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Optimal design of multichannel fiber Bragg grating filters using Pareto multi-objective optimization algorithm

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ABSTRACT

A Pareto-based multi-objective optimization approach is proposed to design multichannel FBG filters. Instead of defining a single optimal objective, the proposed method establishes the multi-objective model by taking two design objectives into account, which are minimizing the maximum index modulation and minimizing the mean dispersion error. To address this optimization problem, we develop a two-stage evolutionary computation approach integrating an elitist non-dominated sorting genetic algorithm (NSGA-II) and technique for order preference by similarity to ideal solution (TOPSIS). NSGA-II is utilized to search for the candidate solutions in terms of both objectives. The obtained results are provided as Pareto front. Subsequently, the best compromise solution is determined by the TOPSIS method from the Pareto front according to the decision maker's preference. The design results show that the proposed approach yields a remarkable reduction of the maximum index modulation and the performance of dispersion spectra of the designed filter can be optimized simultaneously.

1. Introduction

Multichannel fiber Bragg grating (FBG) filter has been widely applied in the dense wavelength division multiplexing (DWDM) systems, owing to its powerful capacity offering a high number of channels of identical spectral performance for wavelength filtering or chromatic dispersion management. The FBGs have many advantageous properties such as low cost, small size, low loss, high reliability and the inherent connectivity to other fiber devices [1–3]. Compared to a single channel FBG, designing a multichannel FBG filter is more difficult because the required maximum index modulation would easily exceed the physically realizable level. Therefore, the design of multichannel FBG filters has received considerable attention and various kinds of methods have been proposed, such as the superimposed method [4], the Talbot-effect method [5], the sampling method [6–10], and the inverse design method [11–15].

The inverse scattering discrete layer peeling (DLP) algorithm is one of the most typical and widely accepted approaches for multichannel FBG synthesis. However, DLP algorithm has an inherent limitation, if it is directly employed to achieve multichannel FBGs, the designed outcome easily exceeds the upper bound of the realizable index modulation. Consequently, some optimization-based methods have been proposed. Li et al. employed the DLP algorithm to synthesize the grating of the given multichannel spectra, and introduced an additional simulated annealing optimization process to find the optimal set of phases for all channels [11]. Lee et al. reported a Lagrange multiplier constrained optimization method, which constrains various parameters of the designed devices for practical application demands through an user-defined cost function [16]. But in [16], the designed FBG did not have a flat group delay response. Gong et al. applied the nonlinear least squares method to optimize the multichannel FBG filters [17]. This is potentially a multi-objective problem since here both the reflective spectrum and the dispersion must be optimized. However, they aggregated the objectives with the weighting factors and used the simple sum of expression. Most recently, we have proposed an effective optimization method based on differential evolution (DE) algorithm to design the multichannel FBG [18,19]. By combining the optimization algorithm with the tailored group delay technology, the approach presents a remarkable reduction of the maximum index modulation.

In this study, we attempt to explore the multi-objective optimization design scheme for the multichannel FBG filters. Instead of optimizing single objective, multi-objective optimization technique considers all design objectives simultaneously. Here, our aim is to minimize the maximum index modulation for a desired

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reflection spectrum and to find an optimal low dispersion profile of the grating. We have established a mathematical model by taking these two objectives into account. A hybrid evolutionary algorithm combining the fast non-dominated sorting genetic algorithm (NSGA-II) and technique for order preference by similarity to ideal solution (TOPSIS) method is developed to solve this model. NSGA-II searches for the so-called Pareto front, which are a set of non-dominated solutions or trade-off candidates. Then, TOPSIS is used to select the best solution from the Pareto front. The Pareto fronts provide more promising solutions to decision makers and enhance the flexibility in the design of multichannel FBG filters.

2. Problem formulation

A key issue in a multichannel FBG synthesis is to ensure the maximum index modulation to the practically realizable level. To address this problem, the basic principle of applying multi-objective optimization technique to design the multichannel FBG is based on the optimization method with the tailored group delay [18]. Our goal is to find an optimal index modulation profile for a desired reflection spectrum and a smooth in-band group delay spectrum (or low dispersion profile). The target reflection spectrum is modified by adding the new group delay parameter. For N channel FBG, the expression can be given by

$$r(\lambda) = \sqrt{R}\sum_{j=1}^{N}\exp\left(-\left(\frac{2\pi n_{eff}}{a}\left(\frac{1}{\lambda}-\frac{1}{\lambda_j}\right)\right)^{b}\right)$$
$$\times\exp\left(i2\pi n_{eff}\left(\frac{1}{\lambda}-\frac{1}{\lambda_0}\right)d_j\right),\quad j=1,2,3\ldots N, \tag{1}$$

where R and n_{eff} are the maximum reflectivity and the effective refractive index, respectively. λ_j stands for the central wavelength for channel j. λ_0 stands for the central wavelength for the full spectrum. The constant parameters of super-Gaussian function are a and b . Here, d_j is the introduced group delay parameter of channel j.

For channel j, the phase $\phi_j(\lambda)$ and group delay τ_j can be given by

$$\phi_j(\lambda) = 2\pi n_{eff}\left(\frac{1}{\lambda}-\frac{1}{\lambda_0}\right)d_j. \tag{2}$$

$$\tau_j = \frac{d\phi_j}{d\omega} = -\frac{\lambda^2}{2\pi c}\frac{d\phi_j}{d\lambda} = \frac{n_{eff}}{c}d_j, \tag{3}$$

where c is the velocity of the light in vacuum. It can be noted that the group delay parameter directly determines the corresponding phase and the group delay, simultaneously. Assigning different group delay parameters for different channels may result in dispersing the index modulation along the grating. In this way, the maximum index modulation can be reduced to the physically realizable level. To obtain good performance, suitable group delay parameters for multiple spectral channel need to be selected. Nonetheless, there is no significant linear relationship between the group delay parameter and the distribution of the index modulation. Simple increasing and diminishing group delay parameters are not the optimal and cannot achieve the desired value of maximum index modulation. On the other hand, if the maximum index modulation is the only consideration, the introduced group delay parameter would lead to the large dispersion in all channel. When the maximum index modulation and the dispersion are simultaneously optimized, how to handle the trade-off between the two factors becomes a difficult problem to be resolved.

In the proposed method, the objective function consists of two parts, including minimizing the maximum index modulation and minimizing the mean value of the dispersion error. The group delay parameters $d(d_1, d_2, \ldots, d_N)$ are used as the decision variable during the process of optimization. First, we utilize the DLP algorithm to establish the mathematical relationship between the index modulation Δn_{ac} and the group delay parameters $d(d_1, d_2, \ldots, d_N)$ [18]. The expression of the index modulation can be calculated as

$$\Delta n_{ac} = \frac{\lambda_0}{\pi}\left|\frac{\operatorname{arctanh}(|\rho(d)|)\rho^*(d)}{|\rho(d)\Delta|}\right|. \tag{4}$$

The dispersion D (ps/nm) is given by

$$D = \frac{d\tau}{d\lambda} = -\frac{2\pi c}{\lambda^2}\frac{d^2\phi_j}{d\omega^2}. \tag{5}$$

The dispersion error is defined as the absolute values of the deviations between the target dispersion and the designed dispersion, the mean dispersion error is calculated by

$$\bar{E}_D = \frac{1}{K}\sum_{k=1}^{K}|D_{target} - D(d)|_k, \tag{6}$$

where D_{target} and $D(d)$ are the target value and the designed one, respectively. K is the number of wavelengths in each channel (-10 dB bandwidth) of the discrete spectrum.

When multiple objectives are involved, the most existing design technique commonly uses an aggregating objective function to combine all the objectives. There are some inherent limitations. This single objective approximations method generally pre-defines the weights and fixes a particular solution before we calculate the possible solutions. And how to define the weights is also a difficult issue.

Instead of using a combined function, the multi-objective method considers all the design requirements simultaneously. The multi-objective optimization design model can be expressed as follows:

$$\text{Minimize: } f_{obj} = \{\max[\Delta n_{ac}], \bar{E}_D\}, \tag{7}$$

$$\text{Subject to: } 2L_L \le d \le 2(L - L_R), \tag{8}$$

where L_L and L_R are the locations of the first channel when counting from the left side and the right side, respectively. This constraint is added to ensure the value of group delay parameter within the valid range. $\max[\Delta n_{ac}]$ and $\bar{E}_D$ are the two conflicting objectives, provided by (4) and (6), respectively. Note that the results of the multi-objective FBG synthesis are not only a unique optimal solution but a set of optimal solutions are obtained in order to satisfying multiple targets. A hybrid evolutionary algorithm is proposed to resolve the model as described in the next section.

3. Multi-objective optimization algorithm

Compared to single objective problems, multi-objective (MO) problems are more difficult to solve, because there is no unique solution. The results of the multi-objective optimization model are provided as a set of acceptable optimal solutions or non-dominated solutions, referred to as Pareto front [20]. None of the solutions in the Pareto front is better than the others with respect to all the objectives. Multi-objective optimization can be in fact considered as the analytical phase of the multi-criteria decision