rate = 50pulse/s) until the maximum reflectivity reached 10% (−10dB), typically requiring a few tens of seconds. The photoimprinted Bragg grating resonates at a centre wavelength of 1557.5nm with a 3dB bandwidth of 1.5nm (see Fig. 2). The sidelobes are ill defined and more than 26dB below the reflection peak. For comparison (also in Fig. 2), a Bragg grating with a similar 3dB bandwidth and peak reflectivity was fabricated with a uniform diffraction efficiency phase mask (the length of the grating must be reduced to ~0.6 mm to yield the same bandwidth). In this case, the sidelobe levels are significantly higher, with the highest sidelobe only 12dB below the peak reflectivity, in good agreement with theoretical calculations. This demonstrates that apodisation with a variable diffraction efficiency phase mask is a practical method to reduce sidelobe levels, by as much as 14dB for the first sidelobe.

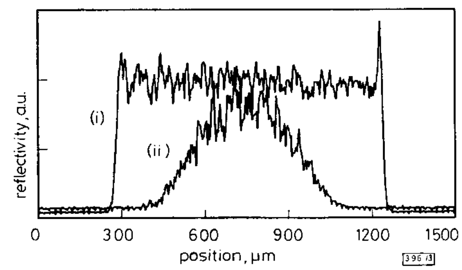

Fig. 3 *Spatial variation of reflectivity of 1mm long unapodised and apodised fibre Bragg gratings, measured along length with a spatial resolution better than 50µm*
(i) Unapodised
(ii) apodised

Further verification that the variable diffraction efficiency phase mask photoimprints gratings whose reflectivity varies with position was obtained directly using low coherence reflectometry [10]. The measured reflectivity as a function of position is shown in Fig. 3 for an apodised grating, whose reflectivity follows a Gaussian-like shape, and for an unapodised grating, whose reflectivity is constant along the length. These two gratings were fabricated with low reflectivity (1%) to minimise the loss of probe light along the length of the gratings.

Conclusion: We have achieved the effective apodisation of the reflectivity of photoimprinted Bragg gratings by tailoring the diffraction efficiency of the phase mask. A suitable chosen Gaussian profile of diffraction efficiency has reduced sidelobe levels by more than 14 dB.

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References

1 MATSUHARA, M., and HILL, K.O.: 'Optical-waveguide band-rejection filters: design', *Appl. Opt.*, 1974, **13**, pp. 2886–2888

2 HILL, K.O., THÉRIAULT, S., MALO, B., BILODEAU, F., KITIGAWA, T., JOHNSON, D.C., ALBERT, J., TAKIGUCHI, K., KATAOKA, T., and HAGIMOTO, K.: 'Chirped in-fibre Bragg grating dispersion compensators: Linearisation of dispersion characteristic and demonstration of dispersion compensation in 100km, 10Gbit/s optical fibre link', *Electron. Lett.*, 1994, **30**, pp. 1755–1756

3 MELTZ, G., MOREY, W.W., and GLENN, W.H.: 'Formation of Bragg gratings in optical fibers by a transverse holographic method', *Opt. Lett.*, 1989, **14**, pp. 823–825

4 HILL, K.O., MALO, B., BILODEAU, F., JOHNSON, D.C., and ALBERT, J.: 'Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask', *Appl. Phys. Lett.*, 1993, **62**, pp. 1035–1037

5 MIZRAHI, V., and SIPE, J.E.: 'Optical properties of photosensitive gratings', *J. Lightwave Technol.*, 1993, **LT-11**, pp. 1513–1517

6 MARTIN, J., and OUELLETTE, F.: 'Novel writing technique of long and highly reflective in-fibre gratings', *Electron. Lett.*, 1994, **30**, pp. 811–812

7 ALBERT, J., HILL, K.O., MALO, B., JOHNSON, D.C., TEMPLETON, I.M., and BREBNER, J.L.: 'Maskless writing of submicron gratings in fused silica by focused ion beam implantation and differential wet etching', *Appl. Phys. Lett.*, 1993, **63**, pp. 2309–2311

8 ALBERT, J., MALO, B., BILODEAU, F., JOHNSON, D.C., HILL, K.O., TEMPLETON, I.M., and BREBNER, J.L.: 'Fabrication and characterization of submicron gratings written in planar silica glass with a focused ion beam'. Int. Symp. on Integrated Optics, Proc. SPIE, 1994, **2213**, pp. 78–88

9 LEMAIRE, P.J., ATKINS, R.M., MIZRAHI, V., and REED, W.A.: 'High pressure H_2 loading as a technique for achieving ultrahigh UV photosensitivity and thermal sensitivity in GeO_2 doped optical fibres', *Electron. Lett.*, 1993, **29**, pp. 1191–1193

10 LAMBELET, P., FONJALLAZ, P.Y., LIMBERGER, H.G., SALATHÉ, R.P., ZIMMER, C., and GILGEN, H.H.: 'Bragg grating characterization by optical low-coherence reflectometry', *Photonics Technol. Lett.*, 1993, **5**, pp. 565–567

Apodised in-fibre Bragg grating reflectors photoimprinted using a phase mask

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Indexing terms: Gratings in fibres, Optical fibres

An apodised in-fibre Bragg grating reflector is fabricated using the phase mask photoimprinting technique. The reflector has a centre wavelength of 1550nm, a bandwidth of 0.22nm and a peak reflectivity of 90%. At 0.4nm (50GHz) from the centre wavelength the reflectivity is 40dB lower than the peak reflectivity; this is an improvement of more than 20dB over an unapodised Bragg grating reflector with similar bandwidth and peak reflectivity.

Introduction: Dense wavelength division multiplexing (WDM) systems require devices that can isolate channels that are spaced by only 100GHz (0.8nm at 1550nm). Photosensitivity [1] provides a versatile means for the fabrication of the gratings used in wavelength selective devices for WDM systems [2–5]. Finite-length in-fibre Bragg grating reflectors with a uniform index modulation along the fibre length have a spectral reflection response with secondary maxima on both sides of the main reflection peak. This characteristic spectral response of the uniform Bragg reflector is not desirable in WDM systems applications because the presence of the sidelobes increases the frequency separation (guard-space) needed between optical carriers to reduce interchannel interference to acceptable levels. In this Letter we report apodised Bragg reflectors with reflection responses exhibiting significantly suppressed sidelobes; the apodised reflectors are fabricated using the phase mask photoimprinting technique [6].

Apodisation: Hill and Matsuhara [7, 8] have shown that the sidelobes in the frequency response of a periodically perturbed optical waveguide filter can be suppressed by designing filters with a grating coupling coefficient that varies spatially along its length. The reduction of the secondary maxima in the Bragg grating reflection response is called apodisation and is achieved by photoinducing a refractive index grating with a modulation amplitude that has a bell-like functional shape along the grating length (for example, one period of $\cos^2$).

Apodised fibre Bragg reflectors have been written using the holographic technique [9] with interfering ultraviolet beams that have a Gaussian spatial profile. Although the sidelobes in the spectral response of these gratings are suppressed, the gratings have a fine structure on the short-wavelength side of their reflection response curve which is particularly strong in high-reflectivity gratings [10]. The fine structure is attributed to Fabry Perot resonances that are obtained in index gratings with a uniform pitch and index modulation whose amplitude has a Gaussian spatial profile. In such structures, the local Bragg resonant wavelength at the grating centre is longer than the local Bragg resonance wavelengths at the grating ends. Consequently, the reflections between the ends of the grating form a Fabry Perot.

In this work, we photoimprint index gratings with a uniform period and index modulation amplitude that has a $\cos^2$ functional variation along the grating length. However, the average local refractive index of these photoimprinted Bragg gratings has been corrected so that the local Bragg resonance is constant along the whole length of the grating. The reflection responses of these apodised Bragg reflectors do not have fine structure on the short-wavelength side that has been observed in the apodised Bragg reflectors of [9].

Experiment and results: The method we use in this work for obtaining pure apodisation of the grating reflection response, while maintaining invariant the Bragg condition throughout the entire length of the grating, is based on a double-exposure technique described earlier with respect to dispersion-compensating Bragg grating devices [1]. In essence, a first exposure (with the phase mask absent) is made using an appropriately designed shadow mask. This first exposure is computer-controlled to precondition the effective index of the optical waveguide in such a way as to compensate for any nonuniform variations in average index that are created in the second stage of the fabrication process. In the second exposure, an index modulation with a bell-shaped profile is photoimprinted using the phase mask technique [6]. This profile is obtained using once again a shadow mask to control the irradiation dose such that it has a $\cos^2$ dependence on grating length. Using this procedure, a Bragg grating was fabricated in standard Corning SMF-28 monomode telecommunication fibre that had been preloaded with hydrogen [12]. The grating is 10 mm long, has a centre resonance wavelength of 1549.8nm and a full width at half maximum (FWHM) of 0.22nm. The reflection response for this grating is shown in Fig. 1. At wavelengths ±0.4 nm (±50GHz) from the centre wavelength of the reflector, the reflectivity is 40dB lower than the peak reflectivity of the Bragg grating. No well defined sidelobes are apparent in the reflection response.

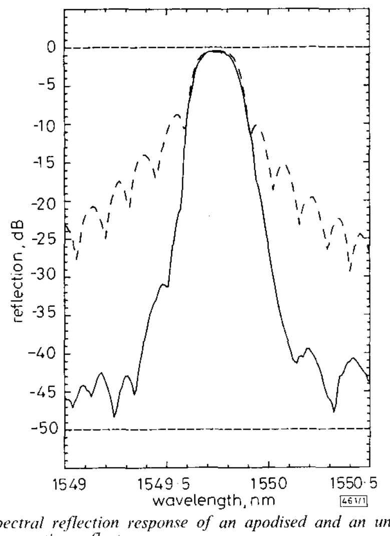

Fig. 1 *Spectral reflection response of an apodised and an unapodised fibre Bragg grating reflector*

For comparison, we fabricated an unapodised Bragg grating with similar peak reflectivity and bandwidth. This grating was fabricated using the standard single-step phase mask photoimprinting technique [6]. The unapodised Bragg reflector has a length of 6 mm, a centre resonance wavelength of 1550nm, a reflectivity of 90% and a bandwidth (FWHM) of 0.24nm. The reflection spectrum for this unapodised grating is also shown in Fig. 1. At ±0.4 nm from the centre wavelength, the sidelobes in the reflection response of the unapodised grating are 20dB higher than those in the reflection response of the apodised grating.

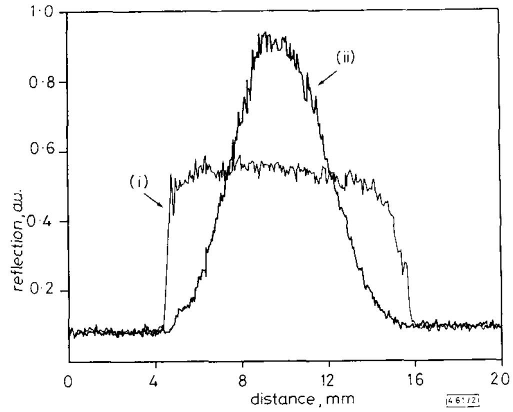

Fig. 2 *Reflectivity of an unapodised and apodised Bragg reflector as a function of position in the Bragg grating*

(i) Unapodised
(ii) Apodised

The variation in index modulation along the length of an apodised Bragg reflector can be measured directly using low coherence reflectometry [13]. We made these measurements using a commercial low coherence reflectometer (Hewlett-Packard, model No. HP 8504A) that has a resolution better than 50μm at 1550nm and maximum return loss of 75dB. The sensitivity of this instrument is insufficient to characterise the high reflectivity Bragg gratings whose reflection responses are shown in Fig. 1. Consequently, we fabricated apodised and unapodised Bragg reflectors with lower reflectivity (≃ 10%). The low-coherence reflectometry measurements (see Fig. 2) give the local reflectivity as a function of position along the length of the grating. The results verify that the profile of the index modulation in unapodised and apodised Bragg gratings are, respectively, flat and bell-like shaped along the grating length.

Conclusions: We have fabricated an apodised Bragg grating reflector with a centre wavelength of 1550nm, a bandwidth (FWHM) of 0.22nm and a peak reflectivity of 90%. At ±0.4nm (±50GHz) from the centre wavelength the reflectivity is 40 dB lower than the peak reflectivity, a 20dB improvement over an unapodised Bragg grating reflector with similar characteristics.

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References

1 HILL, K.O., FUJII, Y., JOHNSON, D.C., and KAWASAKI, B.S.: 'Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication', *Appl. Phys. Lett.*, 1978, **32**, pp. 647–649

2 HILL, K.O., JOHNSON, D.C., BILODEAU, F., and FAUCHER, S.: 'Narrow-bandwidth optical waveguide transmission filters: A new design concept and applications to optical fibre communications', *Electron. Lett.*, 1987, **23**, pp. 465–466

3 JOHNSON, D.C., HILL, K.O., BILODEAU, F., and FAUCHER, S.: 'New design concept for a narrowband wavelength-selective optical tap and combiner', *Electron. Lett.*, 1987, **23**, pp. 668–669

4 BILODEAU, F., HILL, K.O., MALO, B., JOHNSON, D.C., and ALBERT, J.: 'High-return-loss narrowband all-fiber bandpass Bragg transmission filter', *IEEE Photonics Technol. Lett.*, 1994, **6**, pp. 80–82

5 MIZRAHI, V., ERDOGAN, T., DIGIOVANNI, D.J., LEMAIRE, P.J., MACDONALD, W.M., KOSINSKI, S.G., CABOT, S., and SIPE, J.E.: 'Four channel fibre grating demultiplexer', *Electron. Lett.*, 1994, **30**, pp. 780–781

6 HILL, K.O., MALO, B., BILODEAU, F., JOHNSON, D.C., and ALBERT, J.: 'Bragg gratings fabricated in monomode photosensitive optical fiber by UV exposure through a phase mask', *Appl. Phys. Lett.*, 1993, **62**, pp. 1035–1037

7 HILL, K.O.: 'Aperiodic distributed-parameter waveguides for integrated optics', *Appl. Opt.*, 1974, **13**, pp. 1853–1856

8 MATSUHARA, M., and HILL, K.O.: 'Optical-waveguide band-rejection filters: Design', *Appl. Opt.*, 1974, **13**, pp. 2886–2888

9 MELTZ, G., MOREY, W., and GLENN, W.H.: 'Formation of Bragg gratings in optical fibers by a transverse holographic method', *Opt. Lett.*, 1989, **14**, pp. 823–825

10 MIZRAHI, V., and SIPE, J.E.: 'Optical properties of photosensitive gratings', *J. Lightwave Technol.*, 1993, **LT-11**, pp. 823–825

11 HILL, K.O., BILODEAU, F., MALO, B., KITAGAWA, T., THERIAULT, S., JOHNSON, D.C., ALBERT, J., and TAKIGUCHI, K.: 'Chirped in-fibre Bragg grating for compensation of optical-fiber dispersion', *Opt. Lett.*, 1994, **19**, pp. 1314–1316

12 LEMAIRE, P.J., ATKINS, R.M., MIZRAHI, V., and REED, W.A.: 'High pressure H_2 loading as a technique for achieving ultrahigh UV photosensitivity and thermal sensitivity in GeO_2 doped optical fibres', *Electron. Lett.*, 1993, **29**, pp. 1191–1193

13 LAMBELET, P., FONJALLAZ, P.Y., LIMBERGER, H.G., SALATHE, R.P., ZIMMER, CH., and GILGEN, H.H.: 'Bragg grating characterization by optical low-coherence reflectometry', *IEEE Photonics Technol. Lett.*, 1993, **5**, pp. 565–567

Technique for measuring the distributed zero dispersion wavelength of optical fibres using pulse amplification caused by modulation instability

S. Nishi and M. Saruwatari

Indexing terms: Optical dispersion, Optical fibre testing, Optical variables measurement

A novel method for measuring the distributed zero dispersion wavelength λ_0 along a fibre's length is proposed that uses the dispersion dependent amplification induced by modulation instability. The λ_0 distribution of a 10km fibre is successfully measured without cutting the fibre into short pieces. The measured distribution is compared with the average values of each span as measured with the conventional method.

Introduction: The evaluation and management of fibre dispersion along an optical fibre is very important in many applications, for example high speed optical soliton transmission [1] and an optical FDM system experiencing four-wave mixing [2]. However, commonly used measurement techniques [3, 4] cannot reveal the distribution of dispersion, only the average dispersion of the fibre measured. A method that can estimate longitudinal dispersion distributions was recently proposed [5]. This method estimates the distribution of waveguide dispersion from the observed distribution of the mode-field diameter.

This Letter proposes a novel technique for measuring the distribution of zero dispersion wavelength directly. This method uses the gain generation due to the modulation instability that occurs in the anomalous dispersion region near the zero dispersion wavelength.

Measurement principle: Fig. 1*a* shows the principle of the proposed measurement method. The pump light, whose wavelength is swept gradually, is launched into the fibre under measurement. Simultaneously, the loss variation along the fibre length is observed by an OTDR setup. When the wavelength of the pump light enters the anomalous dispersion region from the normal region, modulation instability occurs and the probe pulse from the OTDR setup is amplified. The parts of the fibre at which the loss decreases as shown in Fig. 1 are estimated to exhibit anomalous dispersion. The gain coefficient (m^{-1}) due to modulation instability is given by the following equation [6]:

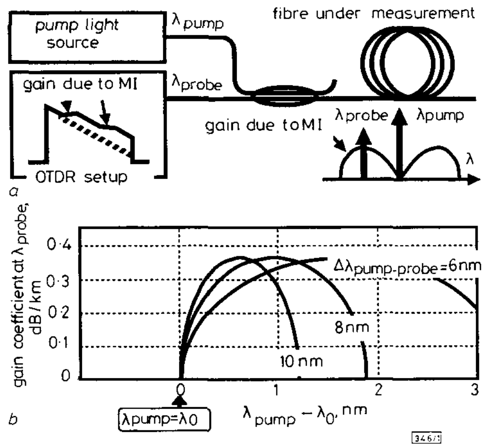

Fig. 1 *Measurement principle*

a Configuration
b Gain coefficient against pump wavelength
$D = s \cdot (\lambda_{pump} - \lambda_0)$, $s = 0.07 ps/km/nm^2$, $P_0 = 100mW$, $n_2 = 3.2 \times 10^{-16} cm^2/W$, $A_{eff} = 50 \mu m^2$

$$G(\Delta\lambda) = \frac{|D|\Delta\lambda}{2\pi\lambda_{pump}}\left\{\frac{8\pi n_2 c P_0}{\lambda_{pump}A_{eff}|D|} - \left(\frac{c}{\lambda_{pump}}\right)^2 (\Delta\lambda)^2\right\}^{1/2} \tag{1}$$

where D is the dispersion at the pump wavelength, n_2 the nonlinear-index coefficient, c the velocity of light in a vacuum, P_0 the power of pump light, A_{eff} the effective core area, λ_{pump} the wavelength of pump light, and $\Delta\lambda$ the wavelength shift from the pump light.

Fig. 1*b* shows the gain coefficient as a function of pump wavelength as calculated by eqn. 1. We assume that the dispersion is given by $|D| = s \cdot (\lambda_{pump} - \lambda_0)$, that the probe signal is also swept and that the difference between pump and probe wavelengths is constant ($= \lambda_{pump\text{-}probe}$). λ_0 is the zero dispersion wavelength and s is the slope of dispersion around λ_0. λ_0 is obtained experimentally by scanning λ_{pump} from the normal to anomalous dispersion region and checking whether gain appears or not.

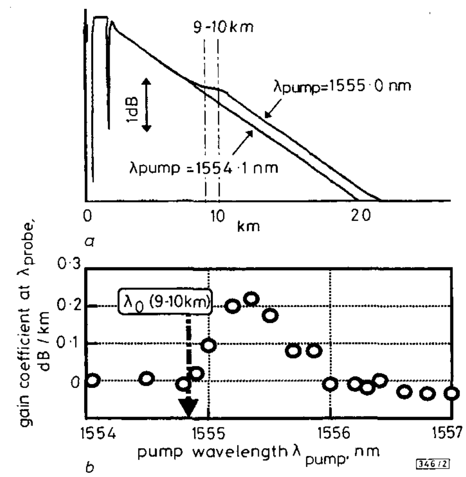

Fig. 2 *Experimental results (using fibre A)*

$\lambda_{probe\text{-}pump} = 8nm$
a OTDR traces
b Gain coefficient against pump wavelength (9–10km)