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99.9% Reflectivity Dispersion-less Square-filter Fibre Bragg Gratings for High Speed DWDM Networks

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Abstract:

We report linear-phase Bragg grating filters with greater than 99.9% reflectivity. The filters are designed to have useful a bandwidth of 75% on a 50GHz grid spacing, and show no dispersion induced penalties over the full useful band when tested at 10Gbit/s in a back-to-back configuration.

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Introduction:
The ever increasing demand for bandwidth, led to the introduction of wavelength division multiplexing (WDM) as one technique to increase capacity in the optical networks. Initially 100GHz was set as the standard channel separation by the ITU, but this spacing is already being reduced to 50GHz to accommodate extra data-traffic. Even 25GHz channel separations are currently being discussed and may very well become the trend of the future on the moderate bit-rate of 10Gbit/s as an alternative to faster bit-rates, whilst faster electronics for data handling is maturing. This trend therefore calls for filters that can perform filtering duties, that on top of a solid functionality, also act as passive frequency ultra-selective filters that can maintain channel integrity at any cost.

Apodised Bragg gratings have previously been shown to exhibit near ideal characteristics for compact and high filling factor values on such small grid spacings [1], but it has also been discussed how these filters, despite their near ideal spectral performance, suffer from non-linear phase attributes in the stop-band, that could limit their use in high bit-rate systems (10Gbit/s and above) [2-4]. Linear phase-filters therefore have been proposed as a solution to this problem [4,5], but some previous demonstrations have suffered from low rejection values [5,6].

In this paper we show for the first time linear-phase (dispersion-less) Bragg grating square-filters for 50GHz channel separations. The demonstrated filter exhibit a grid filling-factor (bandwidth utilisation) of 75% and constant reflectivity in excess of 99.9% (>30dB transmission loss) over the full drop window. We test the filter at 10Gbit/s and show that $<10^{-11}$ bit-error-rate (BER) is obtained for constant received power throughout the useful band. We also compare the filter performance with "traditionally" apodised Bragg grating filters and show, that this new family of gratings will allow for tuning/drift of the transmitter over the full bandwidth of the grating without being affected by dispersion at any point in the stopband.

Bragg grating design and experiment:
The dispersion less Bragg grating demonstrated here is designed using an inverse scattering algorithm for the design of complex grating filters [7]. Fig. 1 shows the refractive index (coupling coefficient) profile of the grating designed to have a 30dB reflective bandwidth of 50GHz (0.4nm) and a 0.5dB reflective bandwidth of 37.5GHz (0.3nm). The grating is 12cm long and has a series of phase-shifts along its length, the peak effective refractive index modulation of $\sim 3 \cdot 10^{-4}$ ($\kappa \sim 620 m^{-1}$). The grating is written using a continuous grating writing technique that has full control of where the individual grating planes are written along the length of the grating [5]. By de-phasing subsequent grating-planes with respect to each other, full control of the amplitude and phase profiles in the grating therefore can be obtained. The combination of the phase-shifts and the periodic envelope function of the refractive index in the demonstrated filter, ensure not only the square spectral response of the grating, but also the linear-phase performance [7]. As seen from Fig.1 the refractive index profile is asymmetric. This asymmetry does not affect the spectral response of the gratings, but can be seen to affect the phase-response (time-delay) of the gratings when these are illuminated from the opposite end. Therefore these gratings are directional. Fig. 2 shows the measured reflectivity and

time-delay spectra when measured from the "right" input side. The time-delay is confirmed to be constant through-out the reflective bandwidth proving the linear-phase and thus dispersion-less attributes of the filter.

To analyse the dispersion performance of the grating, it is tested for dispersion penalties in a back-to-back configuration, where the transmitter is scanned across the bandwidth whilst the eye-diagram and the BER is monitored and measured [2]. A CW-laser is externally modulated at a bit-rate of 10Gbit/s and a 2^{31}-1 PRBS word length is employed to provide the transmitter source. The results of these measurements are shown in Fig. 3. They show that less than 10^{-11} BER is obtained for constant received power over the full 1dB reflective bandwidth of the grating. The eye-diagrams also remain well-defined and symmetric when scanning the source across the bandwidth, indicating a total absence of dispersion induced distortion.

To compare the performance of these linear-phase Bragg grating filters with "traditionally apodised" Bragg gratings [1], (that is gratings apodised with Gaussian, Blackman or similar apodisation profiles) a grating of length 20mm apodised with a Blackman profile was made. Fig. 4 shows the reflection and time delay spectra of this grating. It is clear that near square filter performance can be obtained (in this case ~55% useful bandwidth), but also that the time-delay not is constant across the reflective bandwidth of the grating. This non-constant delay and subsequent dispersion has also previously been shown and discussed to affect high bit-rate signals reflected of such a grating [2,6]. Fig. 5 shows the results of the BER measurements we performed on this grating. These show that the penalties are increasing as the bandgap edge is approached [2]. That it *is* possible to make a "traditionally" apodised Bragg grating with a useful bandwidth of 75% is shown in Fig. 6. This grating is 35mm long, and apodised with a Blackman profile. It has a similar refractive index maximum as the dispersion-less filters. Increased squareness of the Bragg gratings is seen to be possible by increasing the length, but it is also clear that this increased useful reflection bandwidth is generated at the terrible expense of a large increase of the in-band delay and thus dispersion (Fig. 6). BER measurements on this 35mm long apodised grating filter confirm, that the useful bandwidth is reduced to near nothing (Fig. 7). Even with an accepted reduced squareness of a Bragg grating filter, it is often, for the narrow bandwidth gratings in particular, necessary to increase the length, to ensure a sufficient drop function (transmission loss) [1,3]. As shown in Fig. 7, it is this length increase that causes the reduced effective useful bandwidth at the higher bit-rates.

The benefits of these linear-phase Bragg grating filters include, that they are not just dispersion-free, but also, as an added bonus, that they can be made to provide bandwidth utilisation values in excess of 75%, which is important on future DWDM grid spacings. Furthermore the transmission-loss is constant over the full bandwidth, ensuring a uniform drop-function.

Conclusion:

High rejection near square passband linear-phase fibre Bragg gratings have been demonstrated. The filters are designed using an inverse scattering technique for the design of non-uniform Bragg gratings. We show a 50GHz bandwidth fibre Bragg grating filter with a reflectivity in excess of 99.9% over the full drop-window and confirm its dispersion-free performance in a 10Gbit/s back-to-back configuration. The demonstrated filter is also shown to exhibit superior performance compared to standard apodised Bragg grating filters. We believe that these experiments show that high rejection linear-phase filters are possible to manufacture using current Bragg grating manufacturing techniques, and the robustness of our experiments are such, that we have great confidence in these Bragg gratings performance even for 40Gbit/s modulation formats.

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References:

[1] STRASSER, T.A. et al., In proceedings to *OFC'96*, paper PD8, 1996.
[2] NYKOLAK, G. et al., *IEEE Photon. Technol. Lett.*, **10**, (9), pp. 1319-1321, 1998.
[3] IBSEN, M. et al., In proceedings to *ECOC'98*, **1**, pp. 413-414, 1998.
[4] LENZ, G. et al., *IEEE Journal of Quantum Electron.*, **34**, (8), pp. 1390-1402, 1998.
[5] IBSEN, M. et al., *IEE Electron. Lett.*, **34**, (8), pp. 800-802, 1998.
[6] LENZ, G. et al., *IEEE Photon. Technol. Lett.*, **10**, (4), pp. 567-569, 1998.
[7] FECED, R. et al., *IEEE Journal of Quantum Electron.*, **35**, (8), pp. 1105-1111, 1999.

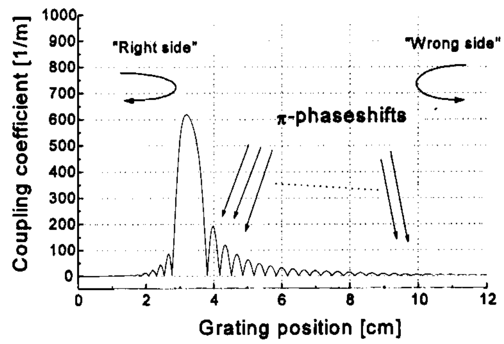

Fig.1 *Refractive index profile of 99.9% reflectivity 50GHz linear-phase filter with directional input.*

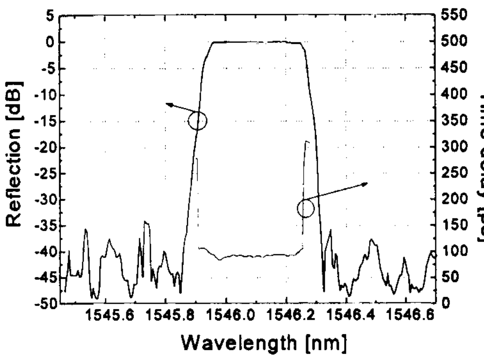

Fig.2 *Measured reflection and time-delay spectra of the linear-phase Bragg grating from the "right side".*

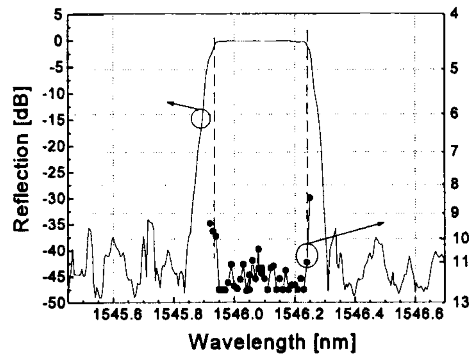

Fig.3 *Measured reflection and BER performance of the linear-phase Bragg grating from the "right side".*

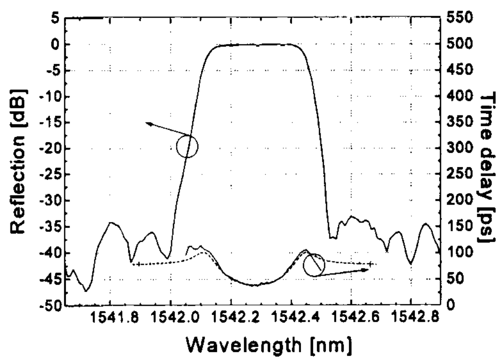

Fig.4 *Measured reflection and time-delay spectra (solid lines) and theoretical time-delay (dotted line) for a 20mm long "standard" apodised Bragg grating.*

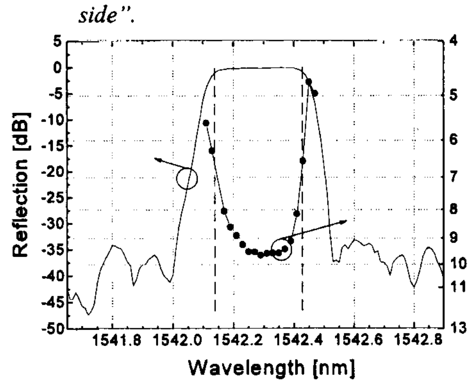

Fig.5 *Measured reflection and BER performance of a 20mm "standard" apodised Bragg grating.*

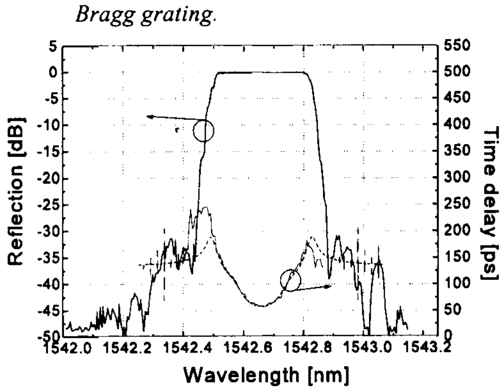

Fig.6 *Measured reflection and time-delay spectra (solid lines) and theoretical time-delay (dotted line) for a 35mm long "standard" apodised Bragg grating.*

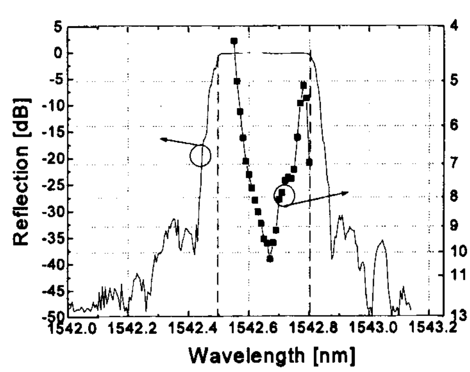

Fig. 7 *Measured reflection and BER performance of a 35mm "standard" apodised Bragg grating.*