Controlled Fabrication of Tunable Delay using Compound Phase Shifted Resonators

Philip Orr[1,2], John Canning[1], Michael Stevenson[1], and Pawel Niewczas[2]
[1] Interdisciplinary Photonics Laboratories (iPL), University of Sydney, Sydney, NSW 2006, Australia.
[2] Institute for Energy and Environment, University of Strathclyde, 204 George Street, Glasgow, G1 1XW, UK

Abstract Summary: *Fine tuned, narrowband group delay ("slow light") is obtained using a compound phase shifted grating and superposing resonances. Both simulation and experiments are reported.*

Keywords- gratings, compound gratings, dispersion, group delay, slow light, sensing

I. INTRODUCTION

Optical tunable and static delay lines – often referred to (questionably) as "slow-light" devices when the group delay is large – are utilized in a number of sensing and communications applications, where a known group delay is introduced to provide, for example, phase modulation, dispersion compensation, or improved physical interaction times [1,2]. A narrowband miniaturised resonant delay line can benefit sensors including magneto-optical transducers for magnetic field or electrical current measurement [3,4]. Other applications include coherence matching between coupled waveguides and potentially to any application requiring delay lines. The scope for these delay lines, however, is likely to include telecommunications. With continued emphasis on wavelength division multiplexing (WDM) and dense WDM (DWDM) as a key element of future optical systems right through the local area networks with fibre to the home (including our own National Broadband Network, NBN), broadband dispersion compensators and broadband delays [5] face a new challenge – there is a likelihood of significant variable delay lines involving complex signal pathways that could lead to unanticipated cross talk in synchronised systems and in variable dispersion between channels. So far, these problems can only be resolved through clever systems manipulation, and there is likelihood as bit rates increase that variable delay and variable dispersion that are spectrally selective as well as temporally selective will become necessary. Compact optical delays or wavelength-tuneable dispersion compensation components can potentially address these concerns. Here, we demonstrate the design and fabrication of such components based on UV-inscribed compound phase shifted fibre Bragg gratings.

It has been shown previously that by tuning substructure lengths between phase-shifts in compound phase-shifted fibre Bragg gratings (FBGs) it is possible to superimpose the narrowband transmissive windows that are introduced to the grating spectra in order to tailor regions of transmission or reflection [6]. However, such symmetrical structures do not correspond to superposition of peaks in the group delay spectra. Here we illustrate a general optimum structure for production of large, narrowband group delay over highly reflective spectral regions. We also demonstrate how these can be readily fabricated using a characterisation process amenable to automation allowing the production of compact all-fibre components possessing large narrowband delay, low insertion loss, and tunability in both peak delay and operating wavelength. The ideas discussed are not confined to fibre optics, and can be extended to include, for example, the manipulation of the resonances within integrated devices such as photonic crystal waveguides.

II. COMPOUND PHASE SHIFTED GRATINGS

The general DFB structure is illustrated in Figure 1, where $N_1 - N_k$ are the lengths of grating substructures bounding k-1 $\pi/2$ step phase shifts in the modulation profile. The grating period Λ determines the structure's peak reflected wavelength in accordance with the Bragg equation ($\lambda_B = 2\Lambda n_{eff}$, where n_{eff} is the effective refractive index over the modulated region seen by the travelling mode). Numerical simulations (using the transfer matrix system) indicate that substructures lengths $N_1 - N_{k-1}$ should follow an approximately logarithmic growth profile for superposition of peaks in group delay, and should correspond to the following rules:

1) Successive substructures are greater in length than the preceding substructure, i.e. $N_n > N_{n-1}$. This is always the case for the superposition of group delay peaks.
2) The difference in length between consecutive substructures reduces with each additional substructure, i.e. $(N_n - N_{n-1}) < (N_{n-1} - N_{n-2})$.

The final substructure N_k is made long enough to allow spectral superposition of group delay peaks while providing complete reflection of delayed light.

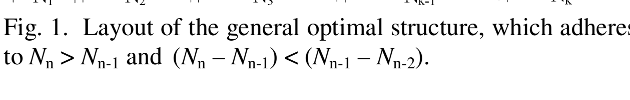

Fig. 1. Layout of the general optimal structure, which adheres to $N_n > N_{n-1}$ and $(N_n - N_{n-1}) < (N_{n-1} - N_{n-2})$.

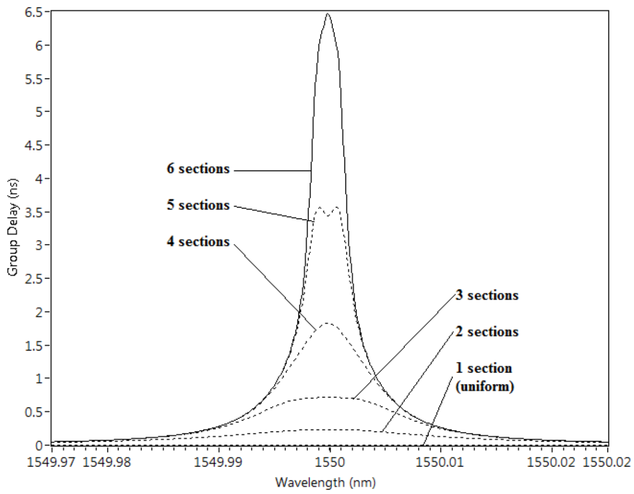

Fig. 2. Enhancement of peak group delay within designed structure from uniform grating to final 6-section logarithmic grating. Final structure is 3000 / 7000 / 8750 / 10000 / 11000 / 20000 (total length 31.72 mm); ($dn = 10^{-3}$).

Figure 2 demonstrates through simulation the achievable enhancement of reflective group delay by successive addition of substructures up to a total of 6 substructures (5 resonances) showing superposition of delay peaks and hence large peak delay (controlling phase coherence between the regions). By making alterations in the substructure lengths ratio it is possible to tune, at the design stage, not only the peak delay and bandwidth of the enhanced region – which in the case of single phase-shifted structures will trade off – but also the spectral shape of the group delay region. In order to illustrate this capability, Figure 3 exhibits an alternative design that yields a widened 'flat top' delay region at the expense of peak delay.

The 6-section structure simulated in Figure 2 possesses a curve area that is a factor of 5 greater than an otherwise identical 2-section (single phase-shifted) grating with similar peak delay, indicating the benefit of multiple phase shifts in terms of improved operating bandwidths. Importantly, by keeping the ratio between substructure lengths constant, both the bandwidth and peak of the delay region can be tuned by adjusting either the grating strength *dn* or total grating length without affecting the general spectral shape. In this way, a reduction in strength can be compensated by a corresponding increase in length, and vice versa. Fabrication of these structures can then be achieved using a pre-determined substructure ratio for any suitable grating length by post-tuning of the modulation depth.

III. FABRICATION

By monitoring reflective group delay during fabrication, the enhancement can be verified at the time of inscription, showing great finesse in enabling the tuning of precision phase shifts. Using this procedure, fibre Bragg gratings based on 2-section and 3-section structures were inscribed in standard boron co-doped germanosilicate (B_2O_3/GeO_2) fibre by a frequency-doubled 244 nm Argon-ion laser using direct writing through a phase mask. CW 244 nm was chosen since it does not contribute significantly to linear birefringence [7].

All gratings fabricated for the study were written with a laser output power of 35 mW at a speed of 1 mm/min. The peak wavelength of all FBGs was approximately 1570 nm. No apodization was applied since this would reduce the finesse of the resonators produced by phase-shifting in this study. The transmission, reflection, and reflective group delay of each grating were recorded at regular intervals during the writing process. Measurement of group delay was performed by the phase difference method [8] using an Agilent/HP 8753D network analyzer. Precise single-pass $\pi/2$ phase-shifts in the index modulation were introduced during the writing process at accurate locations by controlling the voltage applied to a piezoelectric stage supporting the phase mask.

Through feedback from peak reflective group delay, incremental adjustments were made to grating modulation depths by repeated fast overwriting. In this way, the structure can be tuned to approach the simulated optimum design, as indicated by a peak in the growth curve where there is optimal superposition of contributing resonances. This process can be automated by control software so that human monitoring during fabrication is minimal.

The measured and simulated reflective group delays of devices fabricated using the technique are compared in Figures 4 and 5 for single-shift and 2-shift structures respectively. In both cases, the total exposure and hence grating strength *dn* is identical (0.4×10^{-3}) to within ±2.5%, as are the total structure lengths (apertured to 10 mm during writing). These strengths and total lengths are replicated in the simulations.

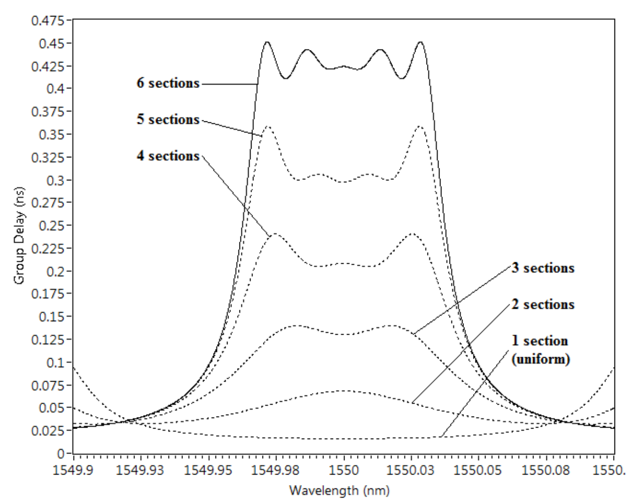

Fig. 3. Production of a 'flat top' delay region by 6-section logarithmic grating. Final structure is 3000 / 7250 / 9000 / 10000 / 11250 / 20000 (total length 32.11 mm). Note the extended x-axis range; ($dn = 0.3\times10^{-3}$).

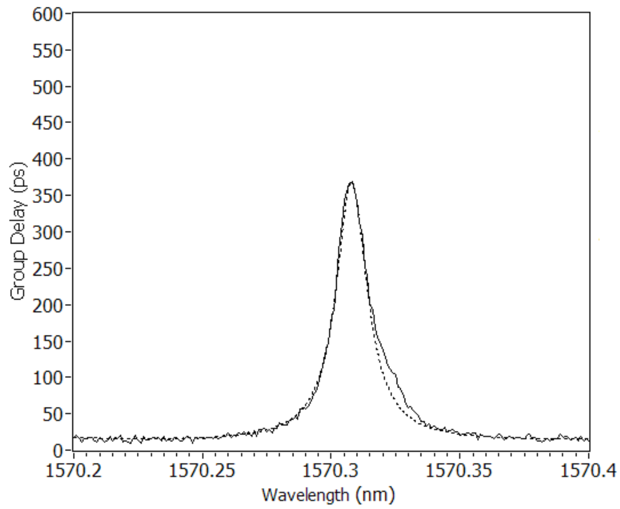

Fig. 4. Simulated (dashed) and measured (solid) group delay for 2-section grating of length 10 mm ($dn = 0.4\times10^{-3}$, structure 6000 / 13000). Peak delay is approximately 350 ps.

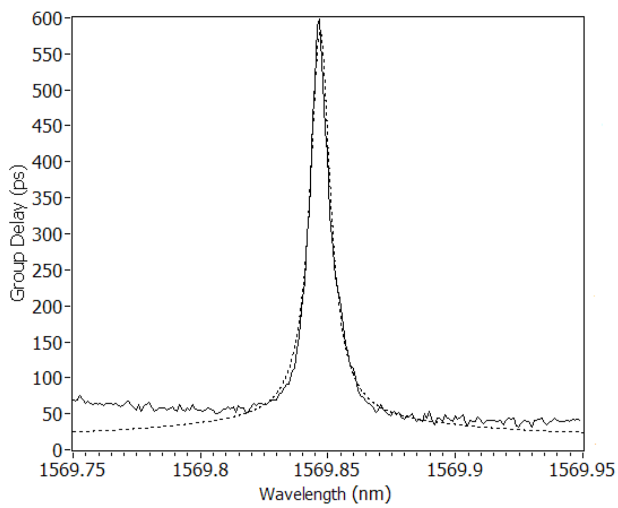

Fig. 5. Simulated (dashed) and measured (solid) group delay for 3-section grating of length 10 mm ($dn = 0.4\times10^{-3}$, structure 1750 / 9000 / 11000). Peak delay is approximately 600 ps.

It can be seen that restructuring the 10 mm gratings from 1-shift to 2-shift results in an enhancement of the group delay and by implication the achievable delay, and that there is good agreement between simulation and measurement in both cases. Comparing Figures 4 and 5 with the corresponding '2-section' and '3-section' curves in Figure 2 it is clear that there is a general agreement between design and fabrication in terms of the relative improvement, indicating that the desired tailoring of dispersive characteristics is achievable in practice using the proposed technique, even where – as is commonly the case – accurate prediction of *dn* produced by a single inscription is not possible.

The resulting delay line is truly narrowband since non-resonant light is immediately reflected back. The wavelength of the resonant, delayed light can be adjusted by strain or thermal tuning of the full grating, while adjustments to the spectral shape and peak of the delay region can be actuated through spot-heating or localised compression of the phase-shift regions. Based on this demonstration a compact delay line that is continually tunable both in terms of operating wavelength and magnitude of delay should therefore be possible to develop by appropriate packaging.

IV. CONCLUSIONS

We have shown that compound phase-shifted DFB structures can be tailored in order to enhance their dispersive properties, which has implications over a wide range of optical measurement and communications applications both in terms of the miniaturisation of present devices and for the implementation of novel highly tunable delay (“slow-light”) components. Rules governing the structural dimensions of tailored fibre DFB structures were developed which indicate that structures incorporating logarithmically-spaced $\pi/2$ phase steps are optimal for superimposing peaks in the reflective group delay spectra.

An automatable feedback-controlled procedure for tuning the grating modulation depths based on feedback from reflective group delay was outlined, enabling practical realization of designs. This method allowed higher resolution of the relevant parameters than could be extracted from, for example, a scanned tuneable source and power meter used to obtained the transmission spectra. Using the method a laboratory proof of principle was conducted for 2- and 3-section gratings, indicating the potential for fabrication of miniaturised, narrowband, tunable delay components based on structured FBGs. It is clear that the technology proposed here can also be implemented in integrated form to add to the photonic tool kit of advanced optical chips, including using the dispersive properties of 2 and 3D coherent scattering structures in a similar way.

ACKNOWLEDGMENT

P. Orr acknowledges a McRobertson Traveling scholarship from Strathclyde and Glasgow Universities, UK. Funding from the Australian Research Council (DP0879465 & DP 0770692) is acknowledged.

REFERENCES

[1] G. J. Tearney, B. E. Bouma, J. G. Fujimoto, “High-speed phase- and group-delay scanning with a grating-based phase-control delay line,” Optics Letters, vol. 22, no. 23, December 1997.

[2] Y. Okawachi et al, “Tunable all-optical delays via Brillouin slow light in an optical fiber,” Physical Review Letters, vol. 94, no. 15, April 2005.

[3] P. Orr, P. Niewczas, J. R. McDonald, M. Walsh, W. Morris, “In-fibre point sensing of magnetic field strength using novel sensor configuration,” Proc. 5th Int. Conf. Condition Monitoring, Edinburgh, UK, pp. 1119–1124, March 2008.

[4] K. Bonhert, P. Gabus, J. Kostovic, H. Brändle, "Optical fiber sensors for the electric power industry," Optics in Lasers and Engineering, vol. 43, pp. 511–526, July 2005.

[5] D. Dahan and G. Eisenstein, "Tunable all optical delay via slow and fast light propagation in a Raman assisted fiber optical parametric amplifier: a route to all optical buffering," Optics Express, vol. 13, no. 16, pp. 6234–6249, August 2005.

[6] R. Zengerle, O. Leminger, "Phase-shifted Bragg-grating filters with improved transmission characteristics," J. Lightwave Tech., vol. 13, no. 12, pp 2354–2358, December 1995.

[7] J. Canning, H. J. Deyerl, H. R. Sørensen, M. Kristensen, "Ultraviolet-induced birefringence in hydrogen-loaded optical fiber," J. Appl. Phys., vol. 97, 2005.

[8] A. Sugimura, K. Daikoku, "Wavelength dispersion of optical fibres directly measured by 'difference method' in the 0.8-1.6 µm range," Rev. Sci. Instrum., vol. 50, no. 3, 1979.