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High Reflectivity Linear-Phase Fibre Bragg Gratings for Dispersion-Free Filtering in DWDM Systems

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***Abstract*:**
Dispersion-less square filter fibre Bragg gratings for 25GHz DWDM-channel separations are demonstrated. The filters show a useful bandwidth of 75% and reflectivity in excess of 99.9%. We test the gratings at 10Gbit/s and demonstrate that they at no point in the stop-band are limited by dispersion-induced distortion.

***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, referred to as dense-WDM (DWDM), 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/. However we recently introduced a linear-phase fibre Bragg grating for 50GHz channels separation and proved its dispersion-less attributes through error-free performance in a 10Gbit/s system configuration /7/.

In this paper we show a linear-phase (dispersion-less) Bragg grating square-filter for the even tighter 25GHz DWDM-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 dispersion properties of the grating in a 10Gbit/s NRZ-experiment and compare the filter characteristic with "traditionally" apodised Bragg grating filters. Our findings 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.

***Linear-phase Bragg grating design*:**
The linear-phase Bragg gratings are designed using an inverse scattering technique that is based on a layer peeling Bragg grating design method /8/. The grating is designed to have a 1dB reflection bandwidth of 0.15nm (~19GHz) and a 30dB reflection bandwidth of 0.2nm (~25GHz). Fig.1 shows the normalised refractive index profile against the normalised length of the grating. It has a maximum index modulation of $\sim 2 \cdot 10^{-4}$ ($\kappa \sim 300\text{m}^{-1}$), is 18cm long and is composed of a series of phase-shifts along its length. As seen from Fig.1a the refractive index profile consist of regions of alternating positive and negative refractive index. This sign-change is realised experimentally by inserting a discrete π-phaseshift after each half period of the modulation (Fig.1b) as a controlled negative refractive index is difficult to induce with the 244nm CW UV laser source used in this experiment.

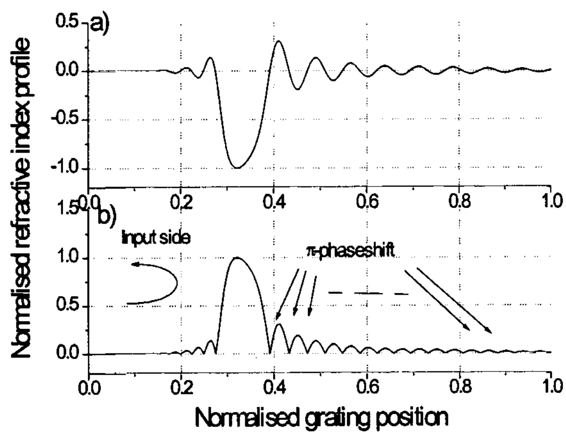

Fig.1. *Normalised refractive index profile against normalised grating length. a) Theoretical design, b) Experimental implementation.*

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 (Fig.1b). 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 /5,7,8/. As seen from Fig.1 the refractive index profile is asymmetric. This asymmetry does not affect the spectral response of the grating, but can be seen to affect the phase-response (time-delay) when illuminated from the opposite end (not shown here due to limited space, but will be demonstrated at the conference). These gratings therefore are directional with an input direction as indicated in Fig.1b.

***Experimental results and discussion*:**

Fig.2 shows the measured reflectivity, time-delay and transmission spectra of the grating when probed as indicated in Fig.1b. The spectral response is confirmed to be near square with ~75% useful reflection bandwidth and a constant transmission-loss of 30dB. The out-of-band reflective spectral features are also confirmed to be below -30dB, resembling a spectral equivalence with "standard" apodised Bragg gratings /1/, that is gratings apodised with Gaussian, Blackman or equivalent apodisation profiles. Furthermore Fig.2 shows that the time-delay is near constant with a 5ps RMS ripple throughout the reflective stop-bandwidth, confirming the linear-phase and thus dispersion-less attributes of the filter.

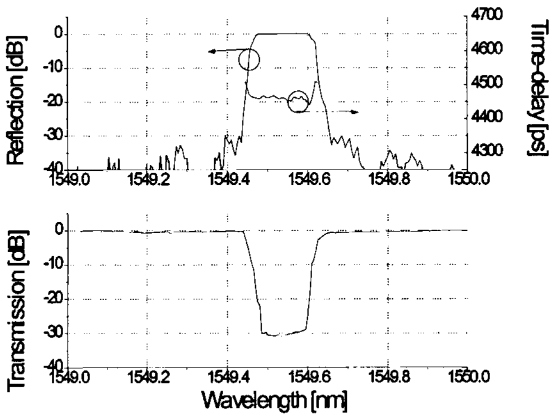

Fig.2. Measured reflection, time-delay and transmission spectra of the 25GHz-bandwidth linear-phase fibre Bragg grating.

To compare the time-delay performance of the linear-phase Bragg grating filters with a "standard" apodised grating, a 3cm long Blackman apodised Bragg grating is made /1/. The measured reflection and time-delay characteristics of this filter is shown in Fig.3b. It shows that the delay is not constant across the bandwidth (compared with Fig. 3a), and therefore that a substancial dispersion is present, despite the uniform underlaying grating pitch. It is the length of the gratings that cause the in-band dispersion to rise /3/. This length is necessary though to ensure a sufficient drop performance of narrowband (~25GHz) Bragg gratings (>30dB). The dispersion performance of the linear-phase filter is tested against the "standard" Bragg grating filter in a back-to-back configuration where a CW source 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 the BER measurements performed on both gratings is shown in Fig. 4. It shows that error-free performance (BER<10^{-9}) throughout the stop-band in the linear-phase Bragg grating (Fig. 4a) thereby providing a useful bandwidth determined by the reflection-bandwidth. The useful bandwidth of the "standard" Bragg grating (Fig.4b) is not given by the reflection-bandwidth but is dictated by the dispersion-limited useful bandwidth /3/. At 10Gbit/s this useful bandwidth is seen to be near to nothing and shows that error-free performance can only be obtained at the center of the Bragg grating stop-band thereby not allowing for drift of the transmitter over the channel bandwidth. This fact does not favor the use of "standard" Bragg gratings for dispersion-free filtering at higher bit-rates at very dense grid spacings, but strongly favors linear-phase Bragg gratings.

***Conclusion*:**

A 99.9% reflectivity 25GHz linear-phase fibre Bragg gratings with near square passbands have been demonstrated. The grating is shown to exhibit superior dispersion-free performance over "standard" Bragg gratings when tested at 10Gbit/s. We believe that this shows that high reflectivity dispersion-free filters are possible to manufacture and that the use of these filters will find important application in future DWDM systems.

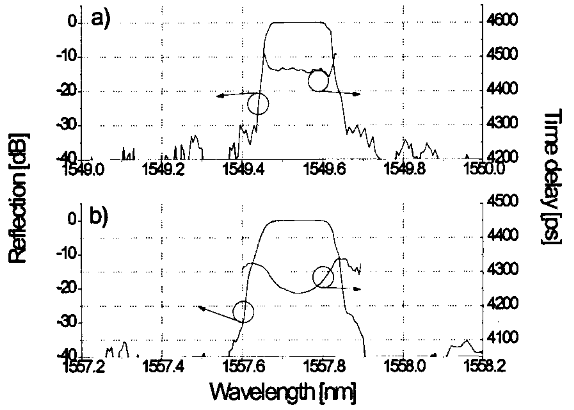

Fig.3. Measured reflection and time-delay spectra of a) linear-phase Bragg grating against the reflection and time-delay spactra of a b) "standard" (Blackman) apodised Bragg grating.

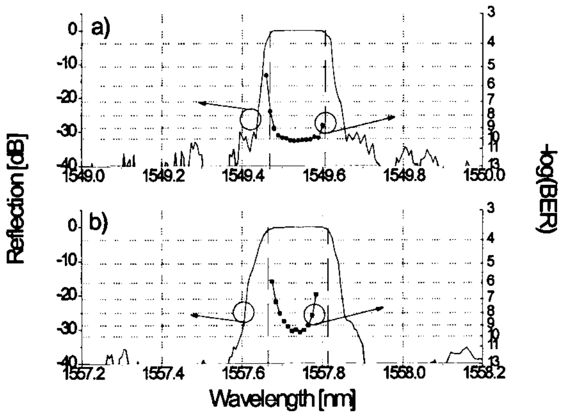

Fig.4. Measured BER performance at 10Gbit/s NRZ of a) the linear-phase Bragg grating against b) the "standard" apodised Bragg grating.

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