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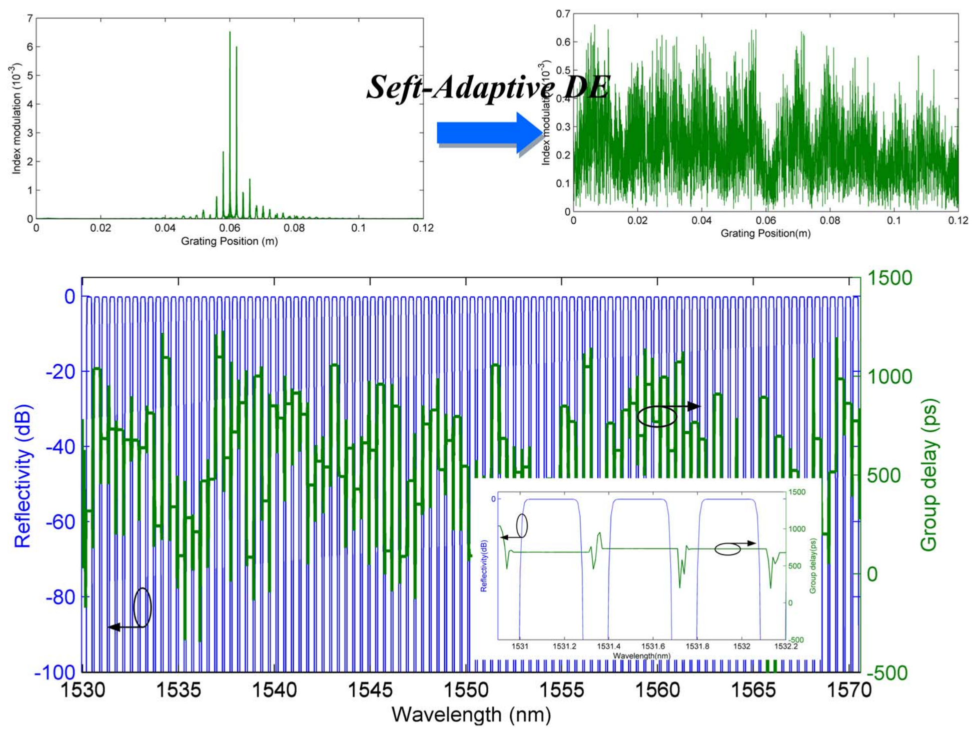

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Optimal Design of High-Channel-Count Fiber Bragg Grating Filters With Low Index Modulation Using an Improved Differential Evolution Algorithm

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Abstract: An effective optimization method based on a self-adaptive differential evolution (DE) algorithm is proposed to design high-channel-count fiber Bragg grating (FBG) filters. By combining the optimization algorithm with the tailored group delay technology, we have established a mathematical model aiming at minimizing the maximum index modulation of the grating. Equipped with a parameter self-adaptive strategy, the improved DE algorithm shows its powerful global searching ability in finding the optimal group delay parameter for each channel. Design examples demonstrate that the proposed approach yields better results with a remarkable reduction in the maximum index modulation compared with the previous works. Furthermore, we numerically present a 1037-channel 50-GHz spaced FBG filter enabling to cover the whole bands $(\mathrm{O}+\mathrm{E}+\mathrm{S}+\mathrm{C}+\mathrm{L}+\mathrm{U})$, which indicates the potential application of this method in the dense wavelength-division multiplexing (DWDM) system.

Index Terms: Fiber gratings, advanced optics design, modeling.

1. Introduction

High-channel-count fiber Bragg grating (FBG) filter, as one of the key optical devices, has been widely applied in the dense wavelength-division multiplexing (DWDM) systems [1]–[4]. The multichannel spectral response of the FBG is highly essential for multiwavelength filtering or chromatic dispersion compensation. However, design a high-channel-count FBG should consider not only the spectral response, but also its maximum index modulation. With the increasing number of channels, fabricate a high-channel-count FBG requires a considerably high index modulation, which is beyond a physically realizable level. Hence, ensuring a realizable maximum index modulation becomes a significant issue in designing high-channel-count FBG, with many methods having been proposed. Of all the methods, the sampling method [5]–[12] and the inverse scattering discrete layer peeling (DLP) algorithm [13]–[19] are the two most typical and widely accepted approaches for high-channel-count FBG design.

Sampling method can produce a multiple channel reflective spectrum by encoding a periodic sampling function for the single channel seed grating. To date, with the utilization of different advanced sampling function, several kinds of sampling method have been proposed, such as the phase-only sampled FBG [5]–[7], the amplitude-only sampled FBG [8], the amplitude-phase sampled FBG [9], the double sampling based FBG [10], [11] and triple sampling based FBG [12].

Generally, there is an additional optimization process for different channel phases to reduce the maximum index modulation, such as genetic algorithms or simulated annealing. However, as the number of channels increases, it is extremely difficult to find the optimal phases because too large numbers of free parameters need to be optimally decided.

Another, simple and efficient, approach to high-channel-count FBG synthesis is based on the inverse scattering discrete layer peeling (DLP) algorithm [13]. The DLP algorithm has an inherent limitation. If it is directly used to achieve multichannel FBGs, the designed maximum index modulation easily exceeds the upper bound of the realizable index modulation. Hence, the additional optimization process is also required. Li *et al.* first assigned an optimal set of additional constant phases to nine channels of the FBG with the simulated annealing algorithm, resulting in uniform reflection and dispersion spectrum channels [14]. Gong *et al.* proposed an effective method based on the nonlinear least squares method [17]. In this method, DLP algorithm was utilized to generate the initial coupling coefficient and the bound condition in the cost function controlled the maximum index modulation to the practically realizable level. Unfortunately, when the lower bound condition is set as zero, the method cannot reach a good final convergence. Such a local adjustment based on the initial index modulation profile by DLP method has a shortcoming of easily plunging into a local optimal solution.

Most recently, tailored group delay is introduced into the target reflection spectra to obtain a more even distribution of the index modulation, simultaneously not affecting the grating performance [19], [20]. Chang *et al.* divided all the single-channel grating structures into several groups by inserting the delay coefficient and realized the optimal constant phases in each group with the stimulated annealing method [19]. However, this approach is not suitable to group the grating in view of a limited grating length. Cao *et al.* proposed a direct design of high channel-count FBG by incorporating a tailored group delay profile for different channel, which is a significant improvement compared with previously reported results [20]. A staircase or wedge shaped group delay is employed to reduce the overlap between subgratings, thereby reducing the maximum index modulation. The group delay for each channel is chosen only relies on experience in the literature and may not be optimal. The optimization technique would make an improvement in appropriate tailored group delay value.

In this paper, an effective optimization method based on the differential evolution (DE) algorithm and the tailored group delay direct design method is explored. DE algorithm, a simple yet powerful evolutionary algorithm, is a recently developed optimization technique and has been shown to outperform both genetic algorithms and simulated annealing on many real-world problems [21]–[26]. We apply an improved DE algorithm, named self-adaptive DE [24]–[26], to optimize the group delay parameters with the goal that the maximum index modulation should be minimum. The self-adaptive DE is equipped with a parameter self-adaptive strategy to enhance the global optimization ability. Our method combines the optimization algorithm and the direct design method together successfully and makes full use of the advantages of both, which lead to a remarkable reduction of the maximum index modulation. Design examples show that the proposed method has advantages of flat-top reflection spectrum, low index modulation and suitability for either uniform or nonuniform channel spacing. With this method, we numerically present a 1037-channel 50-GHz spaced FBG filter enabling to cover the whole bands $(\mathrm{O}+\mathrm{E}+\mathrm{S}+\mathrm{C}+\mathrm{L}+\mathrm{U})$.

2. Principle of the Optimal Design

In general, the target reflection spectrum of an N-channel FBG can be expressed as

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

where R is the maximum reflectivity, N is the channel number, n_{eff} is the effective refractive index, and λ_j and λ_0 are the central wavelength for channel j and the central wavelength of the full spectra, respectively. L is the grating length. a and b are the parameters of super-Gaussian function, which control the spectrum shape of the FBG. Theoretically, the DLP algorithm provides an efficient method to synthesize the multichannel gratings directly from the above given target reflection spectrum [13]. However, the designed index modulation of the FBG is almost entirely concentrated in the midsection of grating and the maximum index modulation easily exceeds the upper limit of 0.001. From target reflection spectrum, we can see that the phase of each channel is $2\pi n_{eff}(1/\lambda - 1/\lambda_0)L$, and each channel has the same group delay value. Therefore, the different wavelengths are reflected at the same grating location and the overlap gives rise to high index modulation.

In order to reduce the maximum index modulation without affecting the grating performance, tailored group delay is introduced into the target reflection spectra [20]. An additional group delay parameter is used to assign different group delays to different channels. The target reflection spectrum of an N-channel FBG can be rewritten as

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

where d_j is the group delay parameter for channel j. The phase $\phi(\lambda)$ and group delay τ_ρ of the grating, respectively, are given by

$$\phi(\lambda) = 2\pi n_{eff}\left(\frac{1}{\lambda}-\frac{1}{\lambda_0}\right)d,\ \ d = (d_1, d_2, \ldots d_j, \ldots d_N) \quad (3)$$

$$\tau_\rho = \frac{d\phi}{d\omega} = -\frac{\lambda^2}{2\pi c}\frac{d\phi}{d\lambda} = \frac{n_{eff}}{c}\, d \quad (4)$$

where c is the velocity of the light in vacuum. We note from Eq. (4) that the group delay is proportional to the group delay parameter. This means the group delay parameter determines the corresponding phase and the group delay, simultaneously. Assigning different group delay parameter for different channel may lead to dispersing the index modulation along the grating, thereby reducing the maximum index modulation to physically realizable level. However, there is no significant linear relationship between the group delay parameter and the distribution of the index modulation. The problem of selecting a set of ideal group delay parameter for each channel becomes a key issue in designing a high-channel-count FBG. As the number of the FBG channel increases, the simple descending or ascending group delay parameters may not be able to achieve the desired goal. To address the issue, the high-channel-count FBG synthesis is converted to an optimization problem in our study.

In our method, directly minimizing the maximum index modulation, the objective function used for this design is defined as follows:

$$f_{obj} = \max[\Delta n_{ac}(d)],\ \ d = (d_1, d_2, \ldots d_j, \ldots d_N) \quad (5)$$

where Δn_{ac} is the index modulation. The group delay parameters $d(d_1, d_2, \ldots d_j, \ldots d_N)$ are the parameters to be optimized during the process of minimizing Eq. (5). Here, the DLP algorithm is utilized to establish the mathematical relationship between the index modulation Δn_{ac} and the group delay parameters d.

The target reflection spectrum $r(\lambda)$ Eq. (2), which contains the group delay parameter, is introduced into the iterative process of the DLP. The grating length is divided into M piecewise uniform sections. And the number of wavelength in the spectrum is also set to be M. According to the DLP, the discrete, complex reflection coefficient $\rho_j (j = 1, 2, \ldots, M)$ is given by

$$\rho_j = \frac{1}{M}\sum_{m=1}^{M} r_j(m) \quad (6)$$

$$r_{j+1}(\delta) = \exp(-i2\delta\Delta)\,\frac{r_j(\delta)-\rho_j}{1-\rho_j^* r_j(\delta)} \quad (7)$$

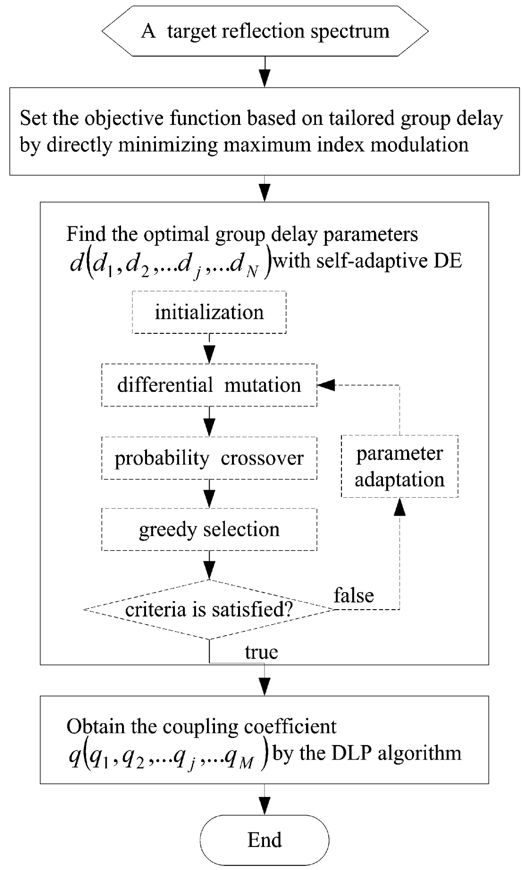


Fig. 1. Flowchart of the proposed optimization-based approach for high-channel-count FBG design with self-adaptive DE.

where, $r_j(m)$ denotes a discrete version of the spectrum $r_j(\lambda)$. From Eq. (2), $r_j(m)$ is varied with respect to the group delay parameter $d(d_1, d_2, \ldots d_j, \ldots d_N)$. Hence, we can iterate to find an expression of $\rho(\rho_1, \rho_2, \ldots, \rho_M)$ that depends on $d(d_1, d_2, \ldots d_j, \ldots d_N)$, denoted by $\rho(d)$. Derived from DLP algorithm, the coupling coefficient of the grating is given by

$$q = -\frac{\text{arctanh}(|\rho(d)|)\rho^*(d)}{|\rho(d)|\Delta}. \tag{8}$$

Finally, we provide a more complete description of the objective function as follows:

$$\min \quad f_{obj} = \max\left[\frac{\lambda_B}{\pi}\left|\frac{\text{arctanh}(|\rho(d)|)\rho^*(d)}{|\rho(d)|\Delta}\right|\right] \tag{9}$$

$$\text{s.t.} \qquad 2L_L \leq d \leq 2(L - L_R) \tag{10}$$

where L_L and L_R are the locations of the first channel when counting from the left side and right side, respectively. The group delay parameter is constrained to take values between $2L_L$ and $2(L - L_R)$. This constraint is added to ensure the validity of the FBG design. The values of L_L and L_R are pre-specified. Our optimization model converts the high-channel-count FBG design to the optimal solutions of the minimization problem. In this paper, the self-adaptive DE algorithm is applied to realize the assignment of the group delay parameter for all channels. Fig. 1 shows the flowchart of the proposed approach for high-channel-count FBG design.

The DE algorithm, a simple yet powerful population-based stochastic search technique proposed by Storn and Price [21], has been demonstrated to be very effective in obtaining a global optimum in the continuous search domain [22]. The implementation of DE is mainly composed of differential mutation, probability crossover and greedy criterion based selection. The mostly characteristics of DE is its novel mutation operation. DE performs mutation based on a difference vector which is calculated using members of the current populations. However, like most evolutionary algorithms, DE is still facing the parameter setting problem. There are three crucial control parameters in DE: scaling factor F, crossover rate CR, and population size NP. F controls the amplification of the differential variation. CR controls the influence of the parent in the generation of the offspring. In classical DE, F and CR are fixed during the evolution process. But determining appropriate control parameters is a time-consuming task that is usually carried out by hand in a trial-and-error way. To improve the efficiency and robustness of the search, self-adapting control parameter mechanism is introduced into DE. Self-adaptive DE, proposed by J. Brest *et al.* [24], is developed for the optimal high-channel-count FBG synthesis in our study. Apart from the population size NP, the control parameters F and CR are encoded into the individual and adjusted by means of evolution process. This self-adaptation allows F and CR adapt themselves to our design problem by reconfiguring themselves accordingly. The self-adaptive DE algorithm is detailed as the following steps.

Let $D_{i,G}$ represent a candidate group delay parameter vector (individual) for N-channel FBG in the population, G denotes one generation. In N-channel FBG design, each individual is a N-dimensional vector, $D_{i,G} = (d_{i1}, d_{i2}, \ldots, d_{iN})$. NP is the population size.

1) Initialization: Randomly generate NP individuals $D_{i,G}(i = 1, 2, \cdots NP)$ by a uniform distribution over the search space.
2) Mutation: Chose three individuals $D_{r1,G}$, $D_{r2,G}$ and $D_{r3,G}$, randomly from the current population, where $r1$, $r2$, $r3 \in [1, NP]$. A mutant vector $V_{i,G+1} = (v_{i1}, v_{i2}, \ldots, v_{iN})$ is generated according to
$$V_{i,G+1} = D_{r1,G} + F_{i,G} \cdot (D_{r2,G} - D_{r3,G}), \quad r1 \neq r2 \neq r3 \neq i \tag{11}$$
where scaling factor $F_{i,G}$ is a real number for individual i. The initial value $F_{i,1}$ is set to be 0.8.
3) Crossover: Generate a trial vector $U_{i,G+1} = (u_{i1}, u_{i2}, \ldots, u_{iN})$ according to the present vector $D_{i,G}$ and the mutant vector $V_{i,G+1}$ as follows:
$$u_{ij} = \begin{cases} v_{ij}, & \text{if } \left(rand(i) \leq CR_{i,G}\right) \\ d_{ij}, & \text{if } \left(rand(i) > CR_{i,G}\right) \end{cases} \quad j = 1, 2, \ldots, N \tag{12}$$
where crossover rate $CR_{i,G}$ presents the probability of creating parameters for trial vector from a mutant vector for individual i. The initial value $CR_{i,1}$ is set to be 0.9.
4) Selection: Use a greedy selection scheme according to the fitness value of the population vector and its corresponding trial vector:
$$X_{i,G+1} = \begin{cases} U_{i,G+1}, & \text{if } f(u_{i,G+1}) < f(x_{i,G}) \\ X_{i,G}, & \text{otherwise.} \end{cases} \tag{13}$$
5) Parameter Adaption: New self-adaptive control parameters $F_{i,G+1}$ and $CR_{i,G+1}$, from parent generation G into child generation $G + 1$, are calculated as follows:
$$F_{i,G+1} = \begin{cases} F_l + rand_1 * F_u, & \text{if } rand_2 < \tau_1 \\ F_{i,G}, & \text{otherwise} \end{cases} \tag{14}$$
$$CR_{i,G+1} = \begin{cases} rand_3, & \text{if } rand_4 < \tau_2 \\ CR_{i,G}, & \text{otherwise} \end{cases} \tag{15}$$
where $rand_j$, $j \in \{1, 2, 3, 4\}$ are uniform random values within the range [0, 1]. τ_1 and τ_2 represent probabilities to adjust control parameters F and CR, respectively. τ_1, τ_2, F_l, F_u are taken fixed values 0.1, 0.1, 0.1, 0.9, respectively.
6) Increment the generation count $G = G + 1$.
7) Stop the search with the optimal group delay parameter is found as the result, if no better solution is found for many generations. Otherwise, go to Step 2.

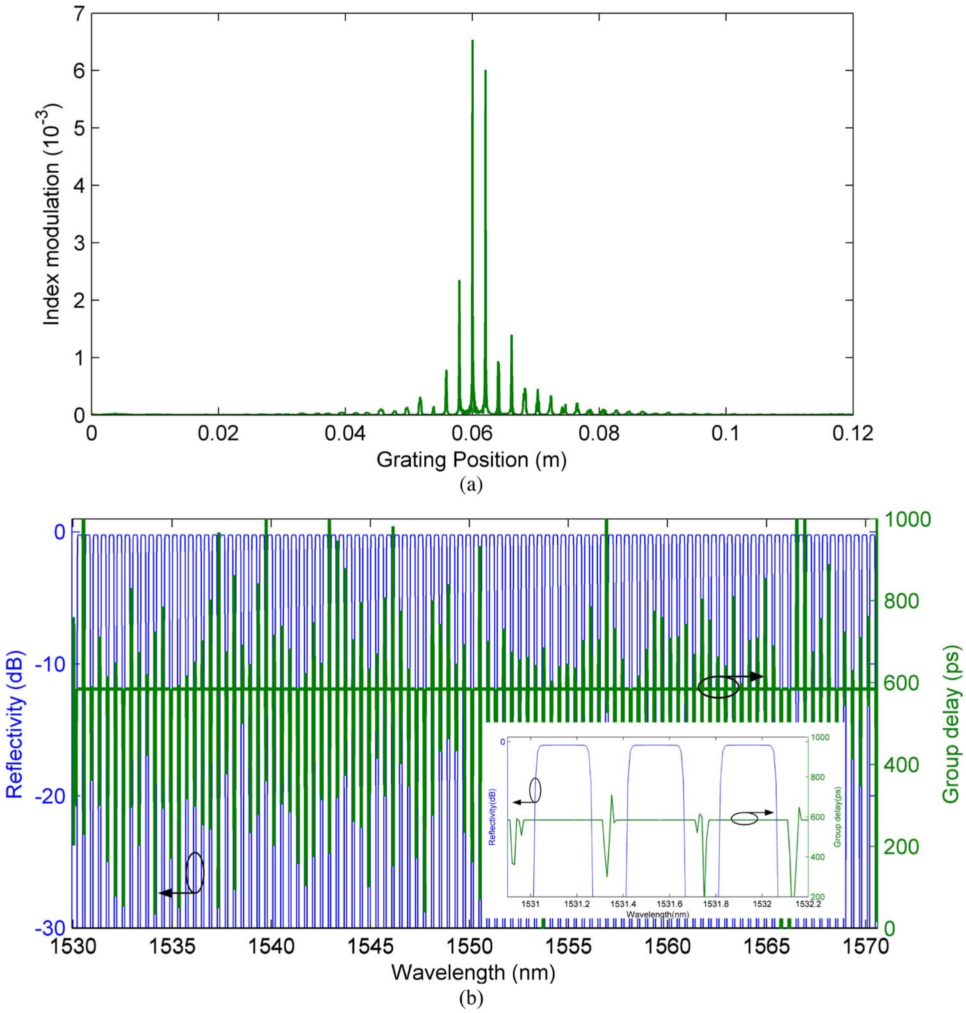


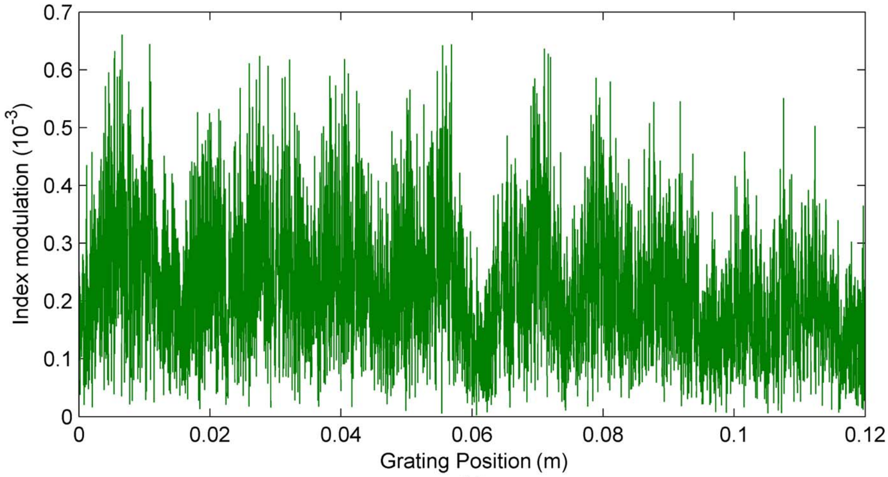
Fig. 2. Designed 101-channel (50 GHz spacing) FBG filter without group delay parameter by DLP algorithm. (a) Synthesized index modulation. (b) Synthesized reflection spectrum (the blue line) and group delay response (the green line). The insets show the details of reflection and group delay spectra for the channels at the central wavelength of 1531.14 nm, 1531.54 nm and 1531.94 nm.

3. Design Results

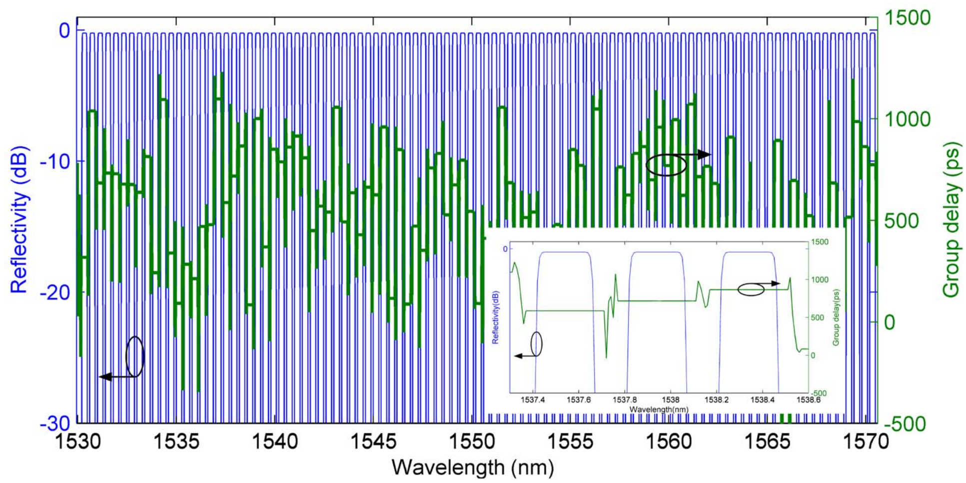
To verify the proposed DE algorithm for FBG filter design, we first present a 101-channel FBG filter design, including uniform and nonuniform channel spacing. Then, a comparison is taken with the other existing methods based on the definition of the reduction factor of the maximum index modulation. In addition, the design results of the a 1037-channel 50-GHz spaced FBG filter enabling to cover the whole bands $(O + E + S + C + L + U)$ are illustrated. The following simulations were conducted using a Xeon 2.13G, RAM 16 GB computer.

3.1. 101-Channel FBG Filter Design

Using the proposed method, first we design non-dispersive 101-channel FBG filter with the identical reflectivity of 95% and the channel spacing of 50 GHz. The target spectrum of the reflectivity given by Eq. (2) is defined by following parameters: $a = 501$, $b = 20$, $N = 101$, $R = 0.95$, $n_{eff} = 1.46$; the grating length L is 12 cm, the central wavelength λ_0 is set to be 1550.3 nm and λ_j is increased from 1529.94 nm to 1570.6 nm as j varies from 1 to 101.



(a)



(b)

Fig. 3. Designed 101-channel (50 GHz spacing) FBG filter with optimal group delay parameter by self-adaptive DE algorithm. (a) Synthesized index modulation. (b) Synthesized reflection spectrum (the blue line) and group delay response (the green line). The insets show the details of reflection and group delay spectra for the channels at the central wavelength of 1531.14 nm, 1531.54 nm and 1531.94 nm.

For comparison, DLP algorithm was used to design the grating structure when group delay parameter was fixed, $d_k = L$. The synthesized index modulation and synthesized reflection spectrum and group delay response are shown in Fig. 2. Fig. 2(a) shows the maximum index modulation is 6.534×10^{-3}, which is well above the physically realizable value 0.001. From Fig. 2(b), we can see that the synthesized reflection spectrum is in good agreement with the target one and the group delay for different channels is same. The previous investigations [6]–[9], [14]–[16] demonstrated the index modulation normally is between $\sqrt{N} \times \Delta n_s$ and $N \times \Delta n_s$, where Δn_s is the index modulation of single channel. In this example, $\Delta n_s = 0.198 \times 10^{-3}$. This means the traditional DLP method is unsuitable to reduce the maximum index modulation. Then, we applied the proposed self-adaptive DE method to optimize the group delay parameter $d(d_1, d_2, \ldots d_j, \ldots d_{101})$ for 101 channels with $L_L = 7.2$ mm and $L_R = 7$ mm. The parameters of self-adaptive DE were chosen: population size $NP = 80$, generation number $GEN = 100$. The design results are shown in Fig. 3 and the computation time is 664.25 s. Fig. 3(a) shows the synthesized index modulation in which the maximum index modulation is 0.661×10^{-3}. We observe that the index modulation is distributed along the grating, thereby significantly reducing the maximum index modulation to below 0.001.

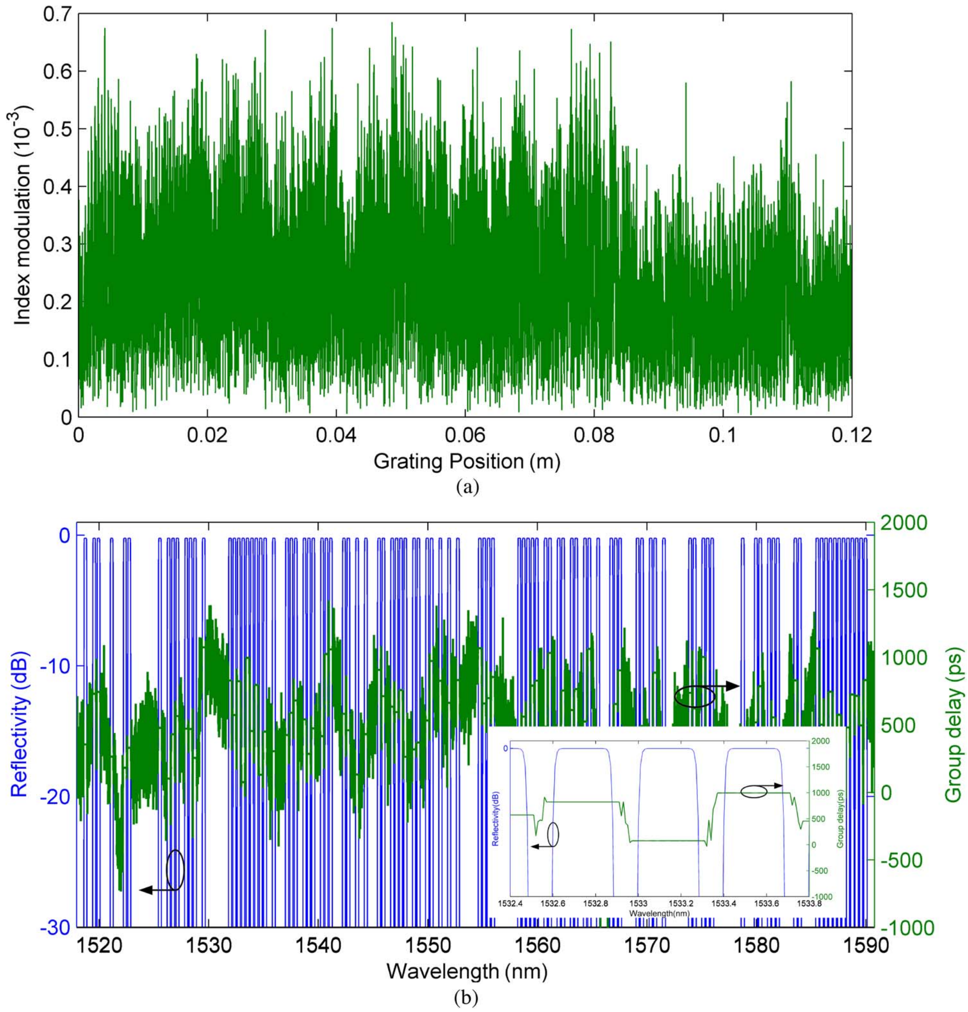


Fig. 4. Designed 101-channel nonuniformly spaced FBG filter with optimal group delay parameter by self-adaptive DE algorithm. (a) Synthesized index modulation. (b) Synthesized reflection spectrum (the blue line) and group delay response (the green line). The insets show the details of reflection and group delay spectra for the channels at the central wavelength of 1532.74 nm, 1533.14 nm and 1533.54 nm.

From Fig. 3(b), the synthesized reflection spectrum meets very well with the target spectrum and meanwhile the different group delays are assigned to different channels appropriately with the optimization process. The results demonstrate the effectiveness of the proposed method for designing the high-channel-count FBG filter.

Furthermore, the proposed technique can also be used to design a high-channel-count FBG filter with nonuniform channel spacing, which is widely used in the DWDM system. In this design of 101-channel nonuniformly spaced FBG, the target reflection spectrum of 101 channels is randomly chosen from the reflectivity of 180 channels 50-GHz spaced grating. The central wavelength λ_0 is set to be 1555.04 nm; the wavelength range is from 1517.94 nm to 1590.76 nm. λ_j is randomly picked 101 values form $\lambda_k = 1517.94 + 0.4 * k$, $k = 1, 2 \cdots 180$. The design results are illustrated in Fig. 4 and the computation time is 703.45 s. Fig. 4(a) shows the synthesized index modulation and Fig. 4(b) shows its reflection spectrum and group delay spectrum. By introducing optimal group delay parameter, the maximum index modulation is reduced from 7.089×10^{-3} (by DLP without group delay parameter) to 0.685×10^{-3}. The index modulation distribution was more even.

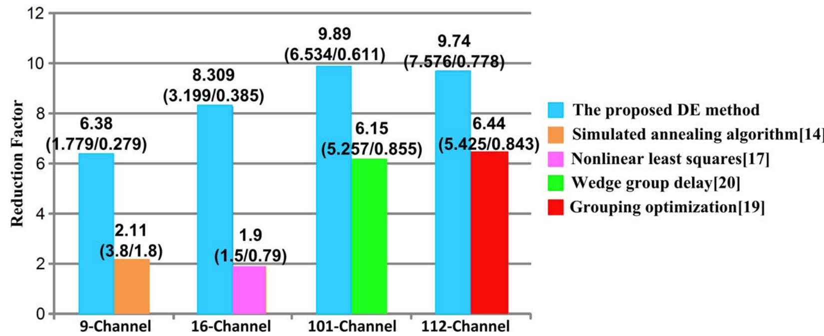


Fig. 5. Comparisons of the proposed method (blue bar) with other methods in [14] (orange bar), [17] (purple bar), [19] (red bar), and [20] (green bar) with the reduction factor of maximum index modulation. For 9 channel example; the reduction factor $6.38 = 1.779/0.279$.

3.2. Performance Comparison

In order to further give the efficiency of the proposed algorithm, comparisons are performed with other multichannel design methods [14], [17], [19], [20] in terms of the reduction factor of the maximum index modulation. The maximum index modulation reduction factor is given by [20]

$$Reduction\ factor = \frac{\max\Delta n_{ac0}}{\max\Delta \mathrm{n}_{\mathrm{ac1}}} \tag{16}$$

where $\max\Delta n_{ac0}$ is the original value of the maximum index modulation before optimization and $\max\Delta \mathrm{n}_{\mathrm{ac1}}$ is the minimized value of the maximum index modulation. This reduction factor evaluates the degree of reduction in the maximum index modulation of the grating, which is better for higher value. Fig. 5 illustrates the comparison results of 9-channel 16-channel, 101-channel and 112-channel FBG filter. As can be seen in Fig. 5, compared with the results reported in previous work [14], [17], [19], [20] without consideration of dispersion, higher reduction factors are obtained by our method. It indicates that there is a significant improvement in the reduction of maximum index modulation.

3.3. The Design of FBG Filter Covering the Whole Bands

With the wide application of DWDM system, the telecom wavelengths used by DWDM system is extend to the full range of all six wavelength bands $(\mathrm{O}+\mathrm{E}+\mathrm{S}+\mathrm{C}+\mathrm{L}+\mathrm{U})$ between 1260 nm and 1675 nm. Here, the proposed technique is applied to design high-channel-count FBG filter covering the whole bands of DWDM system by further increasing the number of the channels and meanwhile to keep the acceptable maximum index modulation. In this design example, the channel spacing is 50 GHz and the channel number increase to 1037 channels. The target reflection spectrum is defined by following parameters: $a = 501$, $b = 20$, $N = 1037$, $R = 0.95$, $n_{eff} = 1.46$; the grating length L is 20 cm, the central wavelength λ_0 is set to be 1468 nm and λ_j is increased from 1260 nm to 1675 nm as j varies from 1 to 1037. The left location of the channel L_L is 7.2 mm and the right location of the channel L_R is 7 mm. The parameters of self-adaptive DE were chosen: population size $NP = 80$, generation number $GEN = 200$. Fig. 6 is convergence curve of self-adaptive DE algorithm for the design of 1037-channel FBG filter, which shows the change of maximum index modulation during the iterative process. The self-adaptive DE algorithm still keeps a fast the convergence speed for 1037 channels. The optimized maximum index modulation is 0.867×10^{-3}, which is practically realizable. The synthesized index modulation is shown in Fig. 7 and the time taken for each calculation is 1583.78 s.

4. Conclusion

In this paper, an effective optimization technique, self-adaptive DE algorithm, has been applied to design high-channel-count FBG filters. By optimizing the introduced group delay parameter,

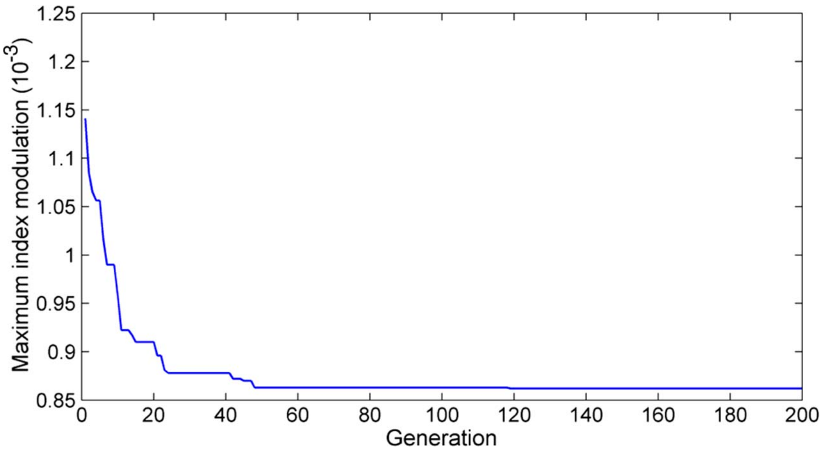


Fig. 6. Convergence curve of self-adaptive DE algorithm for the design of 1037-channel FBG filter.

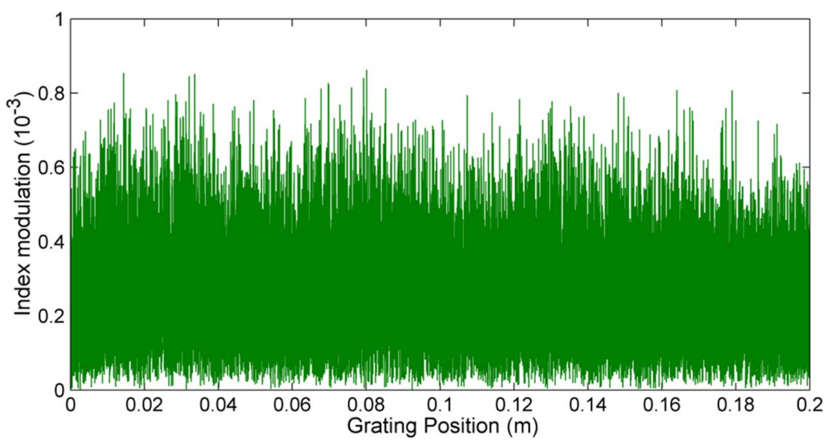


Fig. 7. Synthesized index modulation of 1037-channel (50 GHz spacing) FBG filter.

a significant reduction of the maximum index modulation is achieved. Two design examples of 101-channel FBG filter demonstrate the suitability of the proposed method for designing the high-channel-count FBG filter with either uniform or nonuniform channel spacing. Compared with other design methods, the proposed method has higher reduction factors of the maximum index modulation than those reported in previous work. In addition, the design technique is extended to design a 1037-channel 50-GHz spaced FBG filter enabling to cover the whole bands $(O + E + S + C + L + U)$. Note that while the channel number increases to 1037, the self-adaptive DE algorithm still keeps a rather fast convergence speed and meanwhile the optimized maximum index modulation is 0.867×10^{-3}, which is practically realizable. However, the dispersion and dispersion-slope compensation are not considered in our study and it will be a subject of our future work.

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