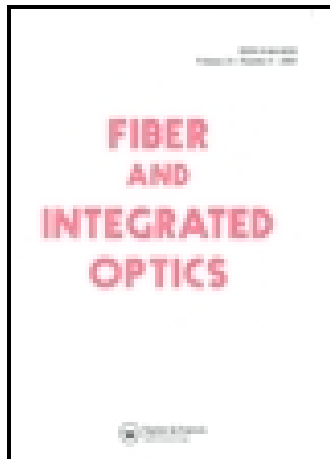


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### Long-Period Fiber Grating Filter Synthesis Using Evolutionary Programming

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## Long-Period Fiber Grating Filter Synthesis Using Evolutionary Programming

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*An innovative algorithm based on the evolutionary programming (EP) method is developed for the synthesis of long-period fiber gratings (LPGs). The proposed method exhibits a number of attractive features that prove to be effective for solving the inverse design problems of LPGs. The basics of EP are reviewed and the detailed programming procedures of the proposed algorithm are presented. A new mutation process using the concepts of leveled adjustment and adaptive weighting factor is proposed and verified. Comprehensive numerical results on designing practical LPG filters are presented to demonstrate the feasibility and the effectiveness of the proposed algorithm.*

**Keywords** long-period fiber gratings, inverse design, evolutionary programming

### Introduction

Long-period fiber gratings (LPGs) are fiber grating devices in which the guided core mode is coupled to the forward propagating cladding modes through the periodic photo-induced index grating. They have found important applications in fiber communication and fiber sensing systems, in which they act as gain flattening filters, band-rejection filters, mode converters, and high-sensitivity fiber sensors [1–5]. In the literature, the synthesis methods for fiber gratings (LPGs and FBGs) can be roughly classified into two categories: (1) the inverse scattering methods [6–12]; and (2) the optimization methods [13–15]. The inverse scattering methods directly calculate the required grating profile from the FBG reflection spectra or the LPG transmission spectra by solving the mathematical inverse problem,

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while the optimization methods directly minimize the difference between the targeted and the synthesized spectra. The minimization can be performed by usual optimization algorithms or, in particular, the genetic algorithms (GA) [13, 14]. When compared to the inverse scattering methods, the optimization approaches do not need to worry about the ambiguity problem caused by the unknown phase spectrum and have the potential capability of obtaining an index profile that can be more practically implemented by properly imposing additional constraints on the solution to be found.

In the present articles, a new approach to the solution of fiber grating synthesis problems (with emphasis on synthesizing LPG) is developed. The new method is an optimization approach based on the evolutionary programming (EP) algorithm. Basically, EP and GA are two important branches in the family of evolutionary algorithms (EA). When compared to traditional optimization methods, stochastic search and optimization approaches like EP and GA are more robust for searching global minimums and are generally more straightforward to apply. When compared to the GA algorithms for fiber grating synthesis, our EP algorithm only uses the mutation process of continuous variables and without using the binary coding and crossover processes. Based on a preliminary study on designing a 4-cm single-period, multi-phase-shifted LPG to be used as the gain-flattening filter for the entire C-band [15], we find that such a simplified evolutionary algorithm may help to solve complicated problems in a higher convergence speed as well as higher reliability. To further investigate the performance and robustness of the proposed EP algorithm, in this study comprehensive simulation studies on designing various practical LPG filters have been carried out. The results, including a Butterworth flat-top-passband filter, a linear-shape filter, and a 5-cm EDFA gain-flattening filter that has better performance than in Lee and Lai [15] have been presented. A simple numerical error-tolerance analysis regarding the grating performance degradation due to possible phase-shift errors in practical fabrication has also been carried out for the 5-cm EDFA gain-flattening filter design example.

### Evolutionary Programming Synthesis of LPGs

In the literature there have been various types of EA algorithms that differ in the procedures of initialization, selection, mutation, and recombination [16–18]. Among them, the evolutionary programming (EP) and the genetic algorithms (GA) are the two important branches. The EP approach was originally developed by Fogel et al. [18] in the 1960s. They used a quite simple model based on the concept of finite-state machines and used the mutation as the only operator. This simple model has been extended by Fogel and others later such that the current EP algorithms can directly handle a large number of variables on any data structure.

To be more specific, let us consider the problem of finding the global minimal of a multi-dimensional error function:

$$\varepsilon(\vec{\kappa}) : \mathfrak{R}^m \rightarrow \mathfrak{R} \quad (1)$$

For our case of LPG synthesis, the complex vector variable  $\vec{\kappa}$  the “individual”) is a vector representation for the coupling coefficient function  $\kappa(z)$  of the LPG and the error function  $\varepsilon(\vec{\kappa})$  represents the difference between the targeted and the synthesized LPG transmission spectra:

$$\varepsilon(\vec{\kappa}) = \sum_{\ell=1}^n |T_{\ell}^{(\text{target})} - T_{\ell}(\vec{\kappa})| \quad (2)$$

Here we have divided the spectral coordinate into  $n$  discrete wavelengths and try to approach the desired transmission coefficients at these wavelengths. We have also divided the grating into  $m$  sections with equal length and every section is assumed to be a uniform LPG. The synthesized LPG transmission spectrum  $T_\ell(\vec{\kappa})$  can be directly calculated by solving the following coupled mode equations for LPGs:

$$\frac{dA^{co}(z)}{dz} = i\delta A^{co}(z) + i\kappa(z)A^{cl}(z) \quad (3)$$

$$\frac{dA^{cl}(z)}{dz} = -i\delta A^{cl}(z) + i\kappa^*(z)A^{co}(z) \quad (4)$$

Here  $A^{co}(z)$  and  $A^{cl}(z)$  represent the core and the cladding modes respectively,  $\delta = (1/2)[\beta^{co} - \beta^{cl} - 2\pi/\Lambda] = \pi \Delta n_{eff}(1/\lambda - 1/\lambda_D)$  is the detuning parameter,  $\Lambda$  is the grating period,  $\lambda_D$  is the designed phase-matched wavelength,  $\Delta n_{eff}$  is the difference of the effective indices for the core and cladding modes,  $\beta^{co}$  and  $\beta^{cl}$  are the propagation constants, and  $\kappa(z) = \eta\pi \Delta n(z)/\lambda_D$  is the coupling coefficient distribution function with  $\Delta n(z)$  being the envelope function of the grating index modulation and  $\eta$  is overlapping factor. Since the  $\kappa(z)$  from our design will be a piecewise uniform function, the transfer matrix method for solving the coupled mode equations are chosen to efficiently calculate the synthesized spectra.

With the above definition for the problem to be solved, our EP algorithm uses the following steps to find the optimal solution.

1. *Definition of the fitness function:* In our calculation the fitness function is simply defined to be the inverse of the error function.

$$F(\vec{\kappa}) = \frac{1}{\varepsilon(\vec{\kappa})} \quad (5)$$

2. *Initialization:* A set of  $N$  “parents”  $\{\vec{\kappa}_i : i = 1, 2, \dots, N\}$  is initialized randomly with the component values selected from a feasible range in each dimension.
3. *Selection:* After calculating the fitness values for every parent, a new set of  $N$  “healthier” individuals are generated via a probability selection algorithm described below. A distribution chart is formed according to the normalized fitness values of the parent set and then  $N$  times random selection are made to form the new set. Since the area of each division in the chart is proportional to the fitness values, the healthier  $\vec{\kappa}_i$  in the parent set will have a higher probability to survive.
4. *Mutation:* In our algorithm, a leveled sectional mutation process is used. The grating is divided into  $m$  sections with equal length. Every section is assumed to be uniform and one of the sections is randomly chosen for performing the mutation process. To be more specific, for a given  $\vec{\kappa}_i$ , we randomly choose one of its (spatial) components  $\kappa_{i,p}(z) = |\kappa_{i,p}|e^{i\phi_{i,p}}$  and change it into

$$\hat{\kappa}_{i,p} = |\kappa_{i,p} + \delta\kappa_{i,p}|e^{i(\phi_{i,p} + \delta\phi_{i,p})}, i = 1, 2, \dots, N \quad (6)$$

Here  $\delta\kappa_{i,p}$  and  $\delta\phi_{i,p}$  are, respectively, the magnitude and phase mutation functions, and in our algorithm they are determined by the following expressions:

$$\delta\kappa_{i,p} = r_{M,i} \times W_i \quad (7)$$

$$\delta\phi_{i,p} = r_{s,i} \times W_i \quad (8)$$

where  $r_{M,i}$  and  $r_{S,i}$  are two random variables between  $-1$  and  $1$ , and  $W_i$  is a weighting factor calculated according to

$$F^q(\vec{\kappa}_i) \times W_i = C \quad (9)$$

Here  $C$  and  $q$  are adjustable numbers called the mutation parameters.

5. *Iteration*: The processes of selection and mutation are repeated until a satisfied solution is reached or the number of generations becomes greater than the pre-specified limit.

Finally, to summarize this section and to provide a clearer picture, we provide the flow chart shown in Figure 1 to accurately describe the whole algorithm. We also want to emphasize again that under the coupled mode equation model, the coupling coefficient function is proportional to the envelope of the quasi-sinusoidal refractive index modulation of the grating:  $\kappa(z) = \eta\pi \Delta n(z)/\lambda_D$ . For a rough estimate, by multiplying a factor of  $\sim 5 \times 10^{-4}$  to the corresponding coupling coefficient values (in units of  $1/\text{mm}$ ), one can get the rough number of refractive index modulation for typical fibers. The actual multiplication factor will depend on the overlap integral of the fiber modes. If in actual fabrication the refractive index modulation profile is not sinusoidal, then the value from the design will only represent the phase-matching component of the LPG grating and a further design step is needed to compute the actual index modulation based on the assumed shape of the index modulation profile (i.e., sinusoidal, on-off, or others). This part of the design can be easily carried out in many ways and thus will not be presented here. The last point to notice is that in Equations (3) and (4) we have assumed the  $dc$  component of the index modulation is constant through the whole grating. This is another important point for actual fabrication of these phase-shifted devices.

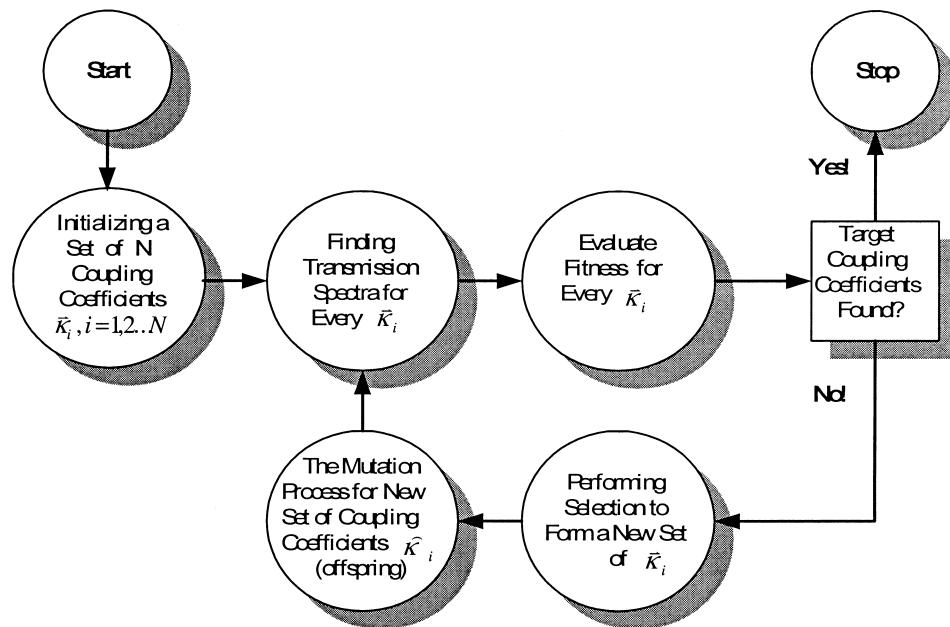


Figure 1. Flow chart of the proposed EP algorithm for LPG.

## Numerical Examples and Discussions

In order to evaluate the effectiveness of the proposed EP-based synthesis algorithm, in this section we will present several numerical examples for designing practical LPG filters.

### *Reconstruction of a linear Chirped LPG*

As a first test example, we will take a known Gaussian-apodized, linear chirped LPG (LCLPG) and calculate its transmission spectrum. The spectrum is then used as the starting point for reconstruction by the EP method. The original Gaussian-apodized, linear chirped LPG has the grating length  $L = 200$  mm and maximum coupling coefficient  $= 0.08\text{mm}^{-1}$ . The FWHM of the coupling coefficient profile is 100 mm, as shown by the solid line in Figure 2(b). The core and cladding mode effective indices are assumed to be  $n_{co} = 1.456$  and  $n_{cl} = 1.446$ , respectively; the grating period is  $\Lambda = 155$   $\mu\text{m}$ , the grating resonance wavelength  $\lambda_D = 1550$  nm, and the grating chirping rate is 0.05 nm/mm. The calculated transmission spectrum is shown in Figure 2(a) by the solid line. For reconstruction using the EP method, we choose  $m = 20$ ,  $\Delta z = 10$  mm and  $n = 401$ . The reconstructed spectrum is also shown in Figure 2(a) by the dashed line. The two spectra are almost indistinguishable on this plot, which indicates that we have done a good job in the inverse synthesis. In Figure 2(b) we show both the reconstructed and the original coupling coefficient profiles. One can see that the two profiles are very different. This is a good example to demonstrate the ambiguity caused by the unknown transmission phase spectrum. In this test example, the mutation parameters  $C$  and  $q$  are set to be  $10^{-4}$  and 1, respectively.

### *Butterworth filter*

In this example, we will synthesize a fourth-order Butterworth filter that has a flat transmission dip. Such flat-band filters can be used as the band-rejection filters in fiber communication and fiber sensing systems where their flat-band properties can achieve better performance.

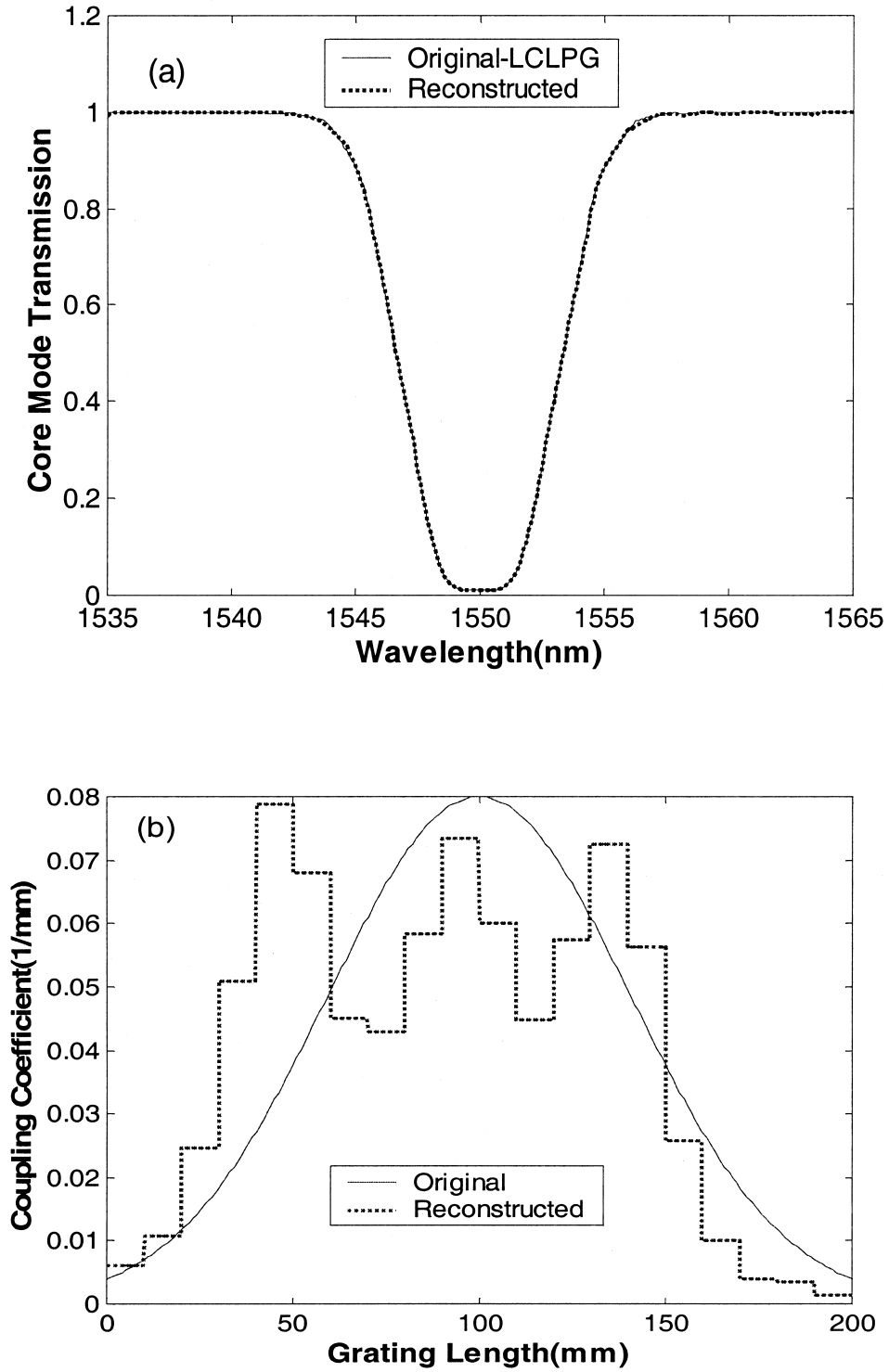
The ideal cladding mode transmission of the  $S$ -th order Butterworth filter is:

$$T_{cladding}(\delta) = \frac{T_{\max}}{1 + (\delta/\delta_c)^{2S}} \quad (10)$$

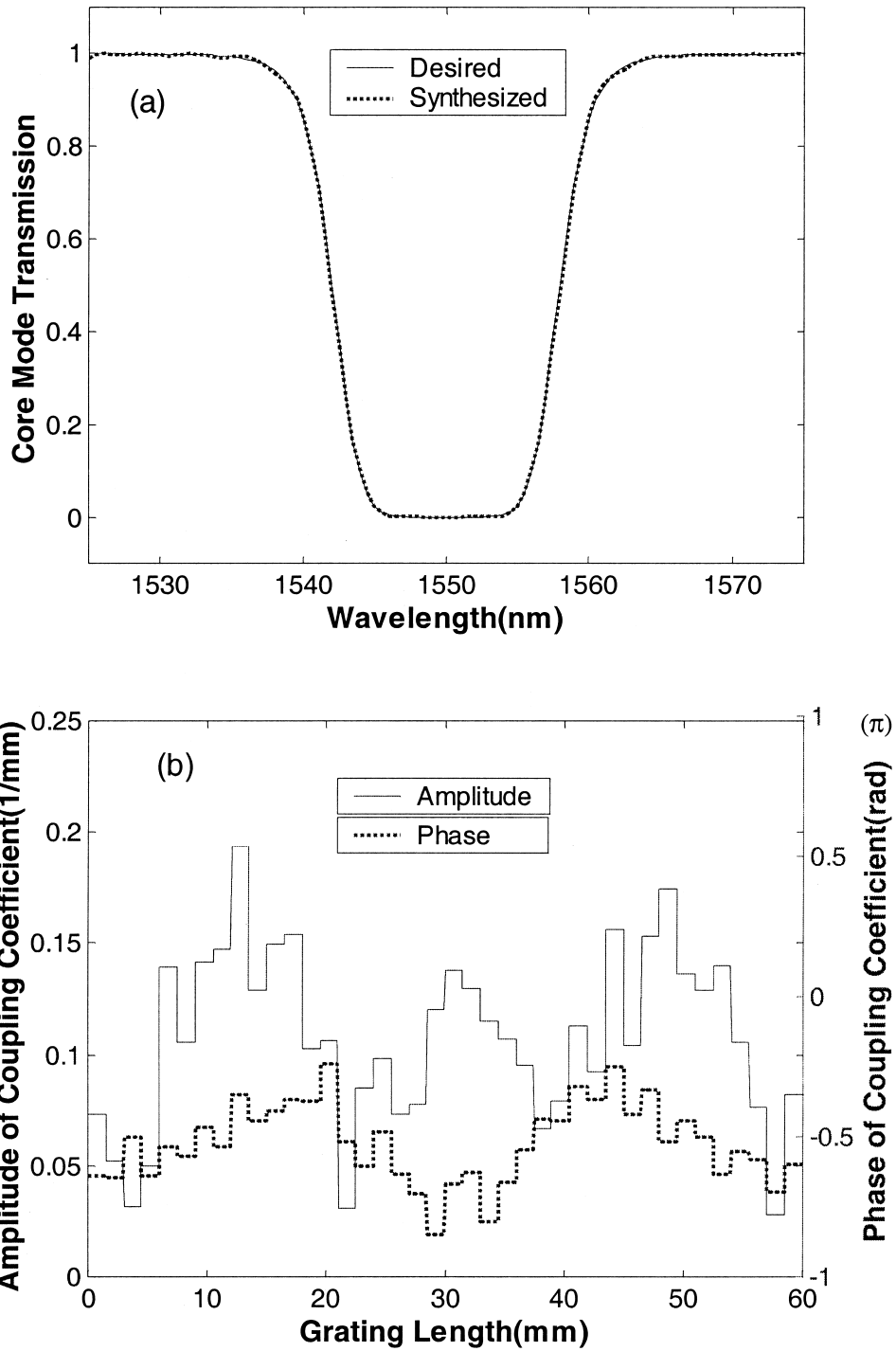
Here  $T_{\max}$  is the maximum transmission,  $\delta$  is the detuning parameter,  $\delta_c$  is the filter width at half-power points, and  $S$  is the order number. We will choose the maximum transmission  $T_{\max} = 1$ ,  $n_{co} = 1.456$ ,  $n_{cl} = 1.446$ ,  $\Lambda = 155$   $\mu\text{m}$ ,  $\lambda_D = 1550$  nm, the grating length  $L = 60$  mm,  $m = 40$ ,  $\Delta z = 1.5$  mm,  $n = 401$ ,  $|\delta_c| = 1.05$   $\text{cm}^{-1}$ , and  $S = 4$ . Figure 3(a) shows the targeted and the designed transmission spectra for the fourth-order Butterworth filter. Figure 3(b) shows the amplitude and phase distribution of the coupling coefficient function calculated by the algorithm. In this example, the mutation parameters  $C$  and  $q$  are set to be  $5 \times 10^{-4}$  and 1, respectively. One can see that the synthesized results can be quite close to the desired spectrum.

### *Linear Filter*

In this example we will design an LPG filter with a linear cladding mode transmission response within a certain range of wavelength. Such a linear transmission filter has found



**Figure 2.** (a) The reconstructed and original linear chirped LPG core mode transmission spectra; (b) the reconstructed and original coupling coefficient profiles.



**Figure 3.** (a) Target and designed transmission spectra of fourth-order Butterworth filter; (b) designed coupling coefficient profile.



applications in many fiber sensing systems in which the wavelength modulation of the optical signal is converted into the intensity modulation after passing through the element and can be readily detected by a photo-detector.

The target spectrum of a linear transmission grating can be described by

$$T_{cladding}(\xi) = \begin{cases} -T_{\max} \times [(\xi/\xi_0) - 1], & 0 < \xi < \xi_0 \\ 0, & \text{elsewhere} \end{cases} \quad (11)$$

Here  $\xi = \lambda_D - \lambda$  is defined as the difference between the optical wavelength and the designed phase-matching wavelength. In this example we choose the maximum transmission  $T_{\max} = 0.8$ , the grating length  $L = 120$  mm,  $n_{co} = 1.456$ ,  $n_{cl} = 1.446$ ,  $\Lambda = 154$   $\mu\text{m}$ ,  $\lambda_D = 1540$  nm,  $m = 40$ ,  $\Delta z = 3$  mm,  $n = 201$ , and  $\xi_0 = 20$  nm. The mutation parameters  $C$  and  $q$  are set to be  $5 \times 10^{-4}$  and 1, respectively. In Figure 4(a) we show the desired and the synthesized spectra. In Figure 4(b) the amplitude and phase distributions of the coupling coefficient function calculated by the EP algorithm are illustrated. It can be seen that pretty good linear response within a wavelength range of about 18 nm can be readily achieved.

### EDFA Gain-Flattening Filter

The erbium-doped fiber amplifier (EDFA) has emerged as a major enabler in the development of worldwide fiber-optics networks. For applications in DWDM systems, it is desirable to have a flat gain curve to ensure the power of every channel can remain roughly equal even after long-distance propagation and cascading amplifications. One way to flatten the EDFA gain spectrum is by using a gain-flattening filter. Since the LPG can be used as a wavelength dependent loss element with very low back reflection, it is quite suitable for this application.

In the literature, EDFA gain flattening utilizing blazed gratings or two (or three) LPGs has been demonstrated [1, 19]. In this example we try to design a single-period, multi-phase-shifted LPG that can be used as the gain-flattening filter for the entire C-band. The grating length is set to be  $L = 50$  mm,  $m = 25$ ,  $\Delta z = 2$  mm,  $n = 401$ , and the mutation parameters  $C$  and  $q$  are set to be  $8 \times 10^{-4}$  and  $1/2$ , respectively. The core and cladding mode effective indices are assumed to be  $n_{co} = 1.456$  and  $n_{cl} = 1.446$ , respectively. The grating period is  $\Lambda = 155.6$   $\mu\text{m}$  and the resonance wavelength is  $\lambda_D = 1556$  nm. Figure 5(a) shows the target spectrum and the spectrum from our design. Figure 5(b) shows the EDFA gain spectrum before and after flattening. The studied spectrum can be flattened to be less than  $\pm 0.06$  dB variation within the bandwidth of 30 nm and less than  $\pm 0.3$  dB variation over the entire 40nm bandwidth. Figure 5(c) shows the designed amplitude and phase profiles of the coupling coefficient function across the grating. This proves that good EDFA gain flattening for the entire EDFA band in fact can be achieved with a 5-cm long single-stage LPG filter that is properly designed. Finally, to conclude this section, in Figure 5(d) we show the results of a simple tolerance analysis for the phase-shift errors when fabricating the EDFA gain-flattening filter designed in the last example. Random phase errors equivalent to maximum  $\pm 50$  nm random position errors are introduced between adjacent sections and the simulated transmission coefficient variation for the typical sample shown in the figure is less than  $\pm 0.14$  dB. This simple analysis provides a rough estimate about the required fabrication precision of such single-period, multi-phase-shifted LPG devices designed in this section. Since such a phase-shift error tolerance is much larger when compared to the phase-shifted FBGs (i.e., dispersionless

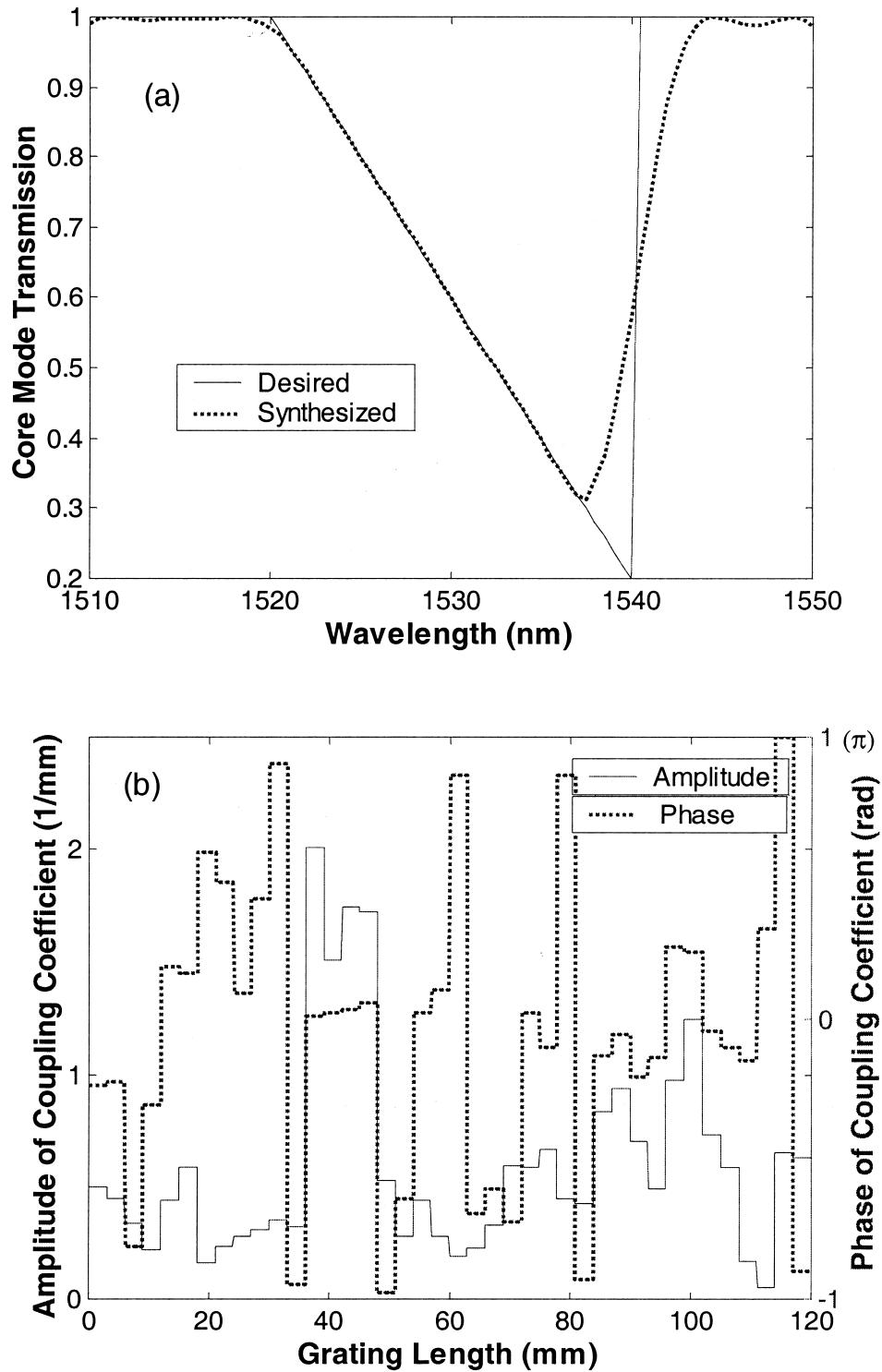
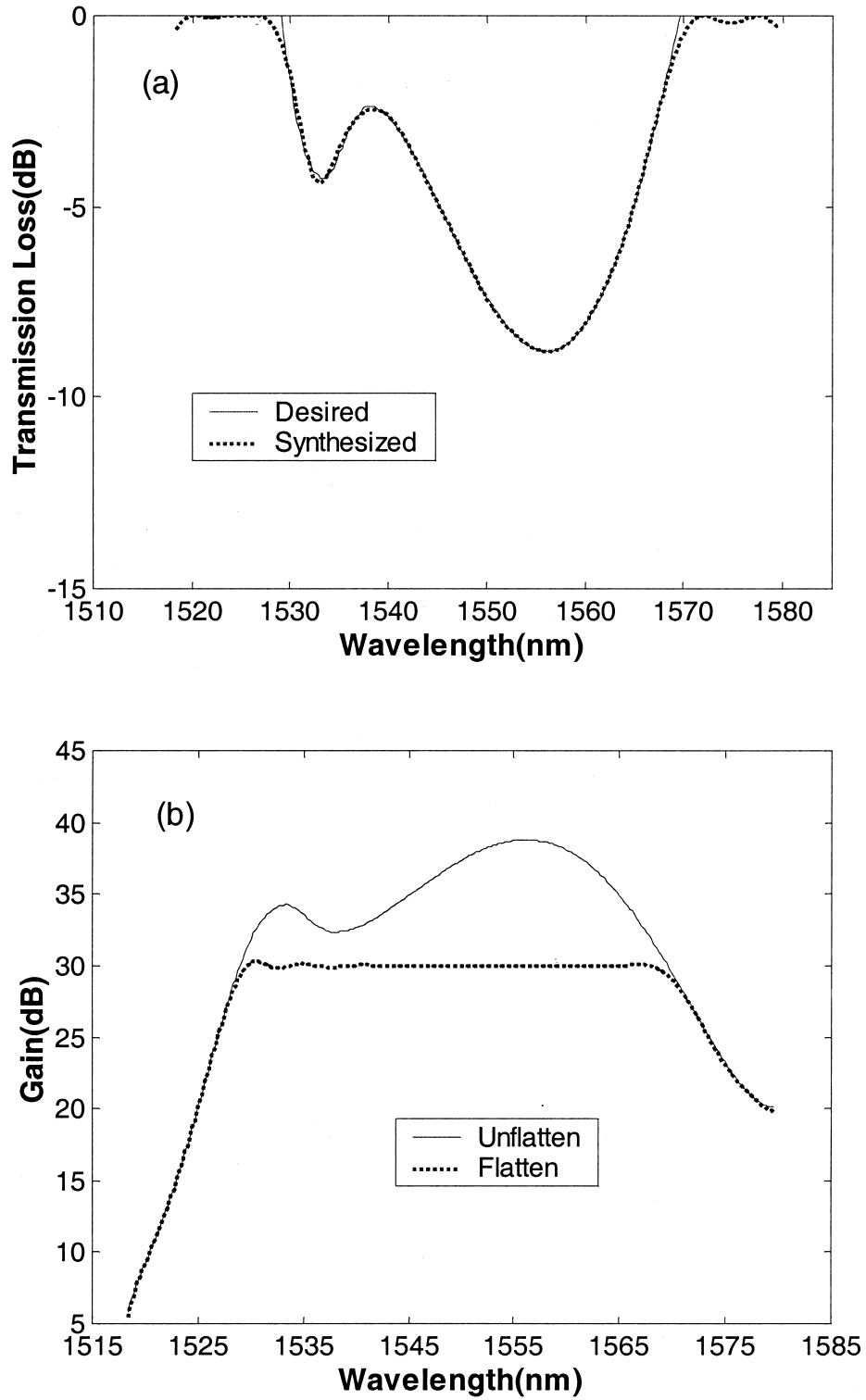


Figure 4. (a) Target and designed transmission spectra of linear filter; (b) designed coupling coefficient profile.



**Figure 5.** (a) Target and designed transmission spectra of EDFA gain flattening filter; (b) flattened gain-profile (dotted line) and unflattened gain profile of EDFA (solid line).

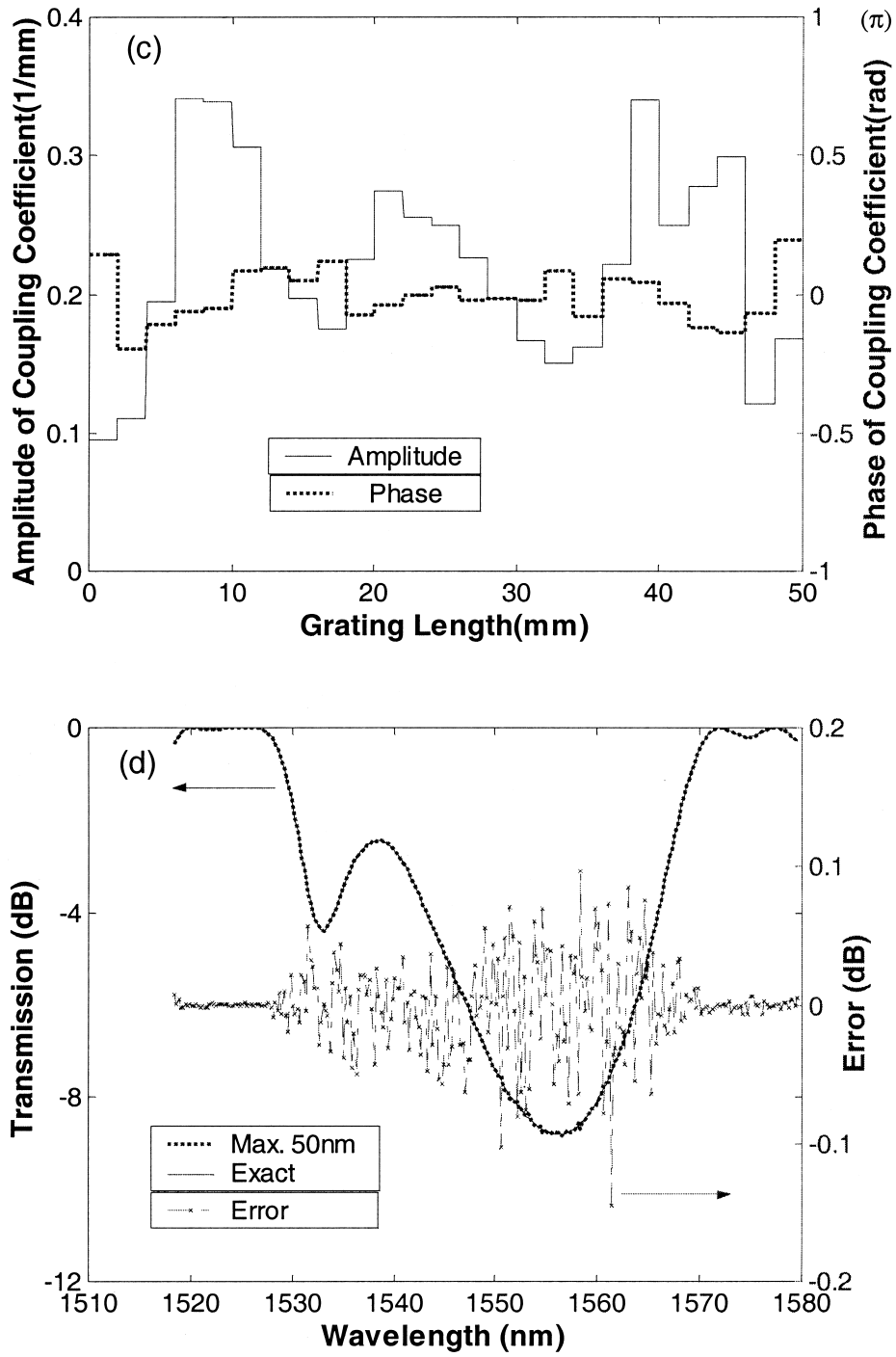


Figure 5. (c) designed coupling coefficient profile; (d) spectra with 50 nm random position errors between adjacent sections.

FBGs), which have been successfully fabricated by step-scan exposure, we believe it should also be quite feasible to actually fabricate the designed single-period multi-phase-shifted LPG devices presented in this article.

## Conclusions

We have developed a novel LPG synthesis method by using a revised evolutionary programming (EP) algorithm. The feasibility and effectiveness of the proposed EP-based synthesis approach have been verified by going through several practical LPG filter design examples. Simulation results have shown that the proposed new EP-based LPGs synthesis method is very effective and robust, which can be further developed to construct a powerful toolbox for practical design of fiber gratings. The coupling coefficient function obtained from the proposed EP algorithm with the modified mutation process tends to have lower values and less complicated profiles when compared to the results from inverse scattering methods. Although the actual fabrication of the designed LPG devices does require accurate phase shifts between adjacent sections, a simple tolerance analysis has shown that it should be quite feasible to meet the required phase-shift accuracy with the state-of-art fiber grating exposure systems.

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### Biographies

**Dr. Cheng-Ling Lee** was born in Yuanlin, Taiwan, on April 13, 1967. She has been working with the Department of Electro-Optical Engineering, National Lien-Ho Institute of Technology, Taiwan, since she received her MS degree in 1991. After several years working as a teacher and a research student, she obtained her Ph.D. degree from the Institute of Electro-Optical Engineering, National Chiao-Tung University, Taiwan, in 2003. Her main employment experiences include the R&T work in NLHIT, Taiwan; many years in teaching technical courses in the fields of optical thin film coating and fiber optics in NUU, Taiwan. She is now a researcher and an associate professor with the Department of Electro-Optical Engineering, National United University, Taiwan. Her special fields of interest include optical thin film coating, fiber grating synthesis, optimization algorithms, and fiber grating sensor applications.

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