Improved layer peeling algorithm for strongly reflecting fiber gratings

Liqun Huang (黄力群)[1], Weiping Huang (黄卫平)[2], Jinkuan Wang (汪晋宽)[1], and Guang Yang (杨 光)[1]

[1]*Department of Computer Engineering, Northeastern University at Qinhuangdao, Qinhuangdao 066004*

[2]*Department of Electrical Engineering, McMaster University, Hamilton, ON L8S 4K1, Canada*

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An improved algorithm based on the layer peeling (LP) method is proposed and demonstrated. The new method is shown to be effective for mitigating the impact of numerical errors on reconstruction of coupling function for strongly reflecting Bragg gratings. As examples, a flat-top dispersion-free fiber grating and a fiber-grating dispersion compensator are designed by the improved LP method. For a chirp grating, more accurate results are demonstrated in comparison with those obtained by the integral layer peeling (ILP) method.

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Bragg gratings based on circular optical fibers and planar optical waveguides are important elements in a variety of applications ranging from telecommunications, signal processing, to sensing[1,2]. As the fabrication technologies for realizing such gratings with complex distribution functions become more mature, there has been a strong interest in efficient and accurate numerical techniques for synthesis of the Bragg gratings to achieve desirable transmission and reflection spectral responses.

Several synthesis methods have been developed and reported based on the coupled-mode formalisms that describe the interaction of the counter-propagating waves due the continuous reflection by the gratings. When the reflectivity of the grating is relatively weak ($R \leq 30\%$), the structure of the grating can be calculated from the complex reflection spectrum by using a Fourier transform[3]. For gratings with a moderate reflectivity, the iterative solution of the Gel'fand-Levitan-Marchenko (GLM) equation can yield reasonably accurate results[4,5], but this method suffers from low computation efficiency. For highly reflecting Bragg gratings, the errors of the iterative solutions do not necessarily vanish, even when the number of iterations is considerably large. An efficient method based on the law of causality was proposed to reconstruct the grating profile, which is referred to as the layer peeling (LP) algorithm[6−8]. The implementation of the LP algorithm presented in Ref. [8], referred to as the frequency-domain layer peeling (FDLP) algorithm, is considered the most efficient inverse scattering algorithm for synthesis of Bragg gratings based on the coupled-wave formalism. The complexity of the FDLP algorithm is equal to $O(N^2)$, compared to $O(N^3)$ of the iterative solution to the GLM equation. However, when the grating reflectivity is high, the LP algorithm may fail to give accurate results[9]. Recently, a new method, the integral layer peeling (ILP) method, which is based on the solution of the GML integral equation by a layer-peeling procedure, was shown to lead to high accuracy in reconstructing a strongly reflecting Bragg grating[10].

In this paper, a simple modification to the FDLP algorithm is proposed and presented. It is demonstrated by way of example that this new algorithm is highly effective in mitigating the impact of numerical errors on the reconstruction of strongly reflecting fiber gratings. The new method does not require the solution of the GLM equation and therefore can be readily implemented and executed as efficiently as the FDLP method.

The discrete model for the Bragg gratings divides the entire grating into a series of discrete, complex reflectors with a distance Δ between the adjacent reflectors. The functions u_m and v_m represent the forward and the backward propagating fields, respectively. The reflection coefficient at the back of a reflector can be derived from that at the front of this reflector as[8]

$$r_{m+1}(\delta) = \frac{v_{m+1}}{u_{m+1}} = \exp(-i2\delta\Delta)\frac{r_m(\delta) - \rho_m}{1 - \rho_m^* r_m(\delta)}, \quad (1)$$

where the parameter ρ_m is the complex reflection coefficient of the mth grating segment of length Δ and $\delta = \beta - \beta_0$ is the wavenumber detuning factor with respect to the Bragg wavenumber. The function $r_m(\delta)$ represents the complex reflection spectrum at the front of the mth reflector by taking account of the multiple reflections from all discrete reflectors of $m+1$ and higher. The corresponding impulse response can be obtained by using Fourier transform,

$$h_m(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} r_m(\delta)\exp(-i\delta t)\mathrm{d}\delta. \quad (2)$$

Since the optical signal does not have sufficient time to propagate from the back reflectors, the impulse response $h_m(t)$ at time $t = 0$ only depends on the complex reflection coefficient of the mth reflector. Moreover, according to the definition of complex reflection coefficients, ρ_m should be equal to $h_m(0)$, hence we can determine ρ_m from Eq. (2). Based on this argument, the reflection coefficients of the back reflectors can be recursively computed using Eqs. (1) and (2) by the standard LP procedure.

The LP algorithm is based on the law of causality in the sense that, for $t < 0$, the impulse response $h_m(t)$ should be equal to zero. However, Eq. (1) is derived from an approximate discrete model. When the grating length Δ is sufficiently short, the well-known transfer matrix of the uniform Bragg grating may be further approximated by the product of two transfer matrices: one that describes a discrete reflector and the other that represents the pure propagation of the optical fields. In this model, the optical signal is reflected only at the front point of the mth grating segment. This approximation is valid for a short grating segment with weak reflection. In the case of strong Bragg gratings, multiple reflections within a segment cannot be neglected even for a very short grating length, and the errors caused by the approximation accumulates along the grating and becomes significant in extracting the grating profile, which leads to the errors in "peeling off" the front impulse response of the target spectrum, and hence $h_m(t)$, for $t < 0$, will be no longer equal to zero. The approximate model does not obey the causality relation in a strict sense. Consequently, the numerical errors arising from the violation of the causality law will accumulate along the gratings. When the reflectivity is high, the errors at the front of gratings increase rapidly, and the impulse response, for $t < 0$, will deviate considerable from zero and in turn make a strong impact on the reconstruction at the back of the gratings. For this reason, the FDLP algorithm may fail to yield accurate results when synthesizing Bragg gratings with strong reflectivity.

To overcome the shortcoming of the FDLP method, we propose a simple modification in the algorithm as follows. For every iteration process, the impulse response during $t < 0$ is replaced with zero, whereas the one during $t \geq 0$ is retained as obtained by the standard FDLP method. Subsequently, the reflection spectrum r_m is derived from the modified impulse response by using the inverse Fourier transform. The rest of the procedure is the same as the FDLP algorithm as described in Fig. 1 and hence the entire algorithm can be readily implemented.

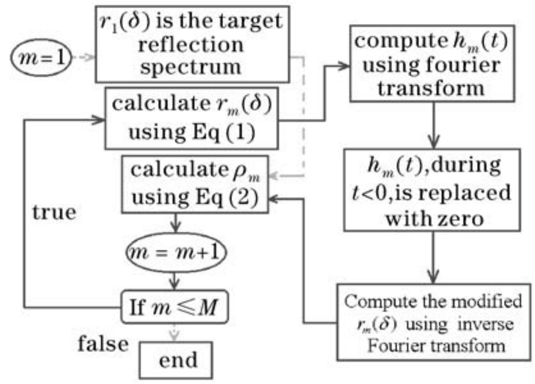

Fig. 1. The iterative procedure in the modified LP algorithm.

To validate the modified LP method, we apply it first to the design of a flat-top dispersion-free fiber Bragg grating with extremely high reflectivity (99.99999%). Figures 2(a)—(d) show the coupling coefficient function, the reflection spectrum, the transmission spectrum, and the time delay calculated by the modified LP, the ILP, and the FDLP methods, respectively. The target complex reflection spectrum was sampled over a bandwidth of 8 nm with a spectral resolution of 0.005 nm. The reflection and the transmission spectra are calculated for the synthesized gratings by using the transfer matrix method.

It is observed from Fig. 2(a) that there is considerable discrepancy between the grating profiles synthesized by the frequency-domain and the modified LP methods. On the other hand, the spectra corresponding to the grating synthesized by the modified LP method are much more closer to the target spectrum than that for the grating by the FDLP method, as evident from Figs. 2(b)—(d). The time delay ripple is less than 0.6 ps within the spectral

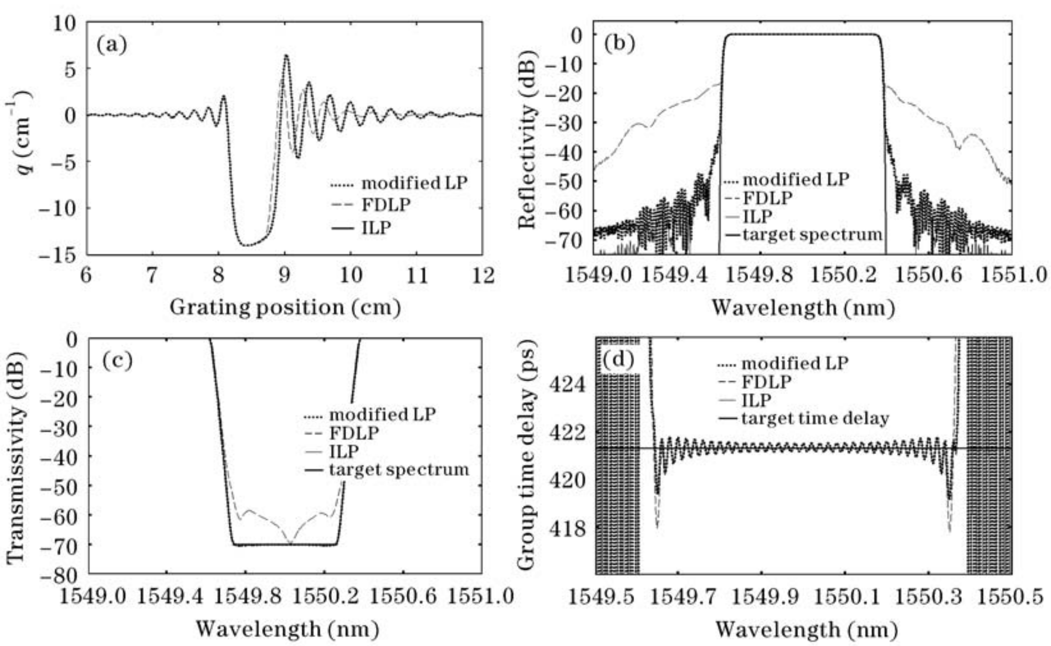

Fig. 2. A flat-top dispersion-free grating with the reflectivity of 99.99999%, reconstructed by the modified LP algorithm (dotted lines), the ILP algorithm (thin lines), and the FDLP algorithm (dashed lines), respectively. (a) Coupling coefficient function q; (b) reflection spectrum; (c) transmission spectrum; (d) time delay curve. The target complex reflection spectrum (thick lines) was sampled over a bandwidth of 8 nm with a spectral resolution of 0.005 nm.

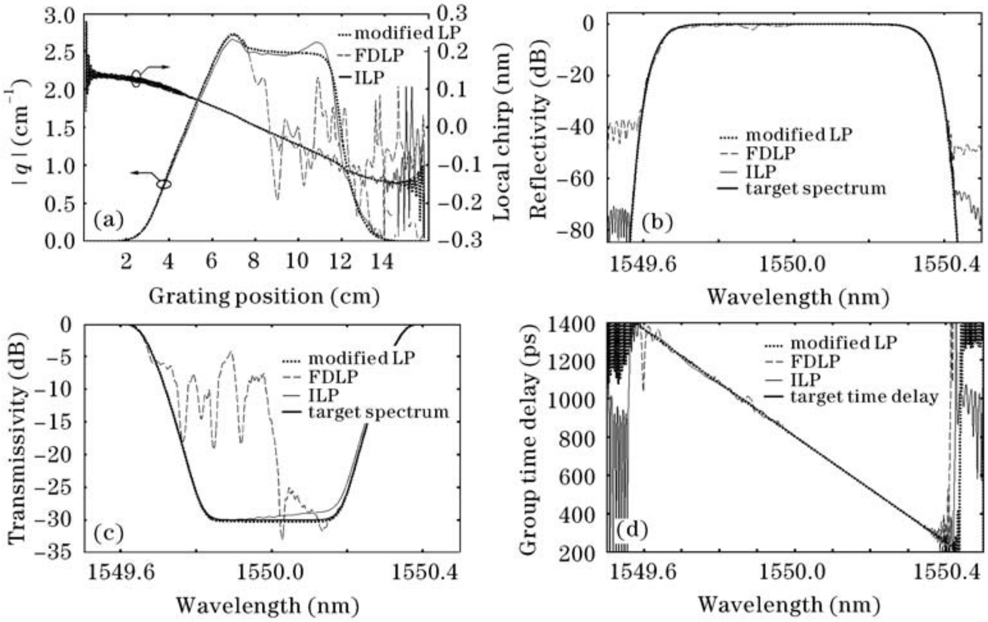

Fig. 3. A chirp grating with the reflectivity of 99.9%, reconstructed by the modified LP algorithm (dotted lines), the ILP algorithm (thin lines), and the FDLP algorithm (dashed lines), respectively, for compensating the chromatic dispersion of a standard SMF link of 80 km. (a) Coupling coefficient function q; (b) reflection spectrum; (c) transmission spectrum; (d) time delay curve. The target complex reflection spectrum (thick lines) was sampled over a bandwidth of 8 nm with a spectral resolution of 0.005 nm.

band of interest for these two methods. In particular, the grating designed by the FDLP algorithm has high out-off-band reflectivity and sharp transmission spectrum within the spectral band of interest. In this example, the grating profile reconstructed by the ILP method is almost the same as the one synthesized by the modified LP method. However, if the target spectrum of a uniform grating with high reflectivity was sampled over a narrower bandwidth with a lower spectral resolution, the results obtained by the ILP algorithm will be more accurate than the one calculated by the modified LP method.

In the second example, a chirp grating with a reflectivity of 99.9% is reconstructed by the modified LP, the ILP, and the FDLP methods, respectively. The synthesized grating is designed to compensate for the chromatic dispersion of a standard single-mode fiber (SMF) link with a length of 80 km. The results of the calculation are shown in Fig. 3. The target complex reflection spectrum was sampled over a bandwidth of 8 nm with a spectral resolution of 0.005 nm. Figure 3(a) shows that the FDLP and the ILP algorithms fail to give a proper grating profile in the case of the limited sampling bandwidth and spectral resolution. On the contrary, the grating synthesized by the modified LP algorithm has a correct spectrum response as evident from Figs. 3(b) and (c).

All the LP algorithms are implemented by using the Matlab language and run on a personal computer with a PENTIUM®III CPU at 866 MHz and a memory of 128 M. When the number of discrete sampling points is equal to 1600, the runtimes of the modified LP, the ILP, and the FDLP methods are 201.8, 202.3, and 195.5 s, respectively.

By constructing the new impulse response based on the law of causality for every iteration step, we have developed a modified LP algorithm for synthesis of strong Bragg gratings with high degree of accuracy and efficiency. The modified LP method has reduced the impact of the numerical errors on the reconstructed grating and hence more accurate than the FDLP algorithm. Compared with the ILP algorithm, the modified LP algorithm can obtain more accurate results in reconstructing a chirp grating with high reflectivity. However, for a uniform grating, the ILP method will lead to higher accuracy.

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