Advanced design of multi-channel fiber Bragg grating based on a layer-peeling method

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Abstract

Multi-channel fiber Bragg grating design (FBG) based on a discrete layer-peeling method (DLP) has been described in details. This novel method enables us to design any kind of multi-channel FBGs where the spectrum response of each channel could be either identical or non-identical. Particularly, a 9-channel dispersion-free FBG and a 9-channel nonlinearly chirped FBG used as simultaneously chromatic dispersion and dispersion slope compensator have been presented. Unlike the general multi-channel FBG designed with a sampling method, these two gratings have ideal flat-top profiles in both the transmission and reflection spectrum. By optimally detuning the relative phases for the multiple spectrum channels with an iterative layer-peeling method, we can make the maximum utilization of the length-limited photosensitive fiber. Moreover, we numerical shows that the oscillation inherently existed in the index-change envelop of our multi-channel FBG could be deduced or eliminated by sacrificing the extinction rate of the in-band signal to the out-band noises.

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1. INTRODUCTION

As one of the fiber-based wide-band promising components, multi-channel fiber Bragg grating (FBG) has recently attracted great interests due to its identical inter-channel response for either wavelength filtering or chromatic dispersion management.\textsuperscript{1-9} In order to make multi-channel FBG realizable in a limited length of photosensitive fiber, sampling method has widely been used, which was originally proposed and used in a multi-wavelength semiconductor laser.\textsuperscript{10} Original idea of the sampling method is to impose a period modulation on the envelop of the seed grating in spatial domain, then this period modulation will result in multiple channel in spectrum domain. To date, various kinds of advanced sampling functions have been proposed. Depending on the utilization of different sampling functions, the refractive index of seed grating could be endured a periodic modulation either in amplitude,\textsuperscript{2,11} or in phase-only,\textsuperscript{12,13} or in both amplitude and phase.\textsuperscript{14} However, all the designs based on sampling method have two inherent limitations. First, the sampling approaches are based on the resonant coupling theory,\textsuperscript{14} which can explain the mechanism of the multiple channel formation, but cannot provide accurate solution of the channel itself. It is correct only when the grating strength is weak. For a strong (greater than 50% in reflectivity) multi-channel grating, sampling method is not precise, there exists some inter-channel interference, which will inevitably make the intra-channel spectrum non-ideal, although these effects could be small when the seeding grating has a smooth slowly varying amplitude and phase.\textsuperscript{15} For some other gratings, especially when the seeding gratings have steep jumps either in phase or in amplitude, the resulted multiple channels would no longer be identical and distortion in intra-channel spectrum would occurs. Buryak et al.\textsuperscript{15} first identified this problem, and no solutions have been analytically given in Ref. 15. Second, it is known that the periodic sampling method is inherently suitable to design a multi-channel FBG with identical
channel-channel response and the channel spacing is constant. It fails if the complex spectrum of each channel or the channel spacing needs to be considerably different. Since this kind of device may be necessary for some practical and potential applications in both the telecommunication and fiber sensor fields, thus, there is a need to find a new method rather than the sampling one, which enables us to design any kinds of multi-channel FBGs where the spectrum response of each channel could be either identical or non-identical.

Most recently, Kolossovski et al have demonstrated a three-stage method for the optimal design of a multi-channel FBG.\textsuperscript{16} Besides the optimization procedures for the sampling function, an additional spectral fine-tuning step was added in order to obtain an ideal spectral response. Since the first two stages are still based on sampling method, it is not available for a design where either the seeding grating has steep jumps in grating profile or each channel response need to be different. In this paper, multi-channel FBG design based on iterative discrete layer-peeling (DLP) method has been demonstrated. First, the sampling method is reviewed based on the coupled mode equations. Second, based on a DLP method, particularly, an identical 9-channel dispersion-free FBG and a 9-channel nonlinearly chirped FBG with non-identical channel-channel dispersion response have been presented to compare with the designs based on the general sampling method. Unlike the general multi-channel fiber Bragg gratings designed with a sampling method, these gratings have nearly ideal flat-top spectrum in both the transmission and reflection. Fourier analysis for the apodization curve also shows that the period sampling method is not suitable when the seed grating is strong enough, especially when the seed grating has abrupt jumps either in phase or amplitude. Third, we propose a method to optimally detune the relative phases for the multiple channels, which is based on the iterative DLP method. Finally,
the optimization to smooth the grating amplitude profiles based on DLP and inverse DLP has been demonstrated.

2. THEORY FOR THE SAMPLED FBG

The sampled FBG is a product of a single channel seed grating with periodic sampling function in spatial domain. In general, the induced refractive index modulation $\Delta n$ can be expressed as

$$\Delta n(z) = \text{Re}\left\{\left(\frac{n_1(z)}{2}\right)\exp\left(i\left(\frac{2\pi}{A} + \phi_g(z)\right)\right)s(z)\right\},$$  

(1)

where $n_1(z)$ is the maximum index modulation, $z$ is the position along the grating, $A$ is the central pitch of the grating, $\phi_g(z)$ is the phase change for one channel grating, and $s(z)$ is a sampling function with period $P$, which can be expressed in the Fourier series

$$s(z) = \sum_{m=-\infty}^{\infty} s_m \exp\left(i\frac{2m\pi}{P} / P\right) = \sum_{m=-\infty}^{\infty} |s_m| \exp\left(i\frac{2m\pi}{P} / P + \phi_m\right),$$  

(2)

where $s_m$ is the $m^{th}$ complex coefficient of the Fourier series. $\phi_m$ is the argument of the Fourier series $s_m$. Substitute Eq. (1) and (2) into the Maxwell’s wave equations, using the slow varying envelope approximation, keeping only the phase-matched terms and neglecting the high orders terms which contain rapidly spatial oscillating $z$ dependence, we obtain, $^{17}$

$$\frac{\partial E_f}{\partial z} = -iE_i \sum_{m=-\infty}^{\infty} |s_m| \kappa_0 \exp\left\{-i\left(\frac{2m\pi}{P} / P + \phi_m + 2\chi - \phi_g(z)\right)\right\},$$  

(3)

$$\frac{\partial E_p}{\partial z} = iE_f \sum_{m=-\infty}^{\infty} |s_m| \kappa_0 \exp\left\{-i\left(\frac{2m\pi}{P} / P + \phi_m + 2\chi - \phi_g(z)\right)\right\},$$  

(4)
where $\kappa_\delta = \pi n_0/(4n_0 \Lambda)$ is the coupling coefficient for one channel, $\delta = \pi(2n_0/\lambda - l/\Lambda)$ is the detuning. $E_F$ and $E_B$ represent the amplitude of the forward and backward mode, respectively. Based on the resonant coupling theory, we can obtain the phase matching condition

$$\delta - \pi m / P = 0.$$  

(5)

Hence, the spectrum of the sampled grating consists of infinite number of channels. Each is around the wavelengths defined by Eq.(5). The neighboring channel spacing is decided by $\Delta \delta = \pi / P$ and the strength of the $m^{th}$ channel is reduced to $|s_m| \kappa_\delta$. We note that the phase of the Fourier series $\phi_m$ can also be regarded as the phase of the $m^{th}$ channel in frequency domain and it is independent of $z$. For the rect-type or sinc-type sampling functions, all the Fourier coefficients $s_m$ are real magnitudes, there are no phase $\phi_m$ terms existed in Eq. (3) and (4). For phase-only sampling functions these phase terms are non-zero, which provide free parameters useful for optimizing the sampling functions. Actually in most of applications, these relative phases between inter-channels will not affect the grating performance itself.

### 3. Synthesis for multi-channel FBG

Layer-peeling algorithm was first proposed by Feced$^{18}$ and Skaar$^{19}$ in synthesis of one-channel FBG, which could be used to efficiently and accurately reconstruct grating structure from any a given reflective spectrum. Principle of that is based on the solutions of the coupled mode equations with piece-wise scattering and propagation matrix. When the length of the piece-wise section is small enough, Fourier transform analysis is reasonable and the coupling coefficient at the front end of the grating could be determined only by the leading edge of the
impulse response,\textsuperscript{19} therefore one can simply find the grating structure layer by layer based on the solution of the local reflectivity using the transfer matrix together with Fourier transform methods.

**A. Multi-channel FBG with identical inter-channel spectrum response**

Based on DLP method, first, one needs a reflective spectrum used as an ideal target. For a multi-channel FBG used in dense-wavelength-division-multiplexed (DWDM) system, all the channels should remain the same properties, so the target for \(2N+1\) channel grating can be expressed as

\[
\sum_{m=-N}^{N} \delta(\lambda - m\Delta\lambda_0) = \left(\sqrt{R} \exp(-i\Phi(\lambda))\right) \otimes \sum_{m=-N}^{N} \delta(\lambda - m\Delta\lambda_0),
\]  

(6)

where \(r_x(\lambda)\) is the single-channel target, \(R\) is the needed grating reflection, \(\otimes\) is the convolution, \(\delta\) is delta function, \(\Delta\lambda_0\) is the channel space in wavelength domain, and \(\Phi(\lambda)\) is the accumulated phase of the central-channel grating. Since the relative phase between inter-channel will not affect the grating performance, so Eq. (6) are rewritten as:

\[
r_M(\lambda) = \left(\sqrt{R} \exp(-i\Phi(\lambda))\right) \otimes \left(\sum_{m=-N}^{N} \delta(\lambda - m\Delta\lambda_0) \exp(i\phi_m)\right).
\]  

(7)

**A.1. Synthesis for 9-channel dispersion-free FBG**

In the following, an example of 9-channel dispersion-free FBG based on layer-peeling algorithm will be given to compare with the one designed with the sampling method. First, a
dispersion-free seed grating was designed. This grating is designed to have strength of 10 dB and a central wavelength $\lambda_0$ (= 1550 nm) as

$$r_s(\lambda) = \sqrt{0.9} \exp \left[ -\ln 2 \left( \frac{\lambda - \lambda_0}{0.5 \times 0.65} \right)^{14} \right].$$  

(8)

The stop bandwidth with –35 dB isolation is of 0.8 nm. Within the quasi-flat-top reflectivity spectrum, we define a central bandwidth of 0.4 nm, where the target dispersion is zero. The reflection and dispersion spectra of the synthesized grating almost satisfy the target specification, as shown in Fig.1. Now we simply multiply the synthesized seed grating by a 9-channel Sinc sampling function

$$S(z) = \sum_{m=-4}^{4} \exp(\frac{2m\pi}{P} z), \text{ with } P \approx 1,$$

(9)

where $z$ is the position along the grating. $P$ is the period of sampling function. The calculated results for 9-channel FBG are shown in Fig.2. It is found that not only the intra-channel of the grating spectrum is considerably distorted, but also the inter-channel spectrum and dispersion become considerably non-uniform. Moreover, the maximum refractive index modulation of the 9-channel sampled grating is approximate 3.8x10^{-3}, which is 9 times higher than that for the seed grating as shown in Fig. 1(a). In order to overcome this problem in sampling method, we apply the DLP method to synthesize the multi-channel gratings directly with the target spectrum as expressed in Eq. (7). First we set the channel phase $\phi_m = 0$. The reconstructed grating apodization profile, the calculated reflection, transmission, and the dispersion spectrum are shown in Fig. 3(a), (b), (c) and (d), respectively. In this case, an ideal flat-top spectrum has been obtained in both transmission and reflection. Moreover, it is found that this 9-channel filter shows excellent
inter-channel uniformity for both the channel dispersion and the grating response. However, the peak index-change for this design with 9-channel is still 9 times higher than that required for the single channel grating. Compared Fig. 2(a), it is found that the grating profile of the DLP design (Fig. 3(a)) is roughly similar to that of the sinc sampling design. However, there exist some differences between them as shown in Fig. 4 in details. As expected from Eq. (9), the grating profile based on sinc sampling method would incur an index modulation with period of $P/(2N+1)$ (where $P$ is the period of the sampling function, $2N+1$ is the total number of the channels). For DLP design with no channel phase detuning ($\phi_m = 0$), it is found that this index modulation becomes a little bit aperiodic and the period of the index modulation is gradually increased along the grating. To make sure this within the whole grating range, we perform Fourier transform to both grating profiles and the results are shown in Fig. 4(b). There exists obvious difference between these two curves. It is the difference in detail of the grating profiles, which makes the improvement of the channel uniformity by the direct numerical DLP design. Since the same phenomena are also existed in other kind of multi-channel designs, we believe that the recovered grating profile based on sampling function is inherently different from the one obtained directly from the solution of the couple-mode equation.

A.2. Optimization for the index profile of 9-channel dispersion-free FBG

Provided that each channel phase is given arbitrarily at first, then we apply the layer-peeling algorithm to the spectrum target as expressed in Eq. (7), the corresponding grating structure can be obtained. Here we name the recovered apodization profile being $E_M(z)$. Noted that $E_M(z)$ is a function of the channel phases. Selections for the channel phase $\phi_m$ provide us
enough free degrees, which is very useful for optimizing the grating apodization to obtain the minimum index modulation. For this purpose, we construct a cost function as

\[ M(z, \phi _{N}, \ldots , \phi _{N}) = \int _{0}^{L} (E_{s}(z, \phi _{N}, \ldots , \phi _{N}) - \sqrt{2N + 1} E_{s}(z))^{2} \, dz, \]

(10)

where \( E_{s}(z) \) is one-channel grating apodization profile as shown in Fig. 1(a). 2N+1 is the channel number. Now, the parameters to be optimized here are the set of phases \( \phi _{m} \), whose values are randomly varied within \((-\pi, \pi)\), respectively. By using simulated annealing algorithm\(^{13,20}\) combined with the iterative layer peeling method, a optimal set of the phase values could be found, which make the value of \( M(z) \) the minimum. Optimal phases for 9-channel are obtained as \( \phi _{m} = [-1.04720, 3.14159, 1.0472, 0, 0, 0, 1.0472, 3.14159, -1.04720] \). The corresponding reconstructed grating apodization profile, the calculated reflection, transmission spectrum, and the dispersion spectrum are shown in Fig. 5(a), (b), (c), and (d), respectively. Compared with Fig. (3), it is found that the index-change required for a FBG with 9 channels is approximately \( \sqrt{9} \) time higher than that required for the single channel grating. Moreover, it can be seen that a set of 9 channels with nearly identical reflectivity and dispersion are generated with the wavelength spacing of 0.8 nm. However, there still exists a fast oscillation with period of \( \approx 110 \) \( \mu \)m somewhere in the envelop of the index modulation, which would make this grating much more difficult to be fabricated compared with that for the single-channel FBG. In order to smooth this envelop while remaining the grating response no change in the useable band, an additional procedure nearly the same as the spectrum fine-tuning methods proposed in Ref. [16] could be further executed by applying the results shown in Fig. 5(a) as an initial condition. In this procedure, the DLP algorithm and grating analysis using the transfer matrix method based on the
coupled-mode equations forms a loop, which is executed iteratively with a certain constraints on both the index-change envelop and the spectrum response until the acceptable index-change envelop is obtained. In general, this task is too burdensome to be realized in a reasonable time. In order to solve this problem, a new efficient layer peeling-algorithm \(^{19}\) could be used and analysis of the grating could be performed by the utilization of the equation:

\[
\begin{align*}
  r(z, \beta) &= \frac{\exp(j2\beta \Delta) r(z + \Delta, \beta) - \frac{\beta^*}{|q|} \tanh(|q| \Delta)}{1 - \exp(j2\beta \Delta) \frac{q}{|q|} \tanh(|q| \Delta) r(z + \Delta, \beta)},
\end{align*}
\]

(11)

where \(q\) is the complex coupling coefficient of the grating. The grating is divided into many sections and \(\Delta\) is the section length of the grating, where the pitch of grating is assumed to be uniform. \(r(z, \beta)\) is the local reflection coefficient defined by \(r(z, \beta) = E_b(z, \beta)/E_r(z, \beta)\). The reflection coefficient of the grating is easily obtained at the front of grating layer by layer by setting the boundary condition \(r(L, \beta) = 0\). This method, called as an inverse discrete layer-peeling(IDLP) algorithm. In our case, it is 50 times faster than that with the general transfer matrix method. As results, the inverse layer-peeling algorithm combined with iterative layer-peeling method provides a quick and precise way to smooth the index-change envelope of the multi-channel FBG. Fig. 6 shows the smoothing results with the above iterative method. Compared with Fig. 5, it is found that the apodization curve shown in Fig. 6(a) becomes much more smooth and the uniformity of the inter-channel reflectivity and dispersion almost remains no change. Due to this smoothing, it is expected that the minimum limitation to the UV beam size is roughly the same as that for one-channel FBG when the grating is fabricated. However, the reflectivity beyond the 9-channel band becomes nonzero and the corresponding phase
response is random. Since the extinction rate for the in-band signal to out-band noise become worse, it need be careful to do this smoothing for some practical applications. For reference, the optimization processes are depicted with flow-charts as shown in Fig.7, where Fig.7(a) shows the processes for the selection of the channel phases and Fig.7(b) shows the processes how to smooth the index-change envelop.

B. Multi-channel FBG with non-identical inter-channel spectrum response

In this section, we will discuss the design of multi-channel FBG with non-identical channel-channel spectrum response based on layer-peeling method. Particularly, 9-channel nonlinearly chirped FBG used as simultaneously dispersion and dispersion slope compensator is considered. Fig. 8 is a particularly design for a one-channel linearly chirped grating with dispersion $D_2 = -1020 \text{ ps/nm}$. This grating is designed to have a super Gaussian reflectivity envelop with the order of 18 and grating strength 10 dB at central wavelength $\lambda_0 = 1550 \text{ nm}$, as expressed by

$$r_s(\lambda) = \sqrt{0.9} \exp \left[ -\ln \left( \frac{\lambda - \lambda_0}{0.5 \times 0.65} \right)^{18} \right] \exp(-i\Phi_s(\lambda)), \quad (12)$$

where $\Phi_s(\lambda)$ is the accumulated grating phase within the central channel, which can be expressed by $\Phi_s(\lambda) = -c \int_{\lambda_{min}}^{\lambda} \left( \frac{2\pi \lambda^3}{\lambda^3} \right) D_z(\lambda - \lambda_0) d\lambda$ and $c$ is the light velocity. The reconstructed grating amplitude profile $E_r(z)$, grating phase profile, the calculated reflection and the dispersion spectrum are shown in Fig. 8(a) and (b), respectively. It can be seen that a linearly chirped grating with length of 12 cm, chromatic dispersion $-1020 \text{ ps/nm}$, and flat-top bandwidth
larger than 0.45 nm has been obtained, these results agree well with the target spectrum given by Eq.(12).

Now we apply the peeling method to a multi-channel fiber Bragg grating (FBG) used as a simultaneously chromatic dispersion and dispersion slope compensator. Contrary to the design in last section (where each channel remains the same properties), each channel would incur a slightly different dispersion, and the target for 2N+1 channel grating are expressed as,

\[
r(\lambda) = \sum_{m=-N}^{N} r_m(\lambda) = \left\{ r_s(\lambda) \otimes \sum_{m=-N}^{N} \delta(\lambda - m\Delta\lambda_m) \exp(i\phi_m) \right\} \exp(-i\Phi(\lambda)),
\]

where \( r_s(\lambda) \) is the amplitude spectrum for the central channel. \( \phi_m, \otimes, \delta, \) and \( \Delta\lambda_m \) have the same meanings as those in Eq. (8). \( \Phi(\lambda) \) is the accumulated phase of the total channels, which can be expressed as

\[
\Phi(\lambda) = -c \sum_{m=-N}^{N} \int_{\lambda_m - \Delta\lambda_m/2}^{\lambda_m + \Delta\lambda_m/2} \frac{2\pi}{\lambda^2} D_2^{(m)}(\lambda) d\lambda,
\]

where \( \lambda_m \) is the central wavelength for \( m^{th} \) channel, and \( D_2^{(m)} \) is the chromatic dispersion for \( m^{th} \) channel, defined by

\[
D_2^{(m)} = (D_2 + D_3 m \Delta\lambda_m), \quad m = -N, -(N-1), \ldots, N-1, N,
\]

where \( D_2 \) and \( D_3 \) is the chromatic dispersion and dispersion slope at the central wavelength. For convenient, we chose \( D_2 \) and \( D_3 \) as \(-1020 \text{ ps/nm}\), and \( 4.2 \text{ ps/nm}^2 \) respectively. Searching for the optimal 9-channel phases are performed and obtained with \( \phi_m = [1.116, 2.744, -1.01, 0.43, -0.285, 0.43, -1.01, 2.744, 1.116] \). Noted that these magnitudes are different from the ones we
obtained in the last section, which means that the optimal magnitudes for the channel phases may be related with the grating structures. Unlike the method proposed in Refs. 14 and 15, the optimization process here need doing the iterative layer-peeling combined with some iterative methods such as the simulated annealing method. The corresponding reconstructed grating amplitude and phase profile, the calculated reflection, transmission, and the dispersion spectrum are shown in Fig. 9(a), (b), (c), and (d), respectively. It can be seen that a set of 9 channels with almost identical transmission and the wavelength spacing of 0.8 nm are generated. The dispersions are about –1020 nm/ps in central channel and ranges from –1006 ps/nm to -1034 ps/nm through the whole 9 channels. Compared with Fig. 8(a), it is also found that the maximum index modulation required for a FBG with 9 channels is approximately 4 times (rather than 3 times) higher than that required for the single-channel grating due to the existence of a fast oscillation in the grating envelope. We can decrease this index modulation further by smoothing the index profile while keeping the in-band spectrum response the same as that shown in Fig. 9(b), just the same as we did in the last section. Fig. 10 shows the final iterative results. It is found that the maximum index modulation is decreased to the magnitude only three times larger than the one for the single channel FBG. As a trade-off, the channels outside of the 9-channel band become non-zero. Noted that there still exists a small oscillation at the top of the grating profile. This oscillation cannot be completely eliminated with our present method in order to remain the uniformity of intra-and inter-channel response. Since the writing beam size of UV light should be at least two times less than the period of the oscillation according to Nyquist sampling theorem, we expect that it will be much more difficult to fabricate it compared with single-channel FBG. Basically, one can design a multi-channel with a trade-off between the perfect spectrum response and the feasibility of FBG fabrication. Compared with Fig. 9(d), it is
also found that the dispersion ripple (as shown in Fig. 10(d)) becomes a little bit large. The same phenomenon has also been observed in Fig. 6(d) compared with the one shown in Fig. 5(d). Since this ripple is of a high frequency one with period of less than 100 pm, it is expected that this enhancement for the dispersion ripple wouldn’t make any considerably effects to cause the power penalty when the signal is reflected from this grating.

In this paper, we discuss the design issues for the two particularly of gratings with DLP method and the optimization to smooth the grating amplitude profiles. Detailed analysis for the tolerance of FBG fabrication and beam size effect on the performances of multi-channel FBG is necessary, however, it is beyond this paper, we will address them elsewhere.

4. CONCLUSION

We have presented a novel method for multi-channel FBG design, which enables us to design any kind of multi-channel FBGs where the spectrum response of each channel could be either identical or non-identical. A 9-channel dispersion-free FBG with identical spectrum response and a 9-channel nonlinear chirp grating with non-identical inter-channel dispersion values have been demonstrated, respectively. Unlike the general multi-channel FBGs designed with a sampling method, these two gratings have ideal flat-top profiles in both the transmission and reflection spectra. By optimally detuning the relative phase of each channel, we can make the maximum utilization of the length-limited photosensitive fiber. Moreover, we numerically shows that the oscillation inherently existed in the envelop of multi-channel FBG could be deduced or eliminated by sacrificing the extinction rate of the in-band signal to out-band noise. This method can be easily extended to design the gratings with up to 40 channels any kind of FBGs covering the whole C- or L- band in DWDM.
References


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Fig. 1. Design results for a one-channel dispersion-free FBG filter. (a) Apodization curve, (b) transmission and dispersion spectrum.

Fig. 2. 9-channel dispersion-free FBG filter based on Sinc sampling function. (a) Apodization curve, (b) transmission spectrum, (c) reflection spectrum, and (d) dispersion spectrum.

Fig. 3. 9-channel dispersion-free FBG filter based on layer peeling method with channel phase \( \phi_m = [0, 0, 0, 0, 0, 0, 0, 0, 0] \). (a) Apodization curve, (b) transmission spectrum, (c) reflection spectrum, and (d) dispersion spectrum.

Fig. 4. Fine structures of the grating profiles for 9-channel dispersion-free FBG filter based on sampling and layer-peeling method. (a) Grating profiles, (b) Fourier transform of the grating profile.

Fig. 5. 9-channel dispersion-free FBG filter based on layer peeling method with channel phase \( \phi_m = [-1.04720, 3.14159, 1.0472, 0, 0, 0, 1.0472, 3.14159, -1.04720] \). (a) Apodization curve, (b) transmission spectrum, (c) reflection spectrum, and (d) dispersion spectrum.

Fig. 6. 9-channel dispersion-free FBG filter after the smoothing procedure for the index-change envelop. (a) Apodization curve, (b) transmission spectrum, (c) reflection spectrum, and (d) dispersion spectrum.
Fig. 7. A flow-chart for the design processes. (a) Optimization for the channel phases, (b) optimization for the index-change envelop smoothing.

Fig. 8. Design results for a linear chirp FBG with chromatic dispersion $D_2 = -1020 \text{ ps/nm}$. (a) Apodization and phase profiles, (b) reflection and dispersion spectrum.

Fig. 9. Design results of 9-channel simultaneously dispersion and dispersion slope compensator with the relative channel phase $\phi_m = [1.116, 2.744, -1.01, 0.43, -0.285, 0.43, -1.01, 2.744, 1.116]$. (a) Apodization and phase profiles, (b) transmission spectrum, (c) reflection spectrum, and (d) dispersion spectrum.

Fig. 10. Design results based on Fig. 9 with grating amplitude smoothing. (a) Apodization and phase profiles, (b) transmission spectrum, (d) reflection spectrum, and (d) dispersion spectrum.
Fig. 1  (Hongpu Li et al)
Fig. 2 (Hongpu Li et al)
Fig. 3  (Hongpu Li et al)
Fig. 4 (Hongpu Li et al)
Fig. 5 (Hongpu Li et al)
Fig. 6 (Hongpu Li et al)
Obtain the index-change profile $E_s$ (1-ch) by using DLP method

Initial $\phi_m (\phi_{-N}, \ldots, \phi_N)$

New $\phi_m'$ are generated around the current $\phi_m$ with a random move

Obtain the index-change profile $E_M$ by applying DLP to the target (Eq. (7))

Cost function $M (\phi_{-N}', \ldots, \phi_N')$ (based on Eq. (10))

Create the criterions used for the simulated-annealing algorithm (based on Refs. 13 and 20)

Criterion satisfied?

No

Yes

End

Fig. 7(a)  (Hongpu Li et al)
Grating response $r(\lambda)$ calculated with the optimal channel phases $\phi_m (\phi_{-N}, \ldots, \phi_N)$

DLP method

Complex coupling coefficient $q$

Criterion satisfied? (for apodization)

Yes → End

No → Add constrains on the apodization profile

Complex coupling coefficient $q'$

Inverse DLP method

Grating response $r(\lambda)$

Add constrains on the grating response

Grating response $r'(\lambda)$

Fig. 7(b) (Hongpu Li et al)
Fig. 8 (Hongpu Li et al)
Fig. 9  (Hongpu Li et al)
Fig. 10 (Hongpu Li et al)