Sinc-sampled fibre bragg gratings for identical multiple wavelength operation

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Abstract

Through a periodic sinc modulation of the refractive index-profile in fibre Bragg gratings we demonstrate gratings with multiple equally spaced and identical wavelength channels. We show 10 cm long gratings with 4, 8 and 16 identical uniform wavelength channels separated by the ITU spacing of 100 GHz and a 22.5 cm long grating with 4 identical dispersion compensating channels with a 200 GHz separation designed to dispersion compensate 80 km data transmission through standard fibre at 1.55 µm.

I. Introduction

Fibre Bragg grating fabrication technology is now well established and grating devices are finding many applications in optical communications networks and sensors. Of particular interest in optical communication is the correction of chromatic dispersion in existing fibre links by chirped fibre Bragg gratings [1], allowing an increase in the transmission data rate and distance. Wavelength division multiplexing (WDM) is being employed to further increase the bandwidth.

A powerful fibre grating approach to the WDM solution is to use chirped Moiré fibre gratings as we recently demonstrated [2]. In order to generate even more channels the use of sampled fibre Bragg gratings as multichannel dispersion compensators has been proposed [3]. A sampled grating is generated by a periodic modulation of the refractive index amplitude and/or phase in the fibre. The resultant reflection spectrum and channel separation is a function of the period and shape of this modulation. Previously reported sampled fibre Bragg gratings have utilised simple binary sampling functions with regions of 'dead-space' that create channels of un-equal strength and bandwidth [3-5]. Identical channel sampled gratings have been demonstrated in semiconductor lasers using a linear change in the grating pitch in each sampling section [6]. In this paper we propose and demonstrate, in contrast, a sinc-shaped sampling function that also causes the overall envelope to be square. Furthermore the individual sections are concatenated thereby ensuring a continuously alternating refractive index amplitude and phase profile. This technique is more attractive than over-writing many gratings at different wavelengths [7] in the same length of fibre since exact wavelength matching of the channels is automatically achieved and the time taken to write these devices minimised.

In this paper we demonstrate sampled fibre Bragg gratings with identical wavelength characteristic in a predictable and finite number of channels. As examples we show short, 10 cm, gratings with up to 16 identical wavelength channels separated by 100 GHz. To demonstrate the potential of these gratings as multi-channel dispersion compensators we show a 22.5 cm long chirped grating with 4 wavelength channels separated by 200 GHz and with channel bandwidths of 200 GHz each channel exhibiting dispersion characteristics to compensate 80 km transmission through standard fibre at 1.55 µm.

II. Theoretical Background

Fourier theory is applicable to grating responses when “weak” gratings are investigated. A sinc-shaped refractive index profile has been shown to generate a flat top or square filter shape when the strength of the grating (R<50 %) is low [8]. As these gratings consist of many identical or nearly identical (if chirped) short grating sections the reflection from each section will at all times experience a full sinc-profile, hence the square overall envelope. This concatenation of identical sinc structures will create channels within this square envelope and the channel separations will be determined by the period between the maxima of this modulation.

As is the case for sampled gratings generated with a digital sampling function the channel separations are given by

$$\Delta\lambda = \frac{\lambda_B^2}{2 \cdot n_{eff} \cdot P} \qquad \textbf{(1)}$$

with n_{eff} being the effective refractive index in the grating and P the period between the maxima of

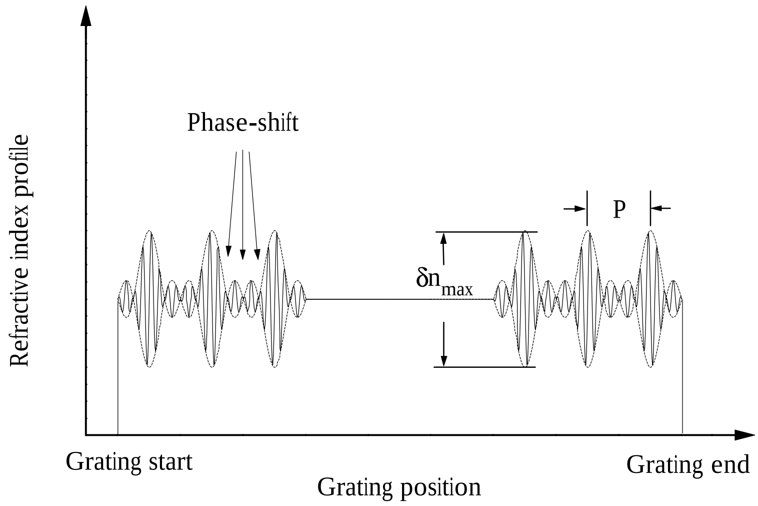

Fig. 1.Refractive index and phase profile of equal strength sampled fibre gratings.

the modulation. Another way of visualising the effect of this refractive index profile is by the adding up of the spectral components from each of the wavelengths.

Fig. 1 shows the complex refractive index profile and the regions of phase shift in the gratings, the exact profile shown gives rise to a 4 channel device. An 8 channel device has 6 side loops between the maxima of the index modulation and a 16 channel device has 14. The sinc-shape of the refractive index modulation is generated using apodisation along the length of the grating. In order to create the "sign" change in the refractive index profile between the side loops a discrete π-phase shift (half a local grating period) is inserted.

III. Fabrication technique

The gratings were written using a recently developed continuous grating fabrication technique [9]. Providing that the index change is in the linear regime with fluence, full control of the apodisation is obtained. The fabrication technique effectively writes grating plane by grating plane, apodisation is obtained by dephasing one grating period with respect to the next one [10], or in other words by filling up the gaps between the grating planes to effectively reduce the index depth δn but keeping the average refractive index n_{ave} constant. An interferometer is used to monitor the position of the fibre during writing to ensure that the individual grating planes are written with a position accuracy of ~ 1 nm.

Each sampled grating was written in a 0.2 NA Deuterium loaded germanosilicate fibre with a 100 mW, 244 nm CW UV-source.

IV. Experimental results and discussion

Fig. 2 a)-c) show examples of 10 cm long sinc-sampled gratings with Bragg wavelengths of 1560.5 nm comprising 4, 8 and 16 wavelength channels respectively, all with *complete* out-of-

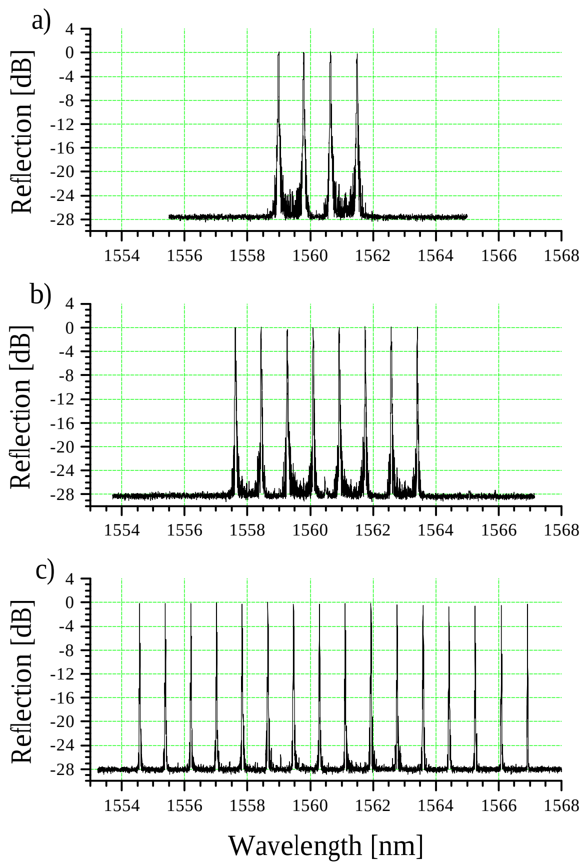

Fig. 2. Measured reflection characteristics of 10 cm long sampled fibre Bragg gratings with channel separations of 100 GHz.

a) 4 channel.

b) 8 channel.

c) 16 channel.

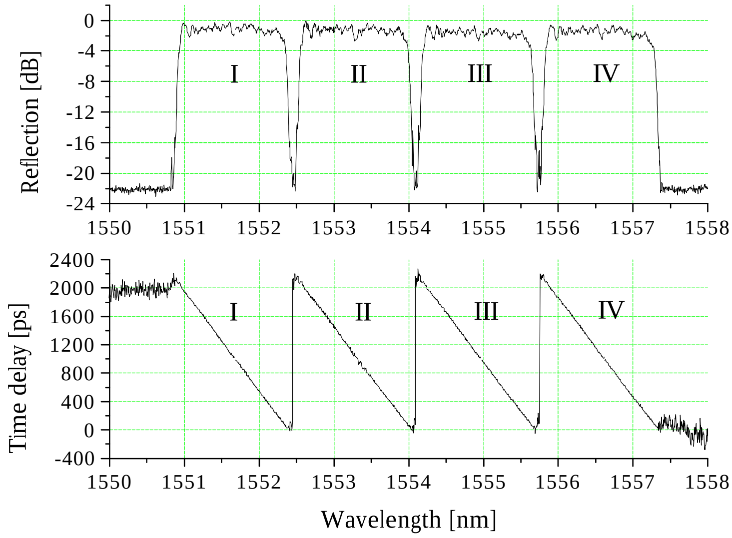

Fig. 3a) Measured reflection and time delay characteristics of a 22.5 cm long continuously chirped fibre grating with 4 wavelength channels separated by 1.6 nm (200 GHz) and channel bandwidths of 1.6 nm. The dispersion in the channels are D_I= -1410 ps/nm, D_{II}= -1406 ps/nm, D_{III}= -1392 ps/nm and D_{IV}= -1392 ps/nm.

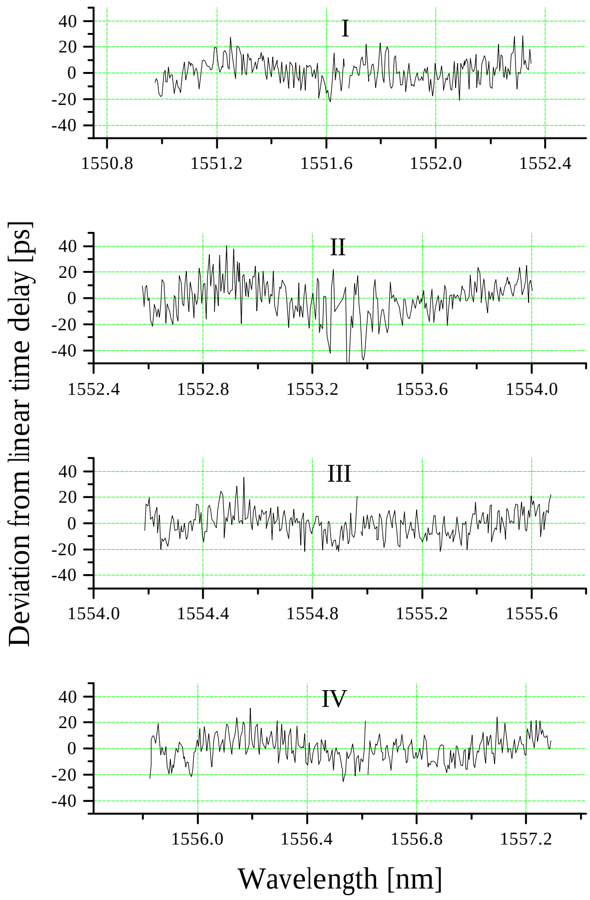

Fig.3b) Measured deviations from linear time delay for channels I, II, III and IV.

band wavelength-channel suppression. All channels exhibit identical characteristics, being uniform with a 16 pm bandwidth and ~10 dB of transmission loss. The channel separation is 100 GHz giving a finesse of 50. The time taken to write the sampled grating with 16 identical channels was just 15 min and the requisite refractive index change for such a structure is ~$1.8 \cdot 10^{-4}$. Additional apodisation of the entire structure would result in identical channels with characteristics determined by the apodisation profile, such as channel side-lobe suppression.

Fig. 3a shows a chirped sinc-sampled fibre grating with a Bragg wavelength of 1554 nm and of length 22.5 cm. The grating has 4 wavelength channels separated by 200 GHz, each with a bandwidth of ~200 GHz. In order to generate this channel separation a sampling period *P* of 521 µm is used, see (1). The resultant average dispersions of the 4 channels are D_I = -1410 ps/nm, D_{II} = -1406 ps/nm, D_{III} = -1392 ps/nm and D_{IV} = -1392 ps/nm. To reduce the ripple in the dispersion characteristics the grating is apodised over 10 % of the total grating length at either end using cosine apodisation. The resultant deviations from linear time delay is 30 ps peak to peak, see Fig. 3b. Each channel exhibits a transmission loss of ~ 8 dB, indicating a reflectivity of approximately 84 %. The gratings were tested for reflectivity with a wavelength resolution of 1 pm using a tunable laser and a wavemeter. The chirped grating was tested for time delay by amplitude modulating the signal from a tunable laser and measure the group delay between successive wavelength steps on a network analyser. The modulation frequency used is 500 MHz.

For these devices to be able to compete with other approaches to WDM gratings [7] they must be easier to fabricate to specification, cheaper to manufacture and more stable when packaged. Benefits of these devices and for sampled gratings in general are that they simplify the manufacturing of multiple matched gratings where very accurate wavelength separations are required. Packaging and temperature stabilisation demands are also reduced because these gratings are all effectively contained within the same length of fibre. Furthermore by chirping the Bragg wavelength they can offer practical, multichannel WDM dispersion compensation exhibiting finite and controllable numbers of wavelength channels with a spectral response devoid of out-of-band wavelength-channels as demonstrated in Fig 3.

V. Conclusion

We have demonstrated sampled fibre Bragg gratings with identical characteristics in all wavelength channels and with complete suppression of out-of-band spectral features. The gratings are generated through a controlled sinc-shaped modulation of the refractive index amplitude and phase profile in the fibre. Examples of 4, 8 and 16 channel gratings with channel separations of 100 GHz and uniform characteristics in all channels are shown. Furthermore we demonstrate the application of these structures to multi-channel dispersion compensators through a 4 channel device with 200 GHz channel separation designed to compensate transmission through 80 km of standard fibre at 1554 nm.

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References

[1] DONG, L., COLE, M.J., ELLIS, A.D., DURKIN, M., IBSEN, M., GUSMEROLI, V., AND LAMING, R.I.: '40 Gbit/s 1.55μm transmission over 109 km of non-dispersion shifted fibre with long continuously chirped fibre gratings', In proceedings to *OFC '97*, paper PD6-1, Dallas, USA, 1997.

[2] IBSEN, M., DURKIN, M.K., and LAMING, R.I.: 'Chirped Moiré fiber gratings operating on two wavelength channels for use as dual-channel dispersion compensators', *IEEE Photon. Technol. Lett.*, 1998, **10**, (1), pp. 84-86.

[3] OUELLETTE, F., KRUG, P.A, STEPHENS, T., DHOSI, G. and EGGLETON, B.J.: 'WDM and broadband dispersion compensation using chirped sampled fibre Bragg gratings', *Electron. Lett.*, 1995, **31**, (11), pp. 899-901.

[4] EGGLETON, B.J., KRUG, P.A., POLADIAN, L. and OUELLETTE, F.: 'Long periodic superstructure Bragg gratings in optical fibres', *Electron. Lett.*, 1994, **30**, (19), pp. 1620-1622.

[5] IBSEN, M., HÜBNER, J., PEDERSEN, J. E., KROMANN, R., ANDERSEN, L.-U. A., and KRISTENSEN, M.: '30 dB sampled gratings in germanosilicate planar waveguides', *Electron. Lett.*, 1996, **32**, (24), pp. 2233-2235.

[6] ISHII, H., TOHMORI, Y., YOSHIKUNI, Y., TAMAMURA, T. and KONDO, Y.: 'Miltiple-phase-shift super structure grating DBR lasers for broad wavelength tuning', *IEEE Photon. Technol. Lett.*, 1993, **5**, (6), pp. 613-615.; ISHII, H., TOHMORI, Y., YAMAMOTO, M., TAMAMURA, T. and YOSHIKUNI, Y.: 'Modified multi-phase-shift super-structure-grating DBR lasers for broad wavelength tuning', *Electron. Lett.*, 1994, **30**, (14), pp. 1141-1142.

[7] STEPHENS, T., ARKWRIGHT, J., STEPANOV, D.Y., KRUG, P.A., SMITH, B., DHOSI, G., YOFFE, G. and OUELLETTE, F.: 'Chirped Bragg grating dispersion compensation', Proceedings *APCC '97*, Session WeJ, pp. 1602-1605. Sydney, Australia, 1997.

[8] STORØY, H., ENGAN, H.E., SAHLGREN, B. and STUBBE, R.: 'Position weighting of fibre Bragg gratings for bandpass filtering', *Optics Lett.*, 1997, **22**, (11), pp. 784-786.

[9] COLE, M.J., LAMING, R. I., ZERVAS, M.N., DURKIN, M.K. and IBSEN, M.: 'Continuous, arbitrary profile fibre Bragg grating fabrication technique', Paper in preparation.

[10] COLE, M.J., LOH, W.H., LAMING, R.I., ZERVAS, M.N. and BARCELOS, S.: 'Moving fibre/phase mask scanning beam technique for enhanced flexibility in producing fibre gratings with a uniform phase mask', *Electron. Lett.*, 1995, **31**, (12), pp. 1488-1489.