Submitted to OECC 2000, Chiba, Japan. (Invited).
Paper 14B1-1 11-14 July, 2000.

Quality Considerations and Improvements of the Time-Delay Characteristics in Chirped Bragg Grating Dispersion Compensators

Morten Ibsen, Michael K. Durkin, Richard I. Laming* and Michalis N. Zervas

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

**Kymata Ltd.*, Starlaw Park, Livingston EH54 8SF, United Kingdom.

Abstract:
We will in this paper discuss how the time-delay performance of chirped Bragg grating dispersion compensators can be improved by paying a close attentation to the design, the fabrication conditions and fibre host quality to the Bragg grating.

Introduction:
The technology of Bragg grating formation has come a long way since the initial demonstrations back in 1978 [1]. Techniques capable of forming nearly any refractive index modulation and imprint nearly any grating pitch at a given position along the length of the grating are now in widespread use [2]. This has lead to an impressive collection of a variety of Bragg grating based components and devices [3], and the robustness of many of these devices in laboratory experiments have pushed their employment in real system environments. Convincing performance, in the relative short lifetime of the technology, led in 1995 to the commercialisation of a series Bragg grating products. Among these were the chirped fibre Bragg grating. It was originally proposed by Ouellette [4] as a device capable of compensation of chromatic dispersion by incorporating reflective differential delay characteristics for different wavelengths along the grating. The pulse broadening suffered when transmitting signals through installed telecommunications fibre therefore can be compensated by delaying the different spectral components of the pulse such that it is reformed to its original shape upon reflection from the grating. Although chromatic dispersion does not impose much limitation to signal recovery when operating systems at bit-rates less than 10 Gbit/s and such data-rates were far from being realised when the chirped fibre grating was proposed, it was foreseen to play an important role in the then future high bit-rate transmission systems. As data-rate transmission at 10 Gbit/s now indeed are beginning to be a well-established technology, and even systems employing wavelength division multiplexed (WDM) technology at the same bit-rate are working solidly, there is a clear need for robust dispersion management in these systems. As a chirped grating exhibits many attractive features such as compactness, low insertion loss, and very importantly, low sensitivity to non-linearities together with low or no polarisation dependancy, it is a leading contestant compared with other proposed dispersion management techniques. These include the use of dispersion compensating fibre (DCF) [5]. The main advantage of DCF is the broad bandwidth over which dispersion compensation can be performed, but high sensitivity to non-linear effects and the missing ability to "shape" the dispersion profile together with the lack of tunability, are major drawbacks to this approach. The previous lack of bandwidth of chirped gratings has been the only limiting factor for them in being the most interesting, simple and robust approach to chromatic dispersion compensation. As very versatile techniques for long and complex Bragg grating formation now are available the design and realisation of high quality truly broadband gratings therefore has taken highest priority among grating manufactures.

We will in this paper discuss from a design point of view how such gratings with large bandwidth and high quality arbitrary dispersion profiles can be achieved. One approach to the fabrication of very long gratings will also by aired supported by a number of experimental grating examples using this technique. A discussion of how imperfections imposed by either the manufacturing process of - or a non-perfect waveguide environment to the gratings, can be minimised by choosing the right host fibre parameters, will also be given.

Chirped Bragg grating quality:
The fabrication of high quality chirped gratings is a non-trivial issue as a variety of effects that can deturiate the quality of the gratings are more than eager to play their part. The types of grating imperfections can be split in to two groups depending on what kind of error they introduce. The *first* one is imperfections induced by the inscription process of the grating. This type of imperfections can arise from a variety of different effects including variation in the fluence or a non-uniform beam profile from the UV source used, imperfect phase-masks and vibrations in the writing setup itself. Variation in the UV fluence will give rise to a variation in the background index of the grating. Imperfect phase-masks implies both masks with a varying groove depth along the length of the mask and a random variation of the period [6]. Phase-mask groove-depth variations will result in a variation of the power in the zeroth order if a zero-order nulled mask is employed and therefore a variation between the interfering -1 and 1 orders, giving rise to a reduced visibility of the interference pattern. The random variations will introduce an error in the grating period and therefore give rise to phase-errors. The effect of vibrations will give rise to a similar effect, if anything though with a higher frequency. The effect of the above mentioned imperfections will typically result in high frequency ripples [7,8] in the time-delay spectrum, that to some extent can be averaged by the signal bandwidth. However, if the ripple frequency is in resonance with the signal bandwidth to be dispersion compensated, it can result in deturiation of system performance [9,10]. The *second* type of imperfections is a more fundamental effect that can give rise to errors in the response of a chirped grating, is a non-ideal fibre host to the grating [11]. This type of imperfection will typically give rise to a long period ripple, that rather than anything results in regions of distinct changes in dispersion.

Imperfect fibres will, no matter how good a writing setup is used, limit the quality of the grating written into the fibre. The quality of the fibre boils down to other effects on the fabrication level of the fibre, e.g drawing conditions of a fibre must be highly optimised. Vibrations in the fibre drawing tower or variations in the diameter of the bobbins onto which the fibre are being wound, will result in small variations of the fibre diameter along the length of the fibre. This will in turn result in a variation in the fibre V-number and therefore in the effective index for a mode propagating in core of the fibre. If many such variation are apparent within on length of fibre that are to be host to a grating, severe distortion to the sensitive phase-matching structure of the grating, uniform or chirped, will occur. It was recently shown [11] that the characteristics of a varying fibre diameter will be directly translated to the spectral properties of the grating and that the effect of such diameter fluctuations on the time delay deviations can, if not being removed, be reduced significantly by employing fibres with low NA values and cut-off frequencies close to operational wavelength of the grating.

Apodisation of chirped gratings:

Another important way to achieve a high quality time-delay of a chirped Bragg grating is apodisation of the refractive index profile towards the edges of in the grating. Furthermore design guidelines of the dispersion profiles of Bragg gratings are somewhat idealised, as the dispersion profile of the grating is not exactly what is put into the chirp profile of the grating, i.e a linear chirp will not necessarily give rise to a pure linear dispersion all the way across the bandwidth of the grating. As a grating is a resonant structure, there are residual ripples in both the reflection and the dispersion characteristics of a grating. Depending on the length of the grating, the period of these ripples changes and at certain positions and therefore wavelengths, the ripple period can match the bandwidth of a signal pulse to be recompressed from the grating. This in turn results in increased errors in the bit-error-rate (BER) performance of the grating as discussed above [9,10]. Although very high frequency ripples to some extent will be averaged by the signal bandwidth itself, low frequency ripples, with periods much larger than the signal bandwidth, will have the effect of changing the dispersion of the grating at a given point. The cavity-like nature to the gratings giving rise to the ripples can be reduced by apodising the grating. Apodisation helps to reduce or "smoothen" out the abrupt transition between inside and outside the grating and in turn reduces the amplitude of the ripples and hence the non-ideal response of both the reflection and time-delay and thus the dispersion performance of the grating can be significantly improved [4,12].

Another key to making a Bragg grating with a highly linearised time delay is by increasing the length of the grating. The advantage of a longer grating is not only that the bandwidth for a given dispersion is increased but also that the period of the ripples in the time delay is increased the further into the grating the signal penetrates. In addition the time delay and therefore the dispersion of a long grating is also approaching the profile that is incorporated into the chirp profile, linear or non-linear [13].

Conclusion:

A number of factors affecting the quality of the time-delay of a chirped Bragg grating dispersion compensator has been discussed. These suggest that a number of steps has to be taken in the design and fabrication of the gratings to ensure a high quality delay performance, such that robust dispersion compensation can be performed. A series of experiments at bit-rates of 10Gbit/s, 20Gbit/s and 40Gbit/s [14,15] confirm the high potential for chirped Bragg grating dispersion compensators in WDM-transmission systems.

References:

[1] Hill, K.O., Fujii, Y., Johnson, D.C. and Kawasaki, B.S.: 'Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication', *Appl. Phys. Lett.*, **32**, (10), pp. 647-649, 1978.

[2] Cole, M.J., Loh, W.H., Laming, R.I., Zervas, M.N. and Barcelos, S.: 'Moving fibre/phase-mask scanning technique for enhanced flexibility in producing fibre gratings with a uniform phase-mask', *Electron. Lett.*, 31, (17), pp. 1488-89, 1995.

[3] Kashyap, R.: 'Fiber Bragg gratings', Academic Press, 1999.

[4] Ouellette, F.: 'Dispersion cancellation using linearly chirped Bragg grating filters in optical waveguides', *Optics Lett.*, **12**, (10), pp. 847-849, 1987.

[5] Vengsarkar, A.M.: *Tutorial* on 'Dispersion compensation', In proceedings to *OFC '98.*

[6] Ouellette, F., Krug, P. and Pasman, R.: 'Characterisation of long phase masks for writing fibre Bragg gratings', In proceeding to *Photosensitivity and Quadratic Nonlinearities in Glass Waveguides: Fundamentals and Applications*, **22**, paper SuB7, pp. 116-119, 1995.

[7] Ouellette, F.: 'The effect of profile noise on the spectral response of fiber gratings', In proceedings to *BGPP '97*, paper BMG13-2, Williamsburg, USA, 1997.

[8] Durkin, M.K., Zervas, M.N. and Laming, R.I.: 'Quality considerations of chirped fibre Bragg gratings for dispersion compensation in WDM systems', In proceedings to *ECOC '98*, **1**, pp. 409-410, Madrid, Spain, 1998.

[9] Garthe, D., Milner, G. and Cai, Y.: 'System performance of broadband dispersion compensating gratings', *Electron. Lett.*, **34**, (6), pp. 582-583, 1998.

[10] Ennser, K., Ibsen, M., Durkin, M.K., Laming, R.I.: 'Influence of non-ideal chirped fibre grating characteristics on dispersion cancellation', *IEEE Photon. Technol. Lett.*, **10**, (10) 1998.

[11] Ibsen, M. and Laming, R.I.: 'Fibre non-uniformity caused Bragg grating imperfections', In proceedings to *OFC'99*, paper FA1, San Diego, USA, 1999.

[12] Ennser, K., Zervas, M.N. and Laming, R.I.: 'Optimisation of linearly chirped grating dispersion compensated system', *Opt. Fiber Technol.*, **3**, pp. 120-122, 1997.

[13] Ibsen, M., Durkin, M.K., Ennser, K., Cole, M.J. and Laming, R.I.: 'Long continuously chirped fibre Bragg gratings for compensation of linear- and 3rd order-dispersion', in proceedings to *ECOC '97*, **2**, pp. 49-52, Edinburgh, UK, 1997.

[14] Gnauck, A.H., Garrett, L.D., Forghieri, F., Gusmeroli, V. and Scarano, D.: '8 x 20Gbit/s 315km, 8 x 10Gbit/s 480km WDM transmission over conventional fiber using multiple broad-band fiber gratings', *IEEE Photon. Technol. Lett.*, **10**, pp. 1495-1497, 1998.

[15] 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 109km of non-dispersion shifted fibre with long continuously chirped fibre gratings', In proceedings to *OFC '97*, Postdeadline PD6, Dallas, Texas, USA, 1997.