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New Generation DWDM Fibre Grating Devices

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Abstract

Using a recently developed inverse scattering layer-peeling algorithm and a modified stroboscopic grating writing technique, we have designed and successfully demonstrated novel grating devices, such as 50GHz-bandwidth dispersion compensators and square dispersionless filters, suitable for future high performance DWDM optical systems.

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Abstract: Using a recently developed inverse scattering layer-peeling algorithm and a modified stroboscopic grating writing technique, we have designed and successfully demonstrated novel grating devices, such as 50GHz-bandwidth dispersion compensators and square dispersionless filters, suitable for future high performance DWDM optical systems.

Introduction

Future high-speed, high-capacity optical communication systems will depend critically on the availability of high performance fibre devices, such as narrow filters for selection of densely packed wavelength-division-multiplexed (WDM) channels or efficient compensation of link dispersion. There are a number of methods and different approaches in designing high quality grating devices. Among them, electromagnetic inverse scattering (IS) techniques [1] are known to offer a great design flexibility with various degrees of accuracy. On the other hand, the UV-writing has improved considerably and enables the practical implementation of high performance grating devices. In this paper, we first review the different methods available for the synthesis of fiber gratings focusing predominantly in a recently developed and very efficient method [2,3], based on a differential layer-peeling algorithm. We also present recent experimental results of novel grating devices, such as 50GHz-bandwidth linear dispersion compensators [4] and square dispersionless filters [5], suitable for future high-performance DWDM optical systems.

Grating Design - Synthesis

Grating design techniques are tools of great importance in implementing devices with a required predetermined response. With a given target response, the aim is to design (synthesise) the complex grating profile that provides the required response. The simplest approach exploits the approximate Fourier transform (FT) relation that exists between the filter spectral response and the grating coupling function. This method, called also first-order Born approximation, takes only into account the first-order reflection from the medium and is applicable to the design of low reflectivity gratings. Several modifications of the method have improved its performance and extended its applicability to relatively high reflectivities [6,7], enabling the design of practical fiber grating filters [8]. However, this synthesis approach remains approximate in nature and, therefore, not reliable for the design of complex and strong filters.

A second group of IS methods can provide exact solutions to the scattering problem, expressed in terms of integral equations [9-14]. These IS integral equations are derived using general causality arguments. The main drawback of integral methods is the difficulty involved in solving the integral equations. Kay has found analytical IS solutions when the spectral response function is written in terms of rational functions [15] and this approach has been used to design practical corrugated filters[16-17]. However, the need to approximate the desired spectral response by rational functions is cumbersome and can result in compromised performance. To overcome this limitation, an iterative solution of the Gelfand-Levitan-Marchenko (GLM) system was proposed to synthesise arbitrary spectral responses [18-19]. Several fiber-grating devices, designed with this method, have already been fabricated proving the usefulness of the method [20]. However, the iterative solution of the GLM equations [21] has two weaknesses. Firstly, the solution is approximate due to the finite number of iterations involved, which means that only a limited number of reflections within the medium are considered. This is particularly noticeable for strong gratings with discontinuities in the coupling strength. The second drawback is the low algorithm efficiency, with a complexity that grows as $O(N^3)$, where N is the number of points in the grating. Both of these weaknesses can be overcome, as the matrix coefficients that appear in the integral equation [11,22] permit the use of fast algorithms of $O(N^2)$ for its solution. We should also point out that several other iterative inverse scattering approaches have been described in the literature [23-24].

Finally, there exists a third group of exact IS algorithms called differential or direct methods [11,25-27]. These techniques, developed first by geophysicists like Robinson and Goupillaud [26], exploit fully the physical properties of the layered-medium structure in which the waves propagate. The methods are based again on causality arguments, and identify the medium recursively layer by layer. For this reason they are sometimes called layer-peeling or dynamic deconvolution algorithms. The complexity of the algorithm grows only as O(N^2) and is usually well suited for parallel computation.

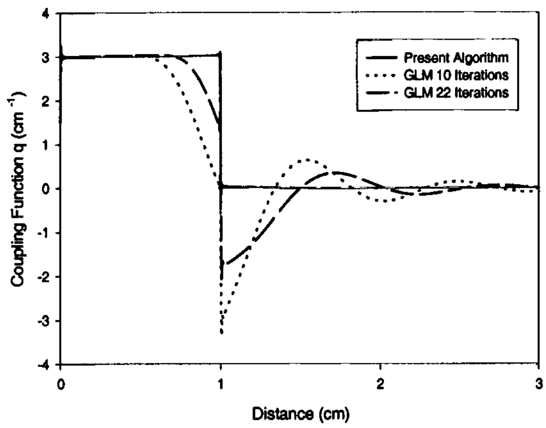

Figure 1: Reconstructed profile of uniform grating.

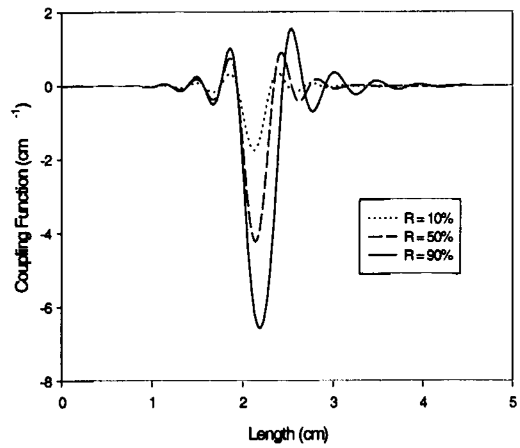

Figure 2: Coupling constant distribution for square dispersionless filters.

Recently we have developed a fiber grating synthesis algorithm based on a differential method [2,3]. The inverse scattering principle relies on the synthesis in the time domain of the grating impulse response. The first step is to build a physically realisable impulse response that closely corresponds to the required spectral response of the filter. At each time instant t_0 and corresponding maximum penetration length $L_p(t_0)$, the impulse response is renormalised, by subtracting the contributions of all the possible previous multiple reflections within the grating (past history), providing uniquely the grating coupling constant at $L_p(t_0)$. The algorithm can be practically implemented in different ways. Initially, the grating has to be adequately discretised. The other important characteristic of the method is its O(N^2) efficiency. In order to test the algorithm, we have reconstructed a uniform grating from its analytical solution. The grating had a coupling strength of $3cm^{-1}$ and a total length of 1cm, giving rise to a resonant reflectivity of 0.99 (-20dB in transmission). Figure 1 illustrates the reconstruction computed with the present algorithm and compares it with the solution provided by iterative integration of the GLM equations. The efficiency of this algorithm is superior to that of the iterative GLM, which could not match the sharp transition at the end of the grating even after 22 iterations. The processing time consumed for each iteration of the GLM method was twice the total execution time of the layer-peeling algorithm.

As the grating is calculated taking into account all the multiple reflections, the reconstruction process is exact. Figure 2 illustrates the increasing importance of multiple internal reflections, as the grating strength is increased. The coupling strength functions (apodisation profiles) along three gratings with square-like spectral filter-response and reflectivities of 10%, 50% and 90%, respectively, are shown. For low reflectivities, the apodisation profile follows a symmetric sinc-like function. Such profiles are easily predicted by simple FT methods. As the grating strength increases, however, the apodisation profile becomes progressively more asymmetric. These features can not be obtained by FT methods and demonstrate the effectiveness of our method. A number of high performance grating devices with different characteristics, such as square dispersionless filters, 2nd and/or 3rd order dispersion compensators etc., have been designed, and results will be discussed at the conference.

Novel Grating Devices for DWDM Applications

A number of different grating devices were designed using the IS layer-peeling technique [3-4] and implemented experimentally using a modified stroboscopic UV-writing technique [28].

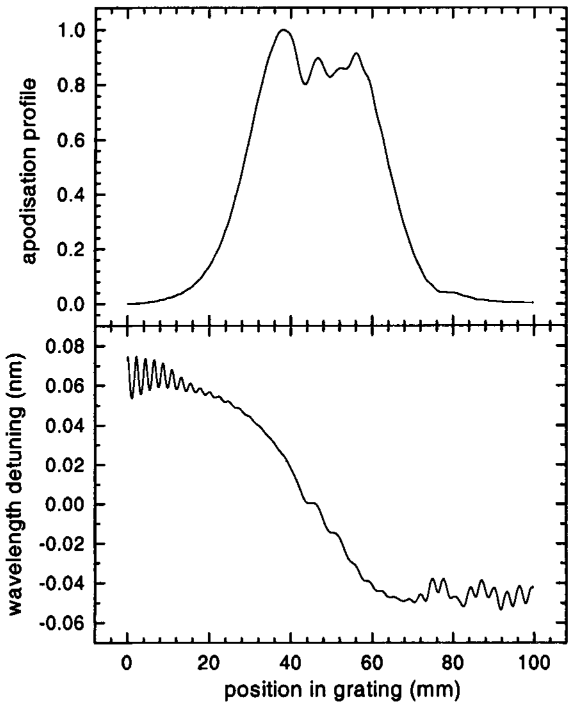

Figure 3: Complex apodisation and chirp profiles.

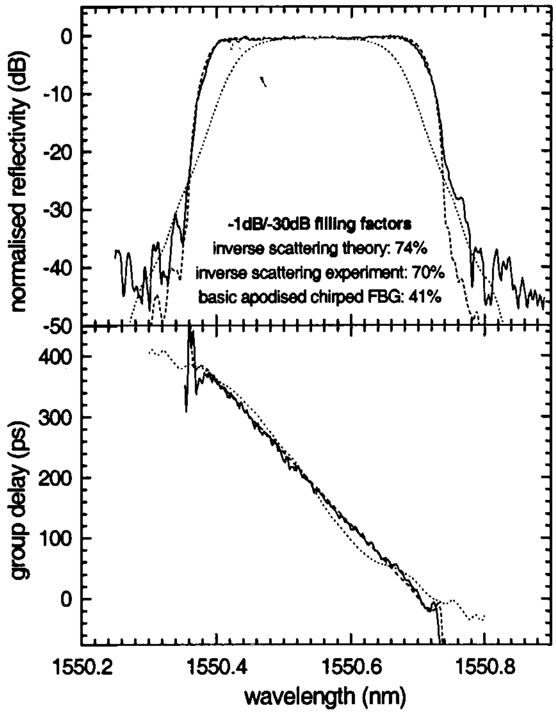

Figure 4: Reflectivity and time delay spectra for grating of Fig. 3.

Using this technique we designed a grating structure with the following characteristics: –1dB bandwidth of 0.3 nm; –30 dB bandwidth of 0.4 nm; 90% reflectivity; dispersion compensation for 80 km of NDSF with a dispersion of 17 ps/nm/km; maximum length 10 cm. The apodisation and chirp profiles of the resulting structure are shown in Figure 3. Figure 4 shows the response of the device. The reflection and the group delay measurements closely match the theoretical response obtained from using the profile shown in Figure 3. Notably the bandwidth utilisation factor (-1dB bandwidth / -30dB bandwidth) of the experimental grating is 70%. This is significantly greater than the 41% theoretical value for the linearly-chirped grating designed using conventional apodisation. This grating offers a –1 dB bandwidth of 0.29nm for a full (-30dB) bandwidth of 0.41nm. The out-of-band noise level is less than –35dB.

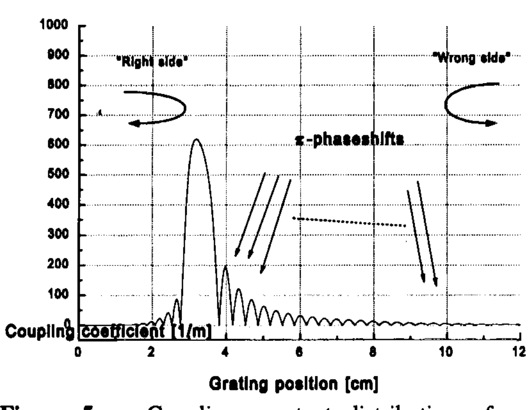

Figure 5: Coupling constant distribution of square dispersionless filter.

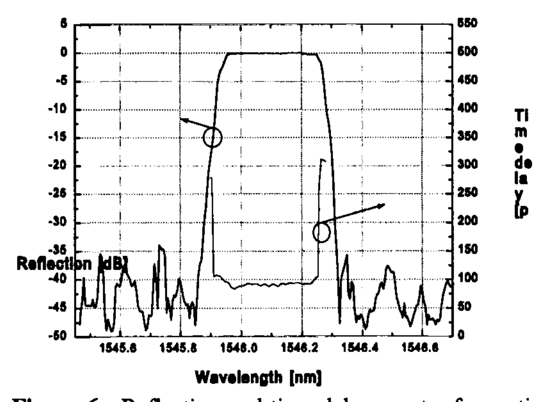

Figure 6: Reflection and time delay spectra for grating of Fig. 5.

The layer-peeling algorithm was also employed to design square dispersion-less filters. Figure 5 shows the apodisation (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 ~3×10^{-4} (κ~$620m^{-1}$). The combination of the successive phase-shifts and non-periodic, asymmetric apodisation function ensure not only the square spectral response of the grating, but also the linear-phase performance. 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. Figure 6 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 characteristics of the filter. In transmission the grating shows square band-stop characteristics.

The grating was further tested by performing BER measurements across the full bandwidth and showed error-less performance ($BER<10^{-9}$) over the entire –1dB bandwidth. Note that the corresponding bandwidth utilisation factor (-1dB bandwidth / -30dB bandwidth) in this case was in excess of 75%. It should be also stressed that conventional grating designs with similar maximum reflectivity resulted in a much smaller bandwidth utilisation factor.

Conclusions

Many different strategies are now available for the design of fiber gratings. In particular, we have presented an exact and very efficient differential (layer peeling) method that outperforms previous techniques. We show that this method meets the requirements of versatility and flexibility needed by practical grating designs. We have designed and experimentally implemented fibre grating devices using the aforementioned method and demonstrated their suitability for use in DWDM optical systems.

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References

[1] K.I. Hopcraft, P.R. Smith, *"Electromagnetic inverse scattering"*, Kluwer Academic, Netherlands, 1992.
[2] R. Feced, M. N. Zervas, M. A. Muriel, *IEEE J. Quantum Electronics*, Vol.35, No.8, pp.1105-1115 (1999).
[3] M. N. Zervas and R. Feced, in *OFC Proc.*, paper TuH1, pp. 112-4, Baltimore (2000).
[4] M. K. Durkin, R. Feced, C. Ramirez and M. N. Zervas, in *OFC Proc.*, paper TuH4, pp. 121-3, Baltimore (2000).
[5] M. Ibsen, R. Feced, P. Petropoulos, M. N. Zervas, in *OFC Proc.*, paper PD21, Baltimore (2000).
[6] J.A. Dobrowolski, D. Lowe, *Applied Optics*, Vol. 17, No. 19, pp. 3039-3050 (1978).
[7] B. G. Bovard, Applied *Optics*, Vol. 27, No. 15, pp. 3062 (1988).
[8] K. A. Winick, J. E. Roman, *IEEE J. Quantum Electronics*, Vol. 26, No.11, pp. 1918 (1990).
[9] I. M. Gel'fand, B.M. Levitan, *Amer. Math. Soc. Trasl., Ser. 2*, Vol. 1, pp. 253-304 (1955).
[10] G.L. Lamb, Jr. *"Elements of soliton theory"*, John Wiley & Sons. New York, 1980.
[11] A. M. Bruckstein, B.C. Levy, T. Kailath, *SIAM J. Appl. Math.* , Vol. 45, No. 2, pp. 312-335 (1995).
[12] P. V. Frangos, D. L. Jaggard, *IEEE Trans. Antennas and Propagation,* Vol. 39, No. 1, pp. 74-79 (1991).
[13] B. Gopinath, M.M. Sondhi, *Proceedings IEEE*, Vol. 59, No. 3, pp. 383-392 (1971).
[14] P.V. Frangos, D.L. Jaggard, *IEEE Trans. Antennas and Propagation*, Vol. 35, No. 11, pp. 1267 (1987).
[15] I. Kay, *Communications in Pure and Applied Mathematics*, Vol. 13, pp. 371-393 (1960)
[16] G.H. Song, S.Y. Shin, *J. of the Optical Society of America A*, Vol. 2, No.11, pp. 1905-1915 (1985).
[17] J.E. Roman, K.A. Winick, *IEEE J. of Quantum Electronics*, Vol. 29, No.3, pp. 975-982 (1993).
[18] E. Peral, J. Capmany, J. Marti, *IEEE J. Quantum Electronics*, Vol. 32, No.12, pp. 2078-2084 (1996).
[19] P.Roberts, G.Town, *IEEE Trans. on Microwave Theory and Techniques*, Vol.43, No.4, pp. 739-743 (1995).
[20] J. Skaar, B. Sahlgren, P.Y. Fonjallaz, H. Storoy, R. Stubbe, *Optics Letters*, Vol.23, No.12, pp. 933 (1998).
[21] P.V. Frangos, D.J. Frantzeskakis, C.N. Capsalis, *IEE Proceedings-J*, Vol. 140, No.2, pp. 141-149 (1993).
[22] J.L. Frolick, A.E. Yagle, *Journal of Lightwave Technology*, Vol. 13, No. 2, pp. 175-185 (1995).
[23] E. Brinkmeyer, *Optics Letters*, Vol. 20, No. 8, pp. 810-812 (1995).
[24] L. Poladian, *Optical Fiber Technology*, Vol 5., pp. 215-222 (1999).
[25] A.M. Bruckstein, T. Kailath, *SIAM Review*, Vol. 29, No. 3, pp. 359-389 (1987).
[26] L.C. Wood, S. Treitel, *Proceedings IEEE*, vol.63, pp. 649-661 (1975).
[27] K.P. Bube, *IEEE Trans. on Geoscience and Remote Sensing*, Vol. 22, No. 6, pp. 674 (1984).
[28] M. J. Cole, W.H. Loh, R. I. Laming, M. N. Zervas, S. Barcelos, *Electron. Lett.* Vol. 31(17), pp. 1488-9 (1995).