# Optimization design of flat-band long-period grating

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Received December 15, 2003

We present a method to optimize the flat-band long-period fiber Bragg grating (FBG) in this letter. The method is based on the particle swarm optimization method and the matrix transmission method. The optimized refractive modulation profile does not introduce so many phase shifts and is easier to fabricate compared with that of layer-peeling method which introduces lots of $\pi$ phase shift at each zero point of apodization profile in designing for the same problem.

*OCIS codes:* 060.2340, 060.5060, 060.2330, 050.2770.

Fiber Bragg grating (FBG) has been extensively used in the fiber communication system and sensing fields since its invention in the 1990s. Long-period grating (LPG) is a transmission-type filter that couples the optical power from the core mode to the matched cladding modes. The synthesis problem is to find the refractive modulation profile that adapts to the target spectrum of FBG or LPG. A lots of FBG synthesis methods have been proposed[1−4], such as layer-peering method, variational method, and Fourier-transform technology. Among them, the layer-peering method is very popular for its high calculation efficiency and reduced calculation complexity. Recently evolutionary algorithms such as genetic algorithm and evolutionary programming are proposed to synthesis the problem of FBGs and LPGs[5,6]. In this paper we use the particle swarm optimization (PSO) algorithm to synthesis a flat-band LPG.

The PSO was first introduced by Kennedy and Eberhart[7]. It can be applied to virtually any problem that can be expressed in terms of an objective function for which extrema must be found. The PSO algorithm is iterative and involves initializing a number of random vectors (particles) within the search space. The collective of the particles is known as the swarm. Each particle presents a potential solution to the problem of the target function. Each particle is also randomly initializing a vector called particle speed. During each time step the objective function is evaluated to establish the fitness of each particle using the particle itself as the input parameter. Then the particle will fly through the search space being attracted to their personal best position as well as the best position found by the swarm so far.

Let the position of particle $i$ be expressed as $X_i = (x_{i1}, x_{i2}, \cdots, x_{id})$, the best position of that particle be expressed as $p_i = (p_{i1}, p_{i2}, \cdots, p_{id})$, and the best position of the swarm be expressed as $p_g = (p_{g1}, p_{g2}, \cdots, p_{gd})$. Then the particle position update can be expressed as $x_{id} = x_{id} + v_{id}$, where $v_{id}$ represents the speed of the $d$ dimension of particle $i$ and is expressed as $v_{id} = wv_{id} + \phi_1\text{rand}()(p_{id} - x_{id}) + \phi_2\text{rand}()(p_{gd} - x_{gd})$, $w$ is the inertia weight determining how much of the particle's previous speed is preserved, $\phi_1$ and $\phi_2$ are two acceleration constants representing the cognition part and the social part respectively, and rand() is uniform random sequences from $\{0,1\}$. The iterative process will not stop until the extrema has been found.

The characteristics of the LPG can be expressed as coupling mode equations (CMT)

$$\left\{\begin{aligned} \frac{\mathrm{d}A}{\mathrm{d}z} &= -ikB - i\delta A \\ \frac{\mathrm{d}B}{\mathrm{d}z} &= -ikA + i\delta B \end{aligned}\right. , \tag{1}$$

where $A$ and $B$ are the complex amplitude of the core mode and the cladding mode, respectively, $k$ is the coupling constants, $\delta$ represents the detuning $\delta = \frac{\pi\Delta n_{\text{eff}}}{\lambda} - \frac{\pi}{\Lambda}$, $\Delta n_{\text{eff}} = n_{\text{cor}} - n_{\text{cla}}$ is the difference of the effective mode refractive indices, and $\Lambda$ is the period of the LPG. The piece wise uniform method, in which the transmission matrix is used to calculate the spectrum of the LPG, is often used for Eq. (1). We use the above method to optimize a flat-band filter, and the loss spectra are expressed as

$$R_{\text{target}} = r^2 = \left\{\begin{array}{ll} 1 & |\delta| > a \\ 0 & |\delta| < a \end{array}\right. . \tag{2}$$

The total length of the LPG is 4 cm, the maximum refractive modulation depth is $1 \times 10^{-3}$, and bandwidth is $B$ = 15 nm, all of which determine the parameter $\alpha = \frac{\pi}{\Lambda} - \frac{\pi n_{\text{eff}}}{\lambda_0 + B}$, where $\lambda_0$ is the central wavelength. We divide the grating uniformly into 12 sections, and the refractive modulation depth for each section is what we should optimize. The PSO parameters $w$, $\phi_1$, and $\phi_2$ are 0.2, 1.1, and 3.0 respectively. We use the following error function to evaluate the fitness of each particle in the swarm

$$\text{Err}\{R_{\text{calc}}, R_{\text{target}}\} = \frac{1}{J}\sum_j (R_{\text{target},j} - R_{\text{clac},j})^2, \tag{3}$$

where $R_{\text{calc}}$ and $R_{\text{target}}$ are the calculated spectrum of the particle and the target spectrum, respectively, and $J$ is the sampled numbers of the spectrum. Figure 1 shows the calculated spectrum using Matlab program after 30 generations, and the optimized data are listed in Table 1.

In another example, we designed a flat-band filter with maximum coupling power 50%, and the optimized index profile data are listed in Table 2.

In the discussion above, we divided the LPG into 12 sections, and the results showed that the PSO algorithm

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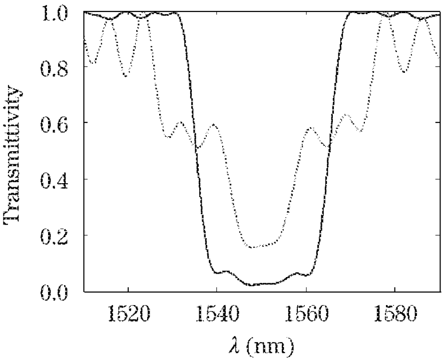

Fig. 1. The best calculated spectrum characteristics after 30 generation iterative. The dotted curve is the best spectrum of the fist generation and the solid curve is the best spectrum of the thirty generation iterative.

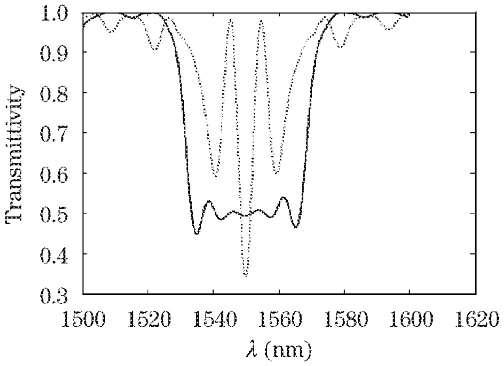

Fig. 2. The best calculated spectrum characteristics with maximum coupling power of 50% after 30 generation iterative. The dotted curve is the best spectrum of the first generation and the solid curve is the best spectrum of the thirty generation iterative.

**Table 1. The Refractive Modulation Depth of the 12 Sections and 100% of the Maximum Target Coupling Power of the LPG**

| | | |
|---|---|---|
| $1 \times 10^{-3}$ | 0.08994556602626 | 0.15421314962640 |
| | 0.05175336204508 | −0.00395723304901 |
| | 0.07284553554800 | 0.19823206886245 |
| | 0.18096495384985 | 0.19798452539471 |
| | 0.10687832503093 | 0.03496484491583 |
| | 0.02904503510161 | 0.02663465792882 |

**Table 2. The Refractive Modulation Depth of the 12 Sections and 50% of the Maximum Target Coupling Power of the LPF**

| | | | | |
|---|---|---|---|---|
| $1 \times 10^{-3}$ | −0.1328 | 0.2195 | 0.2541 | −0.2596 |
| | −0.4994 | 0.0329 | 0.3633 | 0.3840 |
| | 0.2694 | 0.2465 | 0.1927 | 0.1013 |

is very effective. In the following, we divided the LPG into 20 sections to test the effectiveness under the circumstances of the high dimensional particles. The length is still 4 cm, but we assume the bandwidth is $B = 5$ nm. Figures 3 and 4 give the optimized coupling curves where the maximum coupling powers are 100% and 50%, respectively. The optimized index profiles are listed in Tables 3 and 4. From Figs. 3 and 4, we can see the results agree well with the designed targets, which show the robust of the PSO algorithm even in solving the high dimensional problems.

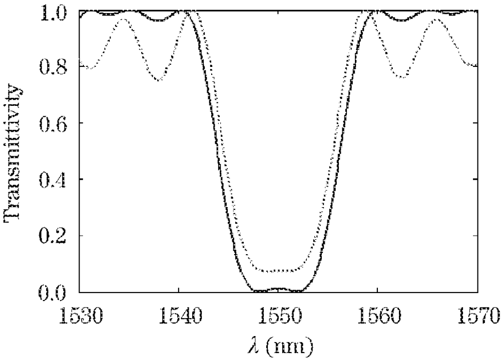

Fig. 3. The best calculated spectrum characteristics after 30 generation iterative. The dotted curve is the best spectrum of the first generation and the solid curve is the best spectrum of the thirty generation iterative.

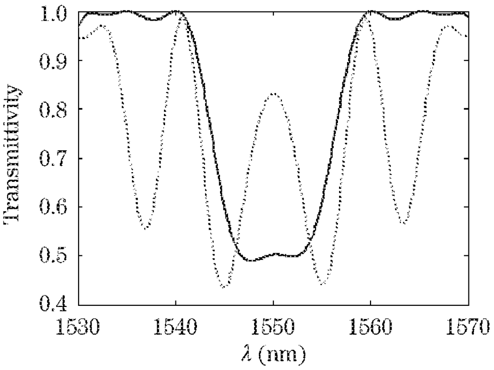

Fig. 4. The best calculated spectrum characteristics with maximum coupling power of 50% after 30 generation iterative. The dotted curve is the best spectrum of the first generation and the solid curve is the best spectrum of the thirty generation iterative.

**Table 3. The Refractive Modulation Depth of the 20 Sections and 100% of the Maximum Target Coupling Power of the LPG**

| | | |
|---|---|---|
| $1 \times 10^{-4}$ | 0.22538102309838 | 0.60332495599654 |
| | −0.09811246557075 | 0.25396450128670 |
| | 0.59764101218133 | 0.30343924298468 |
| | 0.91495685310679 | 0.18636469130744 |
| | 0.65075735478382 | 0.65793814468179 |
| | 0.93478729054978 | 0.69612199014436 |
| | 0.48904102090995 | 0.69515016772913 |
| | 0.82656829345358 | 0.35879030666489 |
| | 0.44541069046077 | 0.51967506098309 |
| | −0.19997578366867 | 0.62301414023656 |

In conclusion, we present a method to realize the flat-band LPG based on the PSO and the transmission matrix method. The results show that the algorithm is

**Table 4. The Refractive Modulation Depth of the 20 Sections and 50% of the Maximum Target Coupling Power of the LPF**

| | | |
|---|---|---|
| $1 \times 10^{-3}$ | 0.03582996134311 | 0.03289178930775 |
| | 0.07213251099941 | 0.00202669371577 |
| | 0.07251665821010 | 0.07051837209594 |
| | 0.06349648237041 | 0.00834276536366 |
| | 0.03574383080428 | 0.03179152427130 |
| | 0.01089241873393 | 0.05056863927242 |
| | −0.11919954067766 | 0.05895217806464 |
| | 0.01291497942950 | −0.08760452131095 |
| | 0.02734732883232 | 0.00750379171112 |
| | −0.06275956353383 | 0.01231258055046 |

very powerful and robust in designing for such problems. Compared with the genetic algorithm, the advantages of the PSO algorithm are its robustness in high dimensional problem, and the easiness to realize because there are only three parameters to control the algorithm. In contrast the genetic algorithm is very difficult to control for there are lots of operators such as selection, crossover, and mutation. In addition, each operator has different selectable parameters to control the convergence and avoid prematurity phenomenon at the same time. So a robust genetic algorithm is greatly dependent on experience of the programmer. To our knowledge, this is the first time that a flat-band LPG is synthesized by the PSO algorithm, which is another branch of the evaluation algorithms.

This work was supported by the National 973 Key Basic Research and Development Program of China (No. 2003CB314901), the National "863" High Technology Project of China (No. 2003AA311070), and Open Project of the State Key Laboratory on Integrated Optoelectronics. Y. Liu's e-mail address is liuyuminhqy@263.net.

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