabrication of such devices is not reliant on statistical good luck: that such a structure can be readily realised is a unique consequence of the concept of the continuous grating fabrication system and the subsequent developments. Secondly it is to highlight the key fact that such devices may be used on a 50 GHz grid whilst maintaining optical transparency: the useable bandwidth of the overlaid spectra is a respectable 0.25 nm (> 60% filling factor for a 50 GHz grid).

10.2.3.2 Group Delay Characteristics

The group delay of the grating is also shown in comparison to the theoretical results for both the inverse scattering and the conventional apodisation designs. The inverse scattering design gives (both theoretically and experimentally) extremely
linear group delay over the complete reflection bandwidth. The low level of noise on the experimental group delay (±10 ps peak to peak) has a very short spectral period (~10 pm compared to typical pulse widths of 100 – 200 pm) and, from recent results [Ennser et al, 1998a] [Garthe et al., 1998] [Scheerer et al., 1999], should not have a significant effect on the transmission of 10 Gb/s signals.
The peak-to-peak group delay noise of the experimental grating is less than the theoretical deviation of the traditional apodised chirped FBG with the same bandwidth. Most importantly, the experimental grating does not exhibit the longer period group delay non-linearity typically associated with short apodised chirped FBGs. This group delay non-linearity, inherent to traditional short chirped FBGs, is comparable to 10 Gb/s pulse widths and suggests a more significant penalty in terms of transmission systems. The 0.29 nm –1 dB bandwidth allows compatibility with increasingly popular RZ transmission formats.

10.2.3.3 Filtering of Out-of-band Noise

The use of such gratings on a 100 GHz grid will provide ideal dispersion management characteristics, whilst providing a new level of filtering rejection for ASE and non-soliton energy in dispersion managed soliton transmission systems. Such an approach can be used efficiently to suppress both soliton interaction and timing jitter [Wabnitz and Westin, 1996]. In addition to realising gratings for 50 GHz grids, it is equally viable to make square dispersion compensators exactly matched to the optical bandwidth of the data pulses. The layer-peeling design technique was used again to design a dispersion compensating grating with a -1 dB bandwidth of 20 GHz and a –30 dB bandwidth of 30 GHz. Such a grating is just wide enough to hold a single 10 Gb/s channel (for NRZ and RZ) and represents the optimum in filtering. It should be appreciated that the group delay response of a traditional
The grating structure required to realise such a spectral response is shown in figure 10.10; again, the length of the grating was restricted to 10 cm for compatibility with phase mask-scanning fabrication techniques and athermal packaging technology. The measured spectral response of a grating fabricated with this profile is also shown in figure 10.10. The characteristics of this grating is not ideal, but certainly exhibits a high bandwidth utilisation and an essentially linear dispersion. Whilst there is a small amount of noise on the group delay response, it should be noted that this is of a spectral period much less than the bandwidth of a 10 Gb/s optical pulse, and should correspondingly induce only a marginal power penalty in a transmission system (see the following chapter).
10.3 SUMMARY

The work presented in this chapter is the first experimental results of fibre Bragg gratings designed by a new inverse-scattering algorithm suitable for dispersion compensating 80 km of NDSF on a 50 GHz grid. These devices offer significantly improved bandwidth utilisation and group delay linearity over conventional designs. The gratings are <10 cm in length; it is thus compatible with compact athermal packages and phase mask-scanning fabrication techniques. A grating is also shown designed to have a – 1 dB bandwidth of just 20 GHz for the maximum in spectral filtering. Such devices overcome the restrictions of simple apodisation techniques, favoured in the past, that lead to group delay non-linearities and poor bandwidth utilisation. These gratings are the first devices that can provide a scalable solution to dispersion compensation, allowing exact channel-specific fibre dispersion management on all channels of a DWDM system with a 50 GHz grid. It is envisaged that there will be increasing application of such gratings in 10 Gb/s DWDM systems, either to accommodate RZ-modulated signals on a 50 GHz grid, or to provide a high level of ASE filtering on a 100 GHz grid whilst maximising the useable bandwidth. These gratings are also compatible with 20 Gb/s data.

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IV

SUMMARY
The internet-driven development of optical telecommunications networks demands high-quality optical components for manipulated closely-spaced wavelength-coded data channels. Fibre Bragg gratings can give wavelength-specific control over the phase and amplitude of optical signals by phase-matched coupling of power between counter-propagating core-guided modes in an optical fibre. Complex (and long) grating structures can give nearly-ideal characteristics both for channel-routing applications, such as add/drop, and pulse-shaping applications, such as dispersion compensation.

11.1 FIBRE BRAGG GRATING FABRICATION

A major part of the work presented in this thesis was to develop technology to fabricate high-quality long, and complex fibre Bragg gratings. The work presented led to the development of the first fabrication system capable of realising continuously-written metre-long chirped FBGs, using the continuous grating fabrication technique developed at the ORC. Control software was developed to allow the fabrication of a wide variety of complex grating structures. This system has been shown to be capable of producing both high-quality apodised gratings, and complex sinc-shaped gratings with square-reflectivity and minimal in-band dispersion.

A novel technique of interrogating the microstructure of gratings was developed, allowing the characteristics of UV-induced fringe patterns to be observed. The effects of finite zeroth-order phase mask diffraction was observed in gratings formed by a phase mask-scanning technique, and were found to agree qualitatively with a simple three-beam interference model. A significant sub-harmonic compo-
Refraction index structures formed by the continuous-grating fabrication technique were examined, and were found to be largely free of the sub-harmonic component. This interrogation technique led to the re-evaluation of the apodisation technique used, resulting in a 4-10-fold improvement in the minimum fringe contrast achievable at the end of apodised gratings.

A description of the effects of refractive index noise on the spectral response of chirped gratings is presented. From numerical consideration of how the coupled-modes evolve in the grating structure, it was possible to identify distinct effects associated with short-period stochastic noise and longer-period perturbations according to the extent of the local bandgap. Sources of short and long-period noise in the fabrication system are identified and their severity measured.

11.2 Chirped FBGs for Dispersion Compensation

The need for dispersion compensation in transmission systems is discussed. The design and realisation of long chirped FBGs is presented. The results shown are of the first demonstrated continuously-written metre-long gratings. The devices realised were free of any of the glitches seen in previous work. The first results of chirped gratings with deliberate spectral shaping are presented, with application to equalising the effects of cladding-mode loss. The need for combined 2nd and 3rd-order dispersion compensation is discussed, before results of the first gratings designed to give exact dispersion compensation (2nd and 3rd-order) for non-zero dispersion shifted fibre.

Recently the combination of dispersion management and soliton transmission has been seen as an attractive option both for new transmission systems, and as an upgrade path for existing systems. Results are presented of the first report of dispersion-managed soliton transmission using chirped FBGs. Error-free transmission over a straight-line 1000 km link was achieved.

A new technique for reverse-engineering grating designs has been developed at the ORC. Results are presented of the first gratings made with this design technique, with application to 50 GHz DWDM dispersion compensators. The results achieved are extremely close to theory, and have improved characteristics compared to gratings designed with traditional apodisation techniques. The band-
width utilisation is sufficient for application in long-haul or metro-network applications. It is envisaged that such gratings will be desirable for application in NDSF links, whilst metre-long, broadband devices will be attractive for dispersion management in NZDSF links.

11.3 AVENUES FOR FUTURE WORK

Most work directly following from the results presented will be of incremental-development nature. Undoubtedly improvements can be made in the fabrication system, but perseverance will be required since no one effect is responsible for fabrication-based imperfection. An area of interest will be to realise gratings of 4 m length to allow 30 nm dispersion compensation over 80 km of NDSF (although by the time that this is successfully realised, 60 nm amplifier bandwidth will be commonplace). Further application of the layer-peeling grating design method will be of paramount importance for the continued development of grating-based devices. Evaluation of the performance of gratings such as those presented in high-bit rate, or long-haul systems will be vital. Additionally, the combined application of gain-shaping and dispersion compensation in long-broad band gratings is appealing.
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References


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