Advanced Bragg grating devices and where they are going

[1,3]M. Ibsen, [2]R. Feced, [1]P.C. Teh, [1]J.H. Lee, [1]M.R. Mokhtar,
[1]P. Petropoulos, [3]M.N. Zervas, [1,3]D.J. Richardson and [1,3]D.N. Payne

[1]*ORC - University of Southampton*, Southampton SO17 1BJ, United Kingdom.
Tel: +44 (0)2380 593138, Fax: +44 (0)2380 593142, Email: mi@orc.soton.ac.uk

[2]*Nortel Networks*, London Road, Harlow, Essex CM17 9NA, United Kingdom.

[3]*Southampton Photonics Inc.*, Chilworth Science Centre, Southampton SO16 7NS, United Kingdom.

Introduction:
Bragg gratings in optical fibre waveguides have now been around for nearly 25years [1] and they were soon after being realised identified as one of the most significant fibre-optic inventions with potentials in a wide variety of areas among telecommunications equivalent to that of the erbium doped fibre amplifier. Following their creation a plurality of in-fibre functions were thought possible with low or no insertion-loss. Although fabrication and control of vital grating parameters was limited in the early stages of their life, initially a number of filtering functions were identified for obvious demonstrations. It soon became apparent though that not just standard filtering manipulation was possible. Identifying the true potential of the devices has let to considerable effort being concentrated on their full exploitation implying building an infrastructure supported by theoretical design [2] and manufacturing techniques [3,4] around them. These techniques combined have let to a scenario where currently it is the imagination more than the actual design and manufacturing capabilities that imposes a limitation to what is being demonstrated.
We will in this presentation discuss and highlight some of the most recent advances in Bragg grating devices and applications in advanced components. In particular we will show examples of the latest in Bragg gratings for dispersion-control, short pulse-manipulation and advanced filtering applications and speculate into what the future holds for these unique devices.

Apodised Bragg gratings for applications in add-drop/mux-demux:
On a number of occations it has been discussed how uniform apodised Bragg gratings exhibit near ideal spectral characteristics for application in dropping and adding channels when using a wavelength division multiplexing (WDM) transmission format [5]. This because they can be made to have near square-filter characteristics with very low side-lobe levels for very high spectral bandwidth utilisation. However, despite the near ideal spectral performance of the apodised filters it has also been discussed how these filters suffer from a non-constant time-delay and thus dispersion both outside and inside the stopband [6,7]. With the evolution of grating manufacturing and design techniques [2] it is now possible though to control both the phase and amplitude of the grating manufacturing process and therefore nearly any filter shape can be made.

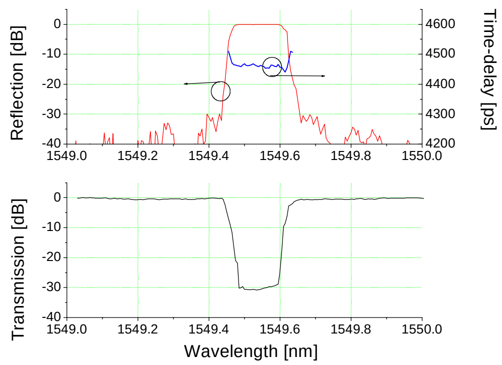

Fig. 1 *Measured reflection, time-delay and transmission spectra of a 25GHz linear-phase (dispersion-free) fibre Bragg grating.*

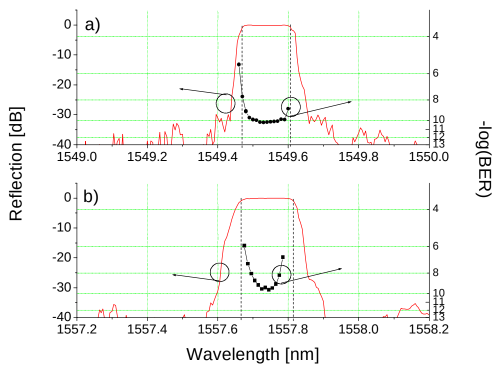

Fig. 2 *Measured reflection and 10Gbit/s NRZ BER performance of a) linear-phase (dispersion-free) 25GHz Bragg grating and b) "standard" apodised (Blackman) 25GHz Bragg grating.*

As the bit-rates in systems continue to increase and therefore the sensitivity to dispersion is increased together with channel-separations that continue to decrease, a filter that has attracted much attention to cope with dense channel demultiplication at is the square-filter linear-phase or dispersion-free Bragg grating (Fig. 1) [8]. Being designed using inverse-scattering techniques [2], its performance enhancement has been confirmed from directly comparing it with standard apodised Bragg grating filters in systems of 10Gbit/s down to 25GHz spacings (Fig. 2) [9]. Recent experiments confirm that up to 75% bandwidth utilisation is possible at bit-rates up to 40Gbit/s for 100GHz channel separations using these gratings (Fig. 3, 4) [10].

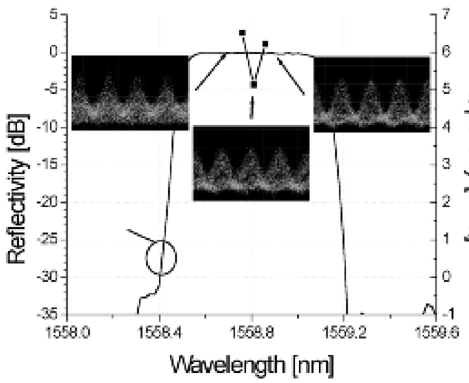

Fig. 3. *Measured reflection and 40Gbit/s RZ performance of a standard apodised (Blackman) 100GHz Bragg grating.*

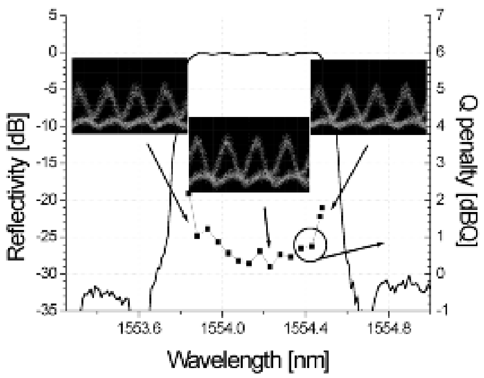

Fig. 4. *Measured reflection and Q-penalty at 40Gbit/s RZ across the 1dB reflection bandwidth of a dispersion-free 100GHz Bragg grating.*

Bragg gratings for pure third-order dispersion compensation:

Recently examples of even more complex profiled Bragg gratings than the dispersion-free gratings shown above were demonstrated through the design and realisation of *single* gratings with broad spectral bandwidth profile and pure dispersion-slope

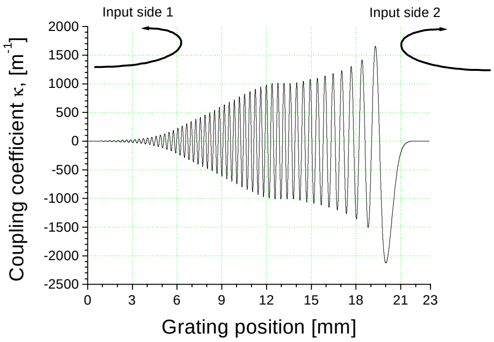

Fig. 5 *Design coupling coefficient profile of a pure 3. order dispersion compensating filter with ±40ps/nm^2 dispersion-slope profile.*

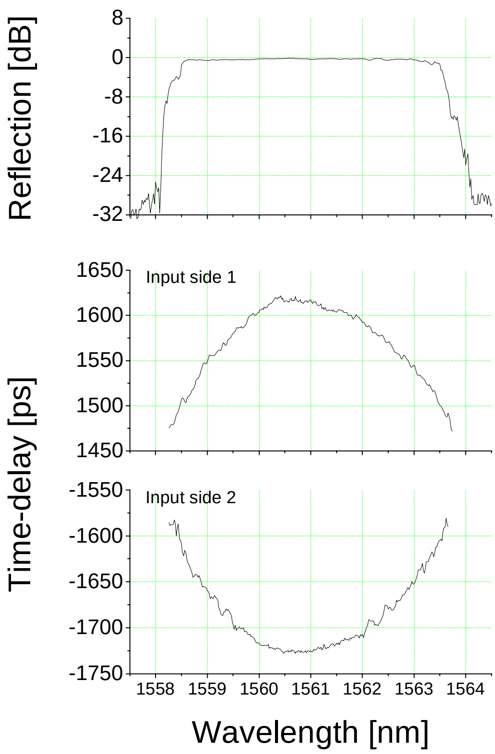

Fig. 6. *Measured reflection and time-delay spectra for pure 3.order dispersion compensating grating with ±40ps/nm^2 dispersion-slope.*

compensation abilities [11]. These gratings require very high maximum index modulations together with full control of both phase and amplitude profiles. Fig. 5, 6 shows the example of a 23mm long Bragg grating with a dispersion-slope of -40ps/nm^2 over a 1dB reflection bandwidth of 5nm and a reflectivity of ~75%. The advantage of these devices includes their relatively short length strongly favouring their incorporation in existing packaging configurations.

Having time-delay characteristics that imply both positive and negative dispersion also suggests their application in dynamic dispersion compensation and as demonstrated in Fig.6 these devices are bi-directional aswell in contrast to most other devices designed using inverse-scattering techniques.

Superstructure Bragg gratings for applications in OCDMA systems:

A topic that has attracted attention over the past years from the perspective of bandwidth enhancement in optical transmission systems is the application of code-division-multiple access (CDMA) technology currently employed in mobil transmission systems. This technology have the advantage of allowing multiple user information to be transmitted on the same carrier-frequency (coherent). A number of approaches using Bragg gratings for the encoding and decoding functions have been described and demonstrated recently. These include encoding in either frequency [12] or time [13].

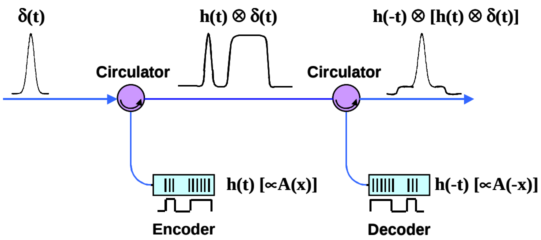

Fig. 7 *Schematic of a coherent OCDMA encoding/decoding system using fibre Bragg gratings.*

The principle of such a encode/decode-scheme is shown schematically in Fig. 7. A short pulse is spread/encoded (in this case) in time using a transmitter Bragg grating with an function given by A(x). The impulse response of the encoding Bragg grating corresponds directly to the slowly varying spatial (super) structure imposed on the fastly varying underlying Bragg grating pitch. In the receiving or decoding grating the spatial-structure simply is reversed to recombine the spectral components. This grating also acts as a match filter to provide maximum signal-to-noise ratio of the received pulse [14]. A correctly decoded pulse then is detected as the autocorrellation function of the received code with a destinctive recognision peak (Fig. 8 (4.) Q1:Q1*). Codes other than the correct (spatially inverse) used for the decoding action will not result in a distinct autocorrelation signature (Fig. 8 (4.) Q2:Q1*). Recently 255 chip codes with 4 levels of phase keying have been demonstrated with the successful encoding and decoding action provided with several interfering channels [15]. The future of this approach will require the ability to dynamically reconfigure codes in real time [16].

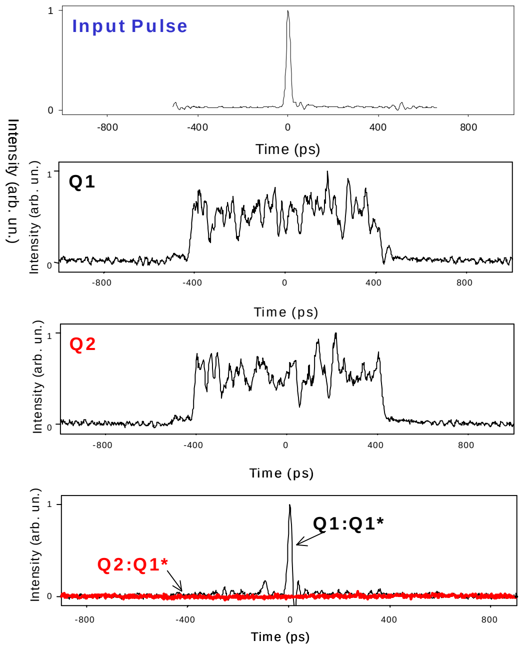

Fig. 7. *Pulse characteristics (oscilloscope traces) of simple multiple user OCDMA system. (1.) input pulse (~2.5ps), (2.) encoded pulse with code Q1, (3.) encoded pulse with code Q2, (4.) decode traces of correct (Q1:Q1*) and incorrect (Q2:Q1*) code matches.*

Conclusion:

In this presentation we have reviewed recent progress in advanced fibre Bragg gratings. Applications of these in various systems contexts have been discussed and some of the most recent device configurations presented.

References:

[1] K.O. Hill et al., *Appl. Phys. Lett.*, **32**, pp. 647-649, 1978.
[2] R. Feced et al., *J. Quantum Electron.*, **35**, pp. 1105-1115, 1999.
[3] R. Stubbe et al., in proc to *BGPP'95*, paper PD-1, 1995.
[4] M.J. Cole et al., *Electron. Lett.*, **31**, pp. 1488-1489, 1995.
[5] T.A. Strasser et al., in proc to *OFC'96*, paper PD8, 1996.
[6] B.J. Eggleton et al., *Photon. Technol. Lett.*, **9**, pp. 1403-1405, 1997.
[7] G. Nykolak et al., *Photon. Technol. Lett.*, **10**, pp. 1319-1321, 1998.
[8] M. Ibsen et al., in proc. to *OFC'00*, paper PD21, 2000.
[9] M. Ibsen et al., in proc. to *OECC/IOOC'00*, paper PD2.1, 2000.
[10] M. Ibsen et al., in proc. to *ECOC'01.*, paper Th.B.2.1, 2001.
[11] M. Ibsen and R. Feced, in proc. to *OFC'02*, postdeadline paper FA7, 2002.
[12] H. Fathallah et al., in proc to *BGPP'97*, paper BMG5, pp. 200-202, 1997.
[13] H. Geiger et al., in proc. to *ECOC'98*, paper TuD10, pp. 337-338, 1998.
[14] H. Geiger and M. Ibsen, in proc. to *OFC'98*, paper WI2, pp. 152-154, 1998.
[15] P.C. Teh et al., in proc. to *OFC'01*, paper PD37, 2001.
[16] M.R. Mokhtar et al., in proc. to *OFC'02*, paper ThGG54, 2002.