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Synthesis of fiber gratings

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Abstract

The main design methods, developed so far for the synthesis of fiber Bragg gratings, are reviewed. We particularly focus on a very efficient method based on a differential layer-peeling algorithm and apply it to design high performance gratings.

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1. Introduction

High-speed high-capacity optical fiber communication systems depend critically on the availability of complex high performance filters for selection of closely packed wavelength-division-multiplexed channels or efficient compensation of link dispersion. The technology of UV-written fiber gratings has reached now the necessary maturity to implement these high performance filters. 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 variety of possibilities for the design of gratings with various degrees of accuracy. In this paper we review the different methods available for the synthesis of fiber gratings focusing, in particular, in a very efficient method based on a differential layer-peeling algorithm.

2. Fourier based methods

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 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 [2,3], enabling the design of practical fiber grating filters [4]. However, this synthesis approach is approximate in nature and, consequently, not reliable for the design of very complex and strong filters.

3. Integral methods

A second group of IS methods can provide exact solutions to the scattering problem, expressed in terms of integral equations. This type of solutions were first developed in the context of the inversion of the unidimensional Schrodinger equation, and then applied to the problem of two-component scattering. Gelfand and Levitan found the first inverse exact solution to the Schrodinger equation in terms of a linear integral equation [5]. Other IS integral equations have been obtained by Marchenko, Krein, Zakharov and Shabat, Gopinath and Sondhi, and Balanis [6-10]. These IS integral equations are usually derived using general arguments resulting from the causality of the propagation of signals.

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 [11]. Song and Shin [12] and subsequently Roman [13] employed this approach to design practical corrugated filters. 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 [14,15]. Several fiber grating devices, designed with this method, have already been fabricated proving the usefulness of the method [16]. However, the iterative solution of the GLM equations [17] 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 [7,18] 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 [19,20].

4. Differential methods

Finally, there exists a third group of exact IS algorithms called differential or direct methods [7,21-23]. These techniques, developed first by geophysicists like Robinson and Goupillaud [22], 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.

Recently we have developed a fiber grating synthesis algorithm based on a differential method [24]. 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 $L(t_0)$, 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 $L(t_0)$. The algorithm can be practically implemented in different ways. Initially, the grating has to be adequately discretised. Then, either mixed time-frequency or purely time leap-frogging strategies can be developed. The use of the transfer matrix method to solve the propagation problem proved convenient in both cases.

As the grating is calculated taking into account all the multiple reflections, the reconstruction process is exact. Figure 1 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.

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 $3 cm^{-1}$ and a total length of 1cm, giving rise to a resonant reflectivity of 0.99 (-20dB in transmission). Figure 2 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.

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.

5. Conclusion

Many different strategies are now available for the design of fiber gratings. In particular, we have presented an exact and very efficient differential method that outperforms previous techniques. We show that this method meets the requirements of versatility and flexibility needed by practical grating designs.

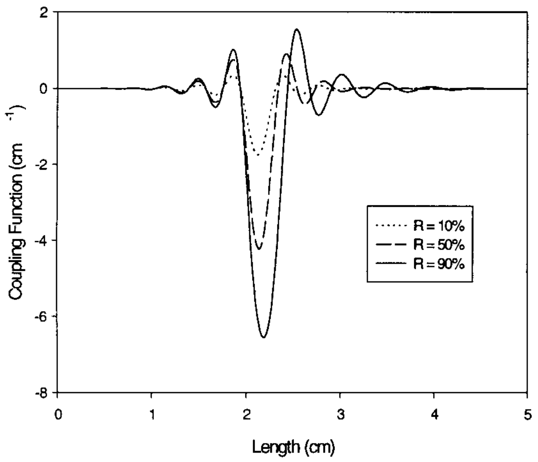

Figure 1: Coupling function of three ideal filters.

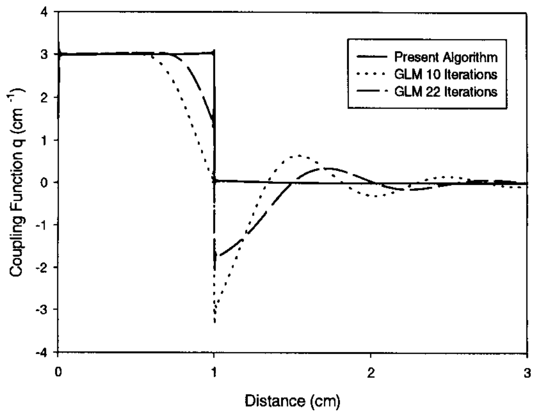

Figure 2: Reconstructed profile of a uniform grating.

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