Evolutionary Programming Synthesis of Optimal Long-Period Fiber Grating Filters for EDFA Gain Flattening

C. L. Lee and Y. Lai

***Abstract*—An innovative long-period fiber grating (LPG) synthesis method based on the stochastic evolutionary programming (EP) algorithms is demonstrated to be effective for designing optimal LPG filters. Synthesis of a single-stage LPG filter for the entire *C*-band erbium-doped fiber amplifier (EDFA) gain flattening is used as an example to show the feasibility and the effectiveness of the proposed algorithm. To the best of our knowledge, this is the first demonstration that good EDFA gain flattening for the entire band can be achieved with a single-stage LPG filter that is properly designed.**

***Index Terms*—Erbium-doped fiber amplifier (EDFA) gain flattening, evolutionary programming (EP), long-period fiber gratings (LPGs).**

I. INTRODUCTION

FIBER gratings are photoinduced fiber devices that have found many applications in optical communication and optical sensing. Among various fiber grating devices, the long-period fiber gratings (LPGs), in which the guided core mode is coupled to one or several forward propagating cladding modes, have been demonstrated to be useful in applications like band-rejection filters, high sensitivity sensors, mode converters, and especially erbium-doped fiber amplifier (EDFA) gain flattening filters [1]. In recent years, several synthesis or inverse design methods to determine the required fiber grating index modulation profile corresponding to a given reflection spectrum have been developed quite successfully for fiber Bragg gratings (FBGs) [2]–[4]. Among these methods, the layer-peeling implementation of the inverse scattering method can effectively calculate the required grating index profile from the targeted reflection spectrum and is, thus, widely used in designing special FBG devices for fiber communication applications. For designing transmission-type fiber grating filters like LPGs, the inverse scattering method is still applicable [5]–[7] and a solution can be uniquely determined if an additional assumption about the filter properties (the under-coupled assumption) is used [6]. In the literature, another class of synthesis methods for FBGs are the optimization methods based on variational or genetic algorithms (GA) [2]. A combinational use of the inverse scattering and genetic optimization methods for designing binary LPGs have also been reported recently [8]. Compared to the inverse scattering method, the optimization approaches have the potential capability of obtaining an index profile that can be more practically implemented by imposing additional constrains on the solution to be found.

In this letter, a novel approach to the problems of synthesizing long-period fiber gratings is proposed. The new method is based on the evolutionary programming (EP) algorithm which employs the population-based optimization mechanism. EP and GA are two important branches in the family of evolutionary algorithms (EA), which are a class of probabilistic search and optimization algorithms gleaned from the organic evolution process. Compared to the genetic algorithms for fiber grating synthesis that have been reported in the literature, we find our EP algorithm has a higher convergence velocity as well as higher reliability. This may be due to the fact that we only use the mutation process of continuous variables in the EP algorithm and without using the binary crossover process. To verify the effectiveness of the proposed approach, the EP-based synthesis algorithm together with the transfer-matrix model based on the couple-mode theory for calculating the transmission spectra of LPGs are implemented by using the Matlab software package. The performance of the algorithm is tested by designing a single-stage LPG filter for the entire *C*-Band EDFA gain flattening. It is worth to note that the coupling coefficients obtained from the proposed algorithm are normally less complex and easy to implement in practice.

II. SYNTHESIS OF LPGs USING EP

Evolutionary programming (EP), an important branch in the field of EA, was originally developed by Fogel *et al.* [9] in the 1960s. At that time they used a quite simple model based on the finite-state machine concept and used mutation as the only operator. The EP algorithm used in this letter can be briefly described as follows. Starting from a population of N "individuals" (parents), a new set of N individuals is generated through some selection rules and then a set of N offsprings is generated through a mutation process. This set of offsprings is then used as the parents for next iteration. Since the main objective of the synthesis is to find a coupling coefficient profile $\kappa(z)$ that produces a transmission spectrum as close as possible to the target spectrum, an "individual" is thus a particular coupling coefficient profile function $\kappa(z)$, which will be descretized later and represented by a complex vector $\overline{\kappa}$. To complete the algorithm, one then needs to define the error function and the fitness func-

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Manuscript received May 20, 2002; revised August 1, 2002. This work is supported in part by the National Science Council of the Republic of China under Contract NSC 91-2215-E-009-026, the Ministry of Education of the Republic of China, and the Lee Center at National Chiao-Tung Univervisity.

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Digital Object Identifier 10.1109/LPT.2002.803910.

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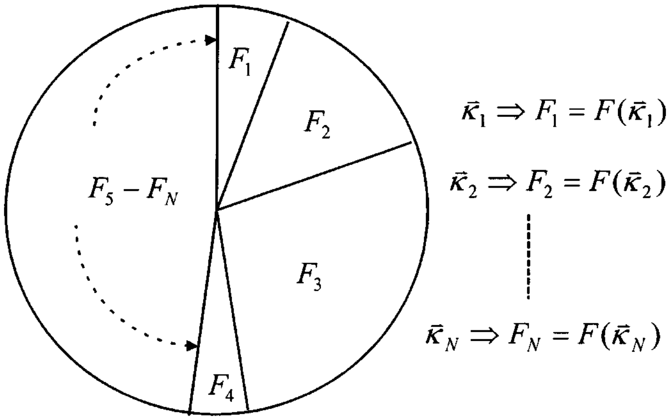


Fig. 1. The distribution chart for making selection.

tion for performing the selection as well as the mutation processes. The details are described in the following.

- *Definition of Error Function and Fitness Function:* For our problem, we divide the spectral window into n discrete wavelengths and try to approach the desired transmission coefficients at these wavelengths. So the error function for the ith individual is defined as

$$\Im(\vec{\kappa}_i) = \sum_{\ell=1}^{n} \left|T_{\text{target},\,\ell} - T_{i,\,\ell}\right|, \qquad i = 1, 2, \ldots, N. \quad (1)$$

The fitness function is simply defined to be the inverse of the error function

$$F(\vec{\kappa}_i) = \frac{1}{\Im(\vec{\kappa}_i)}, \qquad i = 1, 2, \ldots, N. \quad (2)$$

Here, $T_{i,\,\ell}$ is the transmission coefficient produced by ith individual $\vec{\kappa}_i$ at the ℓth wavelength and $T_{\text{target},\,\ell}$ is corresponding target value.

- *Selection:* After the set of fitness values is calculated, the new set of "healthier" coupling coefficient candidates can be selected via a probability algorithm in which the $\vec{\kappa}_i$ with a higher fitness value will has a higher probability to be chosen. This is done by defining a distribution chart formed according to the normalized fitness values as shown in Fig. 1 and then perform N-times random selection to form a new set of $\vec{\kappa}_i$. Since the area of each division in the chart is proportional to the fitness values, the "healthier" $\vec{\kappa}_i$ will have a higher probability to be chosen. It should also be noted that the same $\vec{\kappa}_i$ may be selected more than once through this selection process.

- *Mutation:* The mutation process is an important part in an EP algorithm. For our case we basically add a normally distributed random variable as a perturbation to generate a new offspring from a parent. For a given coupling coefficient profile $\vec{\kappa}_i$, we randomly choose one of its (spatial) components $\kappa_{i,\,j}(z) = |\kappa_{i,\,j}|e^{i\phi_{i,\,j}}$ and change it into

$$\hat{\kappa}_{i,\,j} = |\kappa_{i,\,j} + \delta\kappa_{i,\,j}|\, e^{i(\phi_{i,\,j} + \delta\phi_{i,\,j})}, \qquad i = 1, 2, \ldots, N. \quad (3)$$

Here, $\delta\kappa_{i,\,j}$ and $\delta\phi_{i,\,j}$ are, respectively, the magnitude and phase mutation functions and are determined by the following expressions:

$$\delta\kappa_{i,\,j} = r_{M,\,i} \times W_i \quad (4)$$

$$\delta\phi_{i,\,j} = r_{s,\,i} \times W_i \quad (5)$$

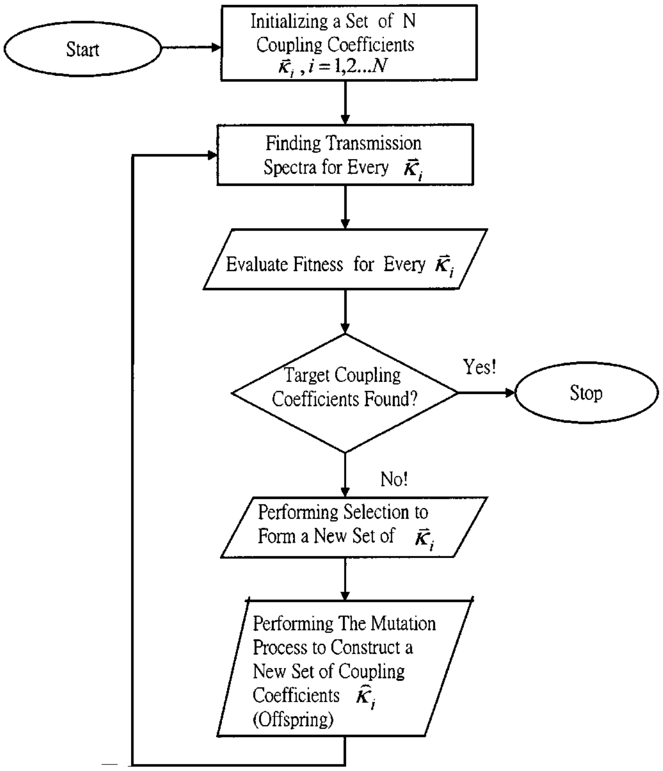


Fig. 2. Flowchart of the proposed EP algorithm for LPG.

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

$$F^q(\vec{\kappa}_i) \cdot W_i = C. \quad (6)$$

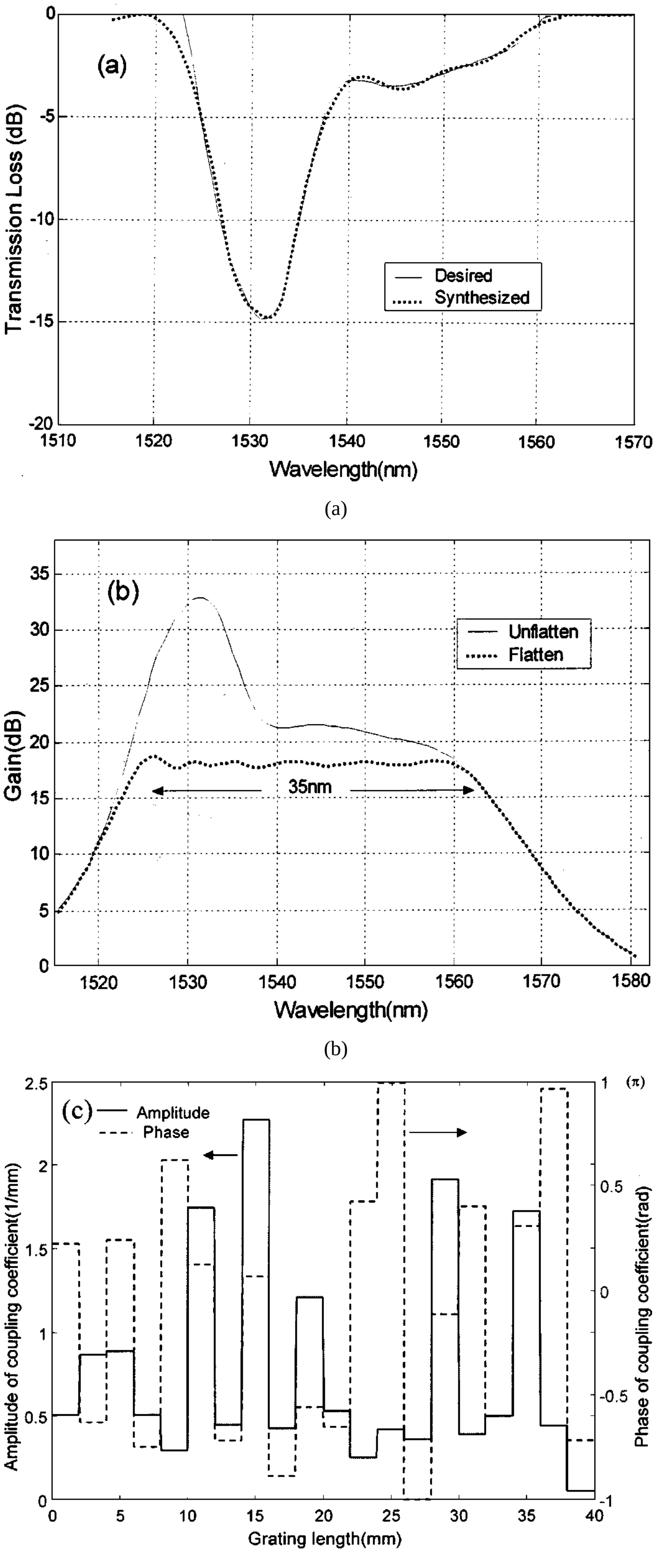
Here, C and q are adjustable numbers called the mutation parameters. It should be noted that the individual with a higher fitness value will be assigned a smaller weighting factor according to (6).

To summarize this section, we describe the proposed EP algorithm by the flow chart shown in Fig. 2. In Section III, we shall use this algorithm to design LPG filters for EFDA gain flattening applications.

III. NUMERICAL EXAMPLE AND DISCUSSION

To evaluate the effectiveness of the proposed EP-based synthesis algorithm, a practical design example of EDFA gain flattening filter is presented in this section. The EDFA has emerged as a major enabler in the development of fiber-optics networks. For applications in dense wavelength division multiplexing (DWDM) systems, it is desirable to have a flat optical 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 several LPGs has been demonstrated. In this letter we have succeeded in designing a single-stage LPG that can be used as the gain-flattening filter for entire *C*-band. The filter



(a)

(b)

(c)

Fig. 3. (a) Target and calculated transmission spectra from the design. (b) Flattened gain profile (dotted line) and original gain profile (solid line) of a typical EDFA. (c) Designed coupling coefficient profile.

is designed by the EP algorithm described in the previous section. The grating length is set to be $L = 4$ cm, which is divided into 20 uniform sections with section width $\Delta z = 2$ mm. The number of spectral points is chosen to be $n = 401$ and the mutation parameters C and q are set to be 5×10^{-3} and 1/2, respectively. The core and cladding mode effective indices are assumed to be $n_{co} = 1.456$ and $n_{cl} = 1.446$. The grating period is $\Lambda = 153.11$ μm and the resonance wavelength is $\lambda_D = 1531.1$ nm. Fig. 3(a) shows the target spectrum and the calculated spectrum from our design. Fig. 3(b) shows the EDFA gain spectrum before and after flattening with our designed filter. The studied spectrum can be flattened to be less than ±0.25 dB variation within the bandwidth of 35nm and less than ±0.5 dB variation over almost 40-nm bandwidth. Fig. 3(c) shows the designed amplitude and phase profiles of the coupling coefficient across the grating. It should be emphasized that this is the result we obtain from a single 4-cm long LPG. To the best of our knowledge, this is the first demonstration that good EDFA gain flattening for the entire EDFA band in fact can be achieved with a single-stage LPG filter that is properly designed.

IV. CONCLUSION

In this letter, a novel LPG synthesis method using a revised evolutionary programming algorithm has been presented. The feasibility and effectiveness of the proposed method have been verified by designing a single LPG filter for *C*-band EDFA gain flattening. Based on the studied results, we believe evolutionary programming is an effective algorithm for optimally designing complicated LPG and other fiber grating filters. Since the EP algorithm is a stochastic search approach, the required computation time can not be precisely predicted. However, the proposed modified mutation process with leveled adjustments and adaptive weighting factors can improve the overall efficiency and reliability of the algorithm to a considerable extent. Our simulation results have shown that the proposed new EP-based LPG synthesis method is very effective and can be further developed to construct a powerful toolbox for practical design of fiber gratings. We have also demonstrated for the first time that a single 4-cm-long LPG with proper design can achieve good gain flattening for the entire EDFA band. Such a design should be useful for fabricating a new generation of practical EDFA gain flattening filters based on LPGs.

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