Design of High-Channel-Count, Multi-Channel Fiber Bragg Gratings Based on a Largely-Chirped Structure

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Abstract—We propose a novel technique to design a high-channel-count, multi-channel fiber Bragg grating (FBG) based on a largely chirped structure. The minimization of refractive-index modulation has been widely discussed in the previously demonstrated multi-channel grating designs. The complexity of the grating structure, however, is also important from the point of view of practical fabrication. In this paper, the degree of grating complexity (DGC) is defined. We show that the DGC of a multi-channel grating can be significantly reduced by designing a grating with a largely-chirped structure. A detailed grating design process based on this technique is discussed, by which four multi-channel gratings are designed and numerically studied, for applications such as periodic and non-periodic spectral filtering, chromatic dispersion compensation and dispersion slope compensation. The proposed theory and examples show that different gratings with high-channel-count and multi-channel responses can be designed and fabricated using a single commercially available phase mask, and all the gratings can be realized by a conventional FBG fabrication facility since the gratings have a low DGC with low index modulation.

Index Terms—fiber Bragg grating, multi-channel, chromatic dispersion slope

I. INTRODUCTION

Fiber Bragg gratings (FBGs) have found important applications in optical communications, sensors, and other optical systems, thanks to the advantageous features such as small size, low loss, high reliability, and compatibility with other fiber components. An FBG with a multi-channel spectral response is highly desirable in a wavelength-division-multiplexing (WDM) system, to perform functions such as multi-wavelength filtering and multi-channel chromatic dispersion management. Therefore, the design and realization of a multi-channel, high-channel-count FBG have been a topic of interest recently.

Although many design approaches have been proposed [1], a high-channel-count, multi-channel FBG is very difficult to realize due to the requirement for both a high index modulation and a very complicated structure. The previously demonstrated approaches are usually trying to optimize the grating structure, to reduce the index modulation to a practically achievable value. An FBG based on the conventional amplitude sampling technique has a simple structure, but the required index modulation is in proportion to the channel number, $N$ [2]. Buryak et al. in [3] provided a solution by modeling a multi-channel grating as a superposition of many sub-gratings. They showed that by dephasing the sub-gratings, the required index modulation will be proportional to $\sqrt{N}$, which is reduced significantly, making the fabrication of the multi-channel FBG practically possible. For example, based on the phase-only sampling technology, multi-channel FBGs for multi-channel filtering and chromatic dispersion compensation have been proposed and experimentally demonstrated [4-6]. Another problem that limits the practical applications of multi-channel FBGs is that a multi-channel grating usually has a very complicated structure. For example, in the phase-only sampling technique, deep phase modulation is required. Therefore, a very fine scale structure is required; the interval between two adjacent phase shifts is as small as 10 $\mu$m, to achieve a grating with a 100-GHz channel spacing and a channel number of 51 [7]. Such a grating cannot be fabricated with a conventional FBG fabrication system, unless a special phase mask is available. The realization of such a fine scale phase mask is also complicated [5], with different gratings using different phase masks, making the grating fabrication inflexible and costly.

The spectral Talbot effect provides another way to realize high-channel-count multi-channel gratings, which is based on an interference effect among the individual overlapped channels [8-11]. This technique has the flexibility and capability in achieving multi-channel FBGs with various channel spacing and dispersions by using only one phase mask. The advantage of this technique is that the designed grating has a much simpler structure than that designed by the phase-only sampling technique, so that it can be fabricated by the conventional FBG fabrication technique. FBGs with a channel spacing of 100 GHz, and a channel count of 40 for multi-channel filtering and chromatic dispersion compensation have been experimentally demonstrated [10-11]. There are, however, two problems that have not yet been resolved. First, in addition to the desired in-band channels there exist a large number of out-band channels which should be eliminated. Second, the spectral responses of the channels are identical or
very similar. For many applications, however, the spectral responses of the channels should not be identical. For example, the filter used in an optical add-drop multiplexer (OADM) should have a non-periodic frequency response. A multi-channel dispersion compensator should have different dispersion values in different channels, which has to be achieved by slightly chirping the sampling period and will result in a non-flat reflection response and non-uniform channel bandwidth. Design techniques based on various multi-channel grating reconstruction algorithms [12, 13] have been proposed to solve the problems. However, the gratings are still too complicated to be fabricated using the conventional FBG fabrication technique.

In this paper, we propose a novel approach to designing multi-channel gratings based on a largely-chirped structure. The problems discussed above can be eliminated by the proposed technique: a non-periodic multi-channel spectral response, or a spectral response with the channels having different properties, can be designed. Meanwhile, the out-band channels can be suppressed. The key advantage of the proposed approach is that the required index modulation is low, and the gratings can be fabricated by the conventional FBG fabrication technique, with different gratings fabricated based on a single commercially available phase mask.

The remainder of this paper is organized as follows. The principle of the proposed technique is described in Section II, which is proposed from the point of view of practical fabrication. A model to describe the conventional grating fabrication system is established, and the degree of grating complexity (DGC) is defined to describe the level of difficulty to fabricate a grating. Then the DGCs of a regular multi-channel grating and a grating based on the proposed design are theoretically analyzed and we conclude that the DGC can be decreased greatly when designing a multi-channel FBG with a largely-chirped structure. In Section III, four design examples including a periodic and a non-periodic filters, a chromatic dispersion compensator, and a dispersion slope compensator, are numerically studied. All these design are made based on a commercially available chirped phase mask. The DGCs are small and the index modulations are low, which enable the fabrication of the gratings using a conventional FBG fabrication facility. In Section IV, the required index modulation is discussed, and a conclusion is drawn.

II. PRINCIPLE

A. Degree of grating complexity

One difficulty in the fabrication of a multi-channel FBG is the requirement for an ultra large index modulation. Many approaches have been proposed recently to minimize the index modulation [3, 12-13]. The problem existing in these approaches is that a multi-channel FBG with an optimized design has a fine-scale and complicated structure when a high channel count is required, which can be hardly fabricated using a conventional FBG fabrication system.

To solve this problem, in this paper we proposed a novel technique to design a grating with a high channel count with a simple structure and low index modulation, which can be fabricated using a conventional FBG fabrication system. Before demonstrating the novel approach, we define a new parameter called degree of grating complexity (DGC). Mathematically, an FBG that is fabricated based on the phase mask technology using a UV light with side writing can be described by

\[ \kappa(z) = \kappa_w(z) \exp \left[ j \frac{2\pi}{\Lambda} z + j\varphi(z) \right] \quad (1) \]

where \( \kappa(z) \) is the coupling coefficient profile along the grating, \( \Lambda \) is the mean grating period, and \( \varphi(z) \) is the phase modulation which is introduced by the phase mask. For example, for a grating that is based on a chirped phase mask, \( \varphi(z) \) is given

\[ \varphi(z) = -\frac{\pi C}{\Lambda^2} z^2 \quad (2) \]

where \( C \) is the chirp rate of the grating. \( \kappa_w(z) \) (which is usually a complex function containing both amplitude and phase) is then the coupling coefficient profile which is actually implemented during the fabrication. Clearly, the DGC should be determined by \( \kappa_w(z) \) rather than \( \kappa(z) \), in terms of the grating fabrication. For example, to fabricate a grating for chromatic dispersion compensation, \( \kappa_w(z) \) is just a super-Gaussian function without any phase modulation, if a proper chirped phase mask is used. An intuitive conclusion is that the DGC would be high if \( \kappa_w(z) \) changes rapidly versus \( z \) along the grating.

To describe the DGC in quantity, a model for the fabrication platform is established. In many fabrication systems, especially those in the laboratories, the UV light is from a frequency-doubled Argon-Ion laser, with the beam focused so that the energy can be much higher at the focus point, especially for the fabrication of a grating with a complicated structure, the UV light with a fine UV beam should be used, as we will discuss below. Assume that the UV-beam-induced coupling coefficient profile along the grating is normalized as \( q(z) \), to form a long grating, such a UV exposure should be made in a series of positions along the fiber,

\[ \hat{\kappa}_w(z) = q(z) * \sum_{k=1}^{M} \alpha_k \delta(z - kP) \quad (3) \]

where \( M \) is the number of exposures, \( \delta(t) \) is the unit impulse function, \( P \) is the interval between the adjacent exposure points, \( \alpha_k \) is the coupling coefficient strength, which can be controlled by the exposure time, and * denotes the convolution operation. To fabricate a complicated grating, phase shift should be introduced so that \( \alpha_k \) is a complex number. Usually,
such a phase modulation is not introduced by the phase mask; instead, it is introduced during the fabrication by a high-precision translation stage, such as a piezoelectric transducer (PZT). A commercially available PZT can have an effective resolution in the sub-nanometer range [14]; a precise phase modulation can therefore be achieved using such a PZT.

The fabrication process is actually to optimize \( \alpha_k \) so that \( \tilde{\kappa}_W(z) \) can approach to the desired \( \kappa_W(z) \):

\[
q(z) \ast \sum_{k=1}^{M} \alpha_k \delta(z-kP) \rightarrow \kappa_W(z)
\]

Mathematically, this problem can be solved by taking the Fourier transform on both sides of (4),

\[
\sum_{k=1}^{M} \alpha_k \exp(-j kP \times 2\pi \sigma) \rightarrow \frac{K_W(2\pi \sigma)}{Q(2\pi \sigma)}
\]

where \( K_W(2\pi \sigma) \) and \( Q(2\pi \sigma) \) are the Fourier transforms of \( \kappa_W(z) \) and \( q(z) \), respectively, and \( \sigma \) is the spatial frequency. From (5) we can see that the bandwidth of \( K_W(2\pi \sigma) \), \( B_{K_W} \), is determined by two factors. First, \( B_{K_W} \) should be less than \( B_Q \), the bandwidth of \( Q(2\pi \sigma) \), since \( K_W(2\pi \sigma) \) is the sum of \( Q(2\pi \sigma) \). Second, (5) shows that the left-hand side equation is just the Fourier series expansion of the right-hand side equation; however, based on the Fourier series expansion theory, the bandwidth of the right-hand side should be confined within \( 1/P \). As a result, to fabricate a grating with a large \( B_{K_W} \), a fine UV beam is required as well as a small exposure interval. A grating that can be fabricated should have a \( B_{K_W} \) that is smaller than the maximum \( B_Q \) achievable by an FBG fabrication system. Since it is required that \( B_{K_W} < B_Q \), and the product of the length of \( q(z) \), \( L_q \) (i.e. the width of the UV beam), and \( B_Q \) is about one, then we have

\[
L_q < \frac{1}{B_{K_W}}
\]

Eq. (6) gives an upper limit of the width of the UV beam, that is, the finesse of the beam of the fabrication system should have at least. Then \( L_q \) can be defined as the DGC of the desired grating, which is a parameter that specifies the finesse of the fabrication system that can fulfill the fabrication task.

The DGC can be used to measure the level of difficulty in fabricating a multi-channel grating. Many previously reported multi-channel grating design techniques, such as the phase-only sampling technique and the techniques in [3, 12-13], are based on the use of a chirp-free phase mask, that is, \( \phi(z) = 0 \) in (1). If a weak grating is considered, the grating spectrum is then just the Fourier transform of \( \alpha(z) \), which is precisely \( K_W(4\pi \sigma) \) [note that \( \phi(z) = 0 \) here]. The relationship between \( \sigma \) and the light wavelength, \( \lambda \), is

\[
\sigma = \frac{n_{eff}}{\lambda} - \frac{1}{2\lambda} \approx \frac{\Delta \lambda}{4n_{eff} \lambda^2}
\]

where \( n_{eff} \) is the effective refractive index of the fiber and \( \Delta \lambda \) is the distance between the light wavelength and the Bragg wavelength of the FBG. Based on (6) and (7) we can see that if the total bandwidth of the required multi-channel grating is \( B_G \), the grating DGC should be

\[
B_{K_W} = \frac{B_G}{2n_{eff} \lambda^2}, \\
L_q < \frac{\lambda^2}{B_G/2n_{eff}}
\]

As an example, if an FBG has a channel number of 51 with a channel spacing of 100 GHz, the total bandwidth \( B_G \) would be about 40 nm, and then the beam width \( L_q \) should be less than 20 \( \mu \)m. Such a fine-scale UV exposure is hard to achieve in the core of a single mode fiber since the standard single mode fiber has a large radius of 62.5 \( \mu \)m. To fabricate an FBG with a high DGC, the fine-scale structures of the FBG are usually encoded in the phase mask, such as the phase-only sampling technique [4-7]. In terms of the DGC, the phase-only sampling moves the required phase modulation from \( \kappa_W(z) \) to \( \phi(z) \), by which the DGC is decreased greatly: \( \kappa_W(z) \) for a multi-channel grating is then the same as that for a single-channel grating.

In brief, any multi-channel grating with \( \phi(z) = 0 \) has a high DGC and cannot be fabricated by the conventional FBG fabrication technique. In this paper, the design of a multi-channel FBG with a largely chirped structure to ease the fabrication difficulty is proposed, where the value of the DGC is significantly decreased. Compared with the phase-only sampling technique, a multi-channel FBG designed based on the proposed technique can be fabricated with a conventional FBG fabrication system using a commercially available phase mask.

B. Design of a multi-channel grating with a largely-chirped structure

![Fig. 1. The multi-channel grating design based on (a) a uniform phase mask and (b) a chirped phase mask.](image)
Fig. 1 shows the difference between the conventional multi-channel grating design and the proposed technique which is based on a largely chirped structure. Generally a multi-channel grating can be designed by summing multiple single channel gratings,

\[ \kappa(z) = \sum_{l=1}^{N} \kappa_{l}(z) \exp \left( j \frac{2 \pi}{\Lambda_{l}} z \right) \]

where \( \kappa_{l}(z) \) and \( \Lambda_{l} \) are the coupling coefficient profile and period of the \( l \)-th grating, respectively, \( \Lambda \) is the mean grating period, and \( \Delta \Lambda_{l} = \Lambda_{l} - \Lambda \). In the conventional summing schemes, such as the phase-only sampling, all the sub-gratings are superimposed at the same position, as shown in Fig. 1(a), which results in a high DGC. In the proposed grating design, however, the sub-gratings are located at different positions,

\[ \kappa(z) = \sum_{l=1}^{N} \kappa_{l}(z - z_{l}) \exp \left( -j \frac{2 \pi \Delta \Lambda_{l}}{\Lambda_{l}^{2}} z + j \frac{2 \pi}{\Lambda_{l}} z \right) \]

In our design such a grating is fabricated based on a chirped phase mask with a chirp rate of \( C \). Therefore, based on (1), (2), and (10) we have

\[ \kappa_{W}(z) = \sum_{l=1}^{N} \kappa_{l}(z - z_{l}) \exp \left( -j \frac{2 \pi \Delta \Lambda_{l}}{\Lambda_{l}^{2}} z + j \frac{2 \pi}{\Lambda_{l}} z \right) \]

which is what we should actually fabricate, and the DGC of the novel multi-channel grating is then determined by (11). We take the \( l \)-th sub-grating as an example:

\[ \kappa_{W,l}(z) = \kappa_{l}(z - z_{l}) \exp \left( -j \frac{2 \pi \Delta \Lambda_{l}}{\Lambda_{l}^{2}} z + j \frac{2 \pi}{\Lambda_{l}} z \right) \]

where \( x = z - z_{l} \), and

\[ \beta = \frac{2 \pi}{\Lambda_{l}^{2}} (C z_{l} - \Delta \Lambda_{l}) \]

\[ \theta_{l} = \frac{\pi}{\Lambda_{l}^{2}} (C z_{l}^{2} - 2 \Delta \Lambda_{l} z_{l}) \]

In our design, we select the grating structure parameters such that \( \beta_{l} \equiv 0 \) for each \( l \), then

\[ z_{l} = \frac{\Delta \Lambda_{l}}{C} \]

The bandwidth of \( \kappa_{W,l}(z) \) can be calculated by taking the Fourier transform of (12) to get \( K_{W,l}(2 \pi \sigma) \). To simplify the analysis, we assume that \( \kappa_{l}(x) \) is a Gaussian function with a full-width at half-maximum (FWHM) of \( L_{s,l} \), which is an approximation of the length of the sub-grating in a real case. Then by the Fourier transform, the bandwidth of \( K_{W,l}(2 \pi \sigma) \) is

\[ B_{K_{W,l}} = \frac{L_{s,l} C}{\Lambda_{l}^{2}} \sqrt{\frac{4 \ln 2}{L_{s,l}^{2}} + \left( \frac{2 \pi}{\Lambda_{l}^{2}} \right)^{2}} \]

which could be further simplified when the following conditions are considered. First, from (14) one can see that the whole grating length should be in inverse proportion to the chirp rate. In order to limit the grating length in an acceptable range (e.g., about 10 cm) the chirp rate should be large. Second, the lengths of the sub-gratings are usually in the order of several centimeters. Then in (15) the right term is much larger than the left term under the radical sign. Therefore,

\[ B_{K_{W,l}} = \frac{L_{s,l} C}{\Lambda_{l}^{2}} \frac{\ln 2}{L_{s,l}} \]
\[
\frac{L}{L^0} = 1 + \frac{B_G}{2n_{eff}CL_s} = 1 + \frac{L_q}{L^0}
\]  

\[\tau_l = \frac{2n_{eff}z_l}{c} = \frac{\lambda_l - \lambda}{c \times C}
\]

where \( L \) and \( L^0 \) are the lengths for the proposed grating and the original design, respectively.

From (18) and (19) one can see the advantage of a multi-channel grating design based on a largely-chirped structure: with the chirped structure, the DGC can be decreased by increasing the grating length. For example, for the grating with 100-GHz channel spacing and 51 channels, if we assume \( L_i \) is 4 cm and \( C \) is 1.2 nm/cm, then \( L_q \) is about 60 \( \mu \)m, which is about three times the beam width in the original design and can be realized by a conventional FBG fabrication system. The grating length is however increased to about 16 cm. Currently, largely chirped phase masks having a length of up to 14 cm (e.g. phase masks from StockerYale, Inc) are commercially available. A long chirped grating fabricated by a long chirped mask has been recently reported [11]. It can be seen that the proposed technique to design a multi-channel grating based on a largely-chirped structure is especially suitable for a grating with a spectral response corresponding to a small \( L_i \).

Another advantage of the proposed design is that the sub-grating, i.e. the spectral responses of the channels, are not limited to be identical for all the channels, and the channel spacing is not required to be uniform either. This is different from the conventional grating design techniques, such as the technique based on sampling, where the spectral responses of the channels and the channel spacing should always be identical. Therefore, the proposed technique shows great flexibility for grating design and fabrication. To demonstrate the effectiveness of the propose technique, a few design examples are provided in Section III.

III. SIMULATION EXAMPLES

To design a grating based on the proposed technique, one should perform the following steps:

1. Define the grating coupling coefficient
   The grating structure can be designed directly based on (9), with each sub-grating being defined separately. A better way is to calculate \( \kappa(z) \) by a reconstruction algorithm from the desired multi-channel frequency response,

\[
H(\omega) = \sum_{l=1}^{N} H_l(\omega - \omega_l) \times \exp(-j\omega \tau_l)
\]

where \( H(\omega - \omega_l) \) is the desired response in the \( l \)th channel, which is a complex function with both the amplitude and the phase responses, \( \omega_l \) is the center angular frequency of the \( l \)th channel, and \( \tau_l \) is the time delay of the \( l \)th channel, which is different for different channels because the sub-gratings are superimposed at different locations, as defined in (14). Then the coupling coefficient profile defines the FBG that should be actually fabricated. Since the grating is fabricated by a chirped phase mask, the desired coupling coefficient profile, \( \kappa(z) \), is then obtained based on (2),

\[
\kappa(z) = \kappa(z) \exp\left(j \frac{\pi c}{\lambda^2 z^2}\right)
\]

2. Calculate the coupling coefficient profile
   The coupling coefficient profile defines the FBG that should be actually fabricated. Since the grating is fabricated by a chirped phase mask, the desired coupling coefficient profile, \( \kappa(z) \), is then obtained based on (2),

3. Select the proper \( q(z) \) and \( P \)
   As discussed in Section II.A, \( l/P \) and the bandwidth of \( Q(2\pi\sigma) \) should be larger than the bandwidth of \( K_w(2\pi\sigma) \).

4. Calculate \( \alpha_k \)
   Finally, the coupling coefficient strength and the phase at each UV exposure position can be obtained from (5). As discussed earlier, \( \alpha_k \) is the Fourier series expansion coefficients of \( K_w(2\pi\sigma)/Q(2\pi\sigma) \). It should be noted that the considered bandwidth should be confined within \( |\sigma| \leq 1/2P \).

Based on the above design process, four examples are numerically studied in this section, to show the capacity of the proposed multi-channel grating design technique. In the examples, the desired spectral responses are defined by following parameters: the channel number \( N \) is 51 and channel spacing is 100 GHz; in each single channel the reflection spectrum has a 4th-order super-Gaussian profile with a reflectivity of 90% and a 3-dB bandwidth of 50 GHz. In the first step of each example, the desired frequency response is defined based on (20), and the coupling coefficient is calculated based on the DLP algorithm. To realize such gratings, the chirp rate \( C \) is -2.0 nm/cm, which means that the four gratings are designed and fabricated based on the same commercially available phase mask. The UV beam is assumed to have a Gaussian profile, which is a good approximation for many practical fabrication systems.

A. Ideal multi-channel filtering
   To perform multi-channel filtering, the grating should be free of chromatic dispersion in each channel. Based on the design process, the coupling coefficient strength and the phase at each UV exposure position are calculated, which are shown in Fig. 2.

One can see that the channels have an identical reflectivity of 90%, a 3-dB bandwidth of 0.4 nm, and zero dispersion, which are identical to the desired values. Fig. 3(c) shows the reflection
and group delay responses of the 1st and the center channels, with identical channel performance demonstrated. A constant group delay difference between the two channels is observed, which is generated due to the largely chirped structure.

![Figure 2](image)

**Fig. 2.** Coupling coefficient strength and phase, $\alpha_k$, at each UV exposure position. The insert shows the details of $\alpha_k$ at the center of the grating.

![Figure 3](image)

**Fig. 3.** The reflection spectrum of the grating with its design shown in Fig. 2. (a) The reflectivity and transmission spectra. (b) The group delay and dispersion. (c) The zoom-in spectra of the channels at the left edge and at the center.

![Figure 4](image)

**Fig. 4.** The reflection spectrum of the grating with nonuniform channel spacing.

It should be noted that in the proposed multi-channel grating the out-of-band reflectivity is significantly suppressed, leading to a diffraction efficiency of 100%, as shown in Fig. 3(a). This is very different from the gratings designed based on the Talbot effect or the phase-only sampling technique where the diffraction efficiency is always smaller than 100%. The reason of the excellent out-of-band reflectivity suppression is due to the fact that the grating structure is reconstructed directly from the desired frequency response, but not based on the sampling technique in which the diffraction efficiency is hard to reach 100% [1]. Furthermore, the proposed technique can also be used to design a multi-channel grating with non-periodic channel spacing. Fig. 4 shows the spectral response of a multi-channel grating having 51 channels with the reflectivities of either 90% or zero.

In the design of this non-uniformly spaced multi-channel grating, the beam width $L_q$ is still 0.12 mm, $P$ is 0.046 mm and the number of UV exposure points is 1703. The grating length is about 78 mm. The maximum index modulation used in our simulation is $6.9 \times 10^{-4}$.

**B. Dispersion and dispersion slope compensation**

One of the important applications of a multi-channel grating is for dispersion compensation in an optical communication system. In our design, a multi-channel grating with a dispersion of -660 ps/nm at 1550 nm and a dispersion slope of -2.4 ps/nm², corresponding to the chromatic dispersion of a length of 40 km single-mode fiber (dispersion parameter of 16.5 ps/nm/km at 1550 nm and a dispersion slope of 0.06 ps/nm²/km). Based on the proposed grating design process, the grating is designed with the distribution of $\alpha_k$ shown in Fig. 5.

![Figure 5](image)

**Fig. 5.** Coupling coefficient strength and phase, $\alpha_k$, at each UV exposure position. The insert shows the details of $\alpha_k$ at the center of the grating.

Although the grating design, as shown in Fig. 5, is complicated, it can be fabricated by a conventional FBG fabrication system, since in the design the FWHM of the UV beam, $L_q$, is 0.06 mm, and exposure position interval, $P$, is 0.027 mm, which are practically implementable. The number of exposure points is 4438, and then the grating length is 120 mm. The maximum coupling coefficient is 1335 m⁻¹, corresponding to an index modulation of $6.6 \times 10^{-4}$.

The grating is designed and the reflection spectrum is shown in Fig. 6. As can be seen the channels have an identical reflectivity of 90% and a 3-dB bandwidth of 0.4 nm. The dispersion varies from -614 to -709 ps/nm, and the dispersion slope is about 2.4 ps/nm².
In general, the length of a grating for dispersion compensation is proportional to the desired bandwidth and the dispersion. In our design, the length for each sub-grating is about 2.7 cm. However, the total grating length is 12 cm, which is about four times the length of the sub-grating. As can be seen, the DGC is decreased by increasing the length of the grating. If a larger dispersion in each channel is desired, the grating length will be longer than 12 cm, which requires a longer chirped phase mask. A grating with a short length is desirable for most of the applications. To realize a large dispersion in each channel (which is used in long haul optical fiber transmission systems) by a single grating designed based on the proposed technique is difficult, which is the main limitation of this technique. However, multi-channel dispersion gratings based on the proposed technique has other important applications [16], such as optical spectral filtering and not-long-haul dispersion compensation, where a grating with not-so-large dispersion value is required.

Another issue that should be addressed is the uniformity of the reflectivity among channels. In a sampling-based multi-channel grating, the dispersion slope is achieved by slightly chirping the sampling period, which would result in the channel non-uniformity, that is, the reflectivity among channels will not be flat, and the bandwidths of the channels will not be identical either. In a grating designed based on our proposed technique, however, the uniformity is maintained throughout the channels. In the proposed technique, the grating structure is reconstructed directly from the desired spectral response, the dispersion slope will not show impact on the reflectivity profile, and the channel spectral responses are identical, as shown in Fig. 6(a) and (c). To demonstrate this property more clearly, a grating for multi-channel dispersion slope compensation is designed. In this grating, the dispersion slope is 24 ps/nm² and the dispersion at the center channel is zero. Therefore the grating can be used to compensate for the dispersion slope of about 400 km of single-mode fiber.

In the design of the grating, \( L_q \) is 0.80 mm, \( P \) is 0.043 mm, and the number of UV exposure points is 2770, so the grating length is about 120 mm. The maximum index modulation used in our simulation is \( 7 \times 10^{-4} \). The reflection spectrum is shown in Fig. 7.

It can be seen that the dispersion in each channel changes linearly from about -470 to 470 ps/nm within a bandwidth of 40 nm, which corresponds to a dispersion slope of 23.5 ps/nm². The reflectivity profile of all the channels is kept unchanged, which is different from a multi-channel grating designed based on the sampling technique with no-flat reflectivity profile.

In the design of the grating, \( L_q \) is 0.80 mm, \( P \) is 0.043 mm, and the number of UV exposure points is 2770, so the grating length is about 120 mm. The maximum index modulation used in our simulation is \( 7 \times 10^{-4} \). The reflection spectrum is shown in Fig. 7.

IV. DISCUSSION AND CONCLUSION

In Section II, we have introduced the concept of DGC and have emphasized that DGC is an important factor that characterizes the difficulty and complexity in designing a multi-channel grating. It is known, however, the index modulation is another factor that limits the number of channels of a multi-channel grating. For the previously demonstrated multi-channel grating designs [2-8], the index modulation is
between $\sqrt{N} \times \Delta n_s$ and $N \times \Delta n_s$, depending on the degree of dephase of the sub-gratings, where $\Delta n_s$ is the index modulation of one of the sub-gratings. In the proposed technique, however, the $N$ sub-gratings are not superimposed at the same position. Because of the largely chirped structure, there are only $\tilde{N}$ sub-gratings written at the same positions, as shown in Fig. 1(b). To calculate $\tilde{N}$, we assume that the multi-channel grating response is equally spaced. Based on (14) the distance between any two adjacent sub-gratings is $\Delta \lambda/2n_{eff} C$, where $\Delta \lambda$ is the channel spacing. Then we have

$$\tilde{N} = \frac{2n_{eff} CL_s}{\Delta \lambda} \quad (23)$$

Note that $B_G = N \times \Delta \lambda$, then based on (18) we have

$$\tilde{N} = \frac{2n_{eff} CL_s}{B_G} = \frac{L_q}{L_q^0} \quad (24)$$

which means the required index modulation will also be decreased when $L_q$ is increased, since the number of the superimposed sub-gratings is decreased. In the examples given in Section III, we assume that all the sub-gratings are superimposed inphase. The required index modulation is easy to be achieved. If an optimization algorithm is used to make the sub-gratings dephaseless, less index modulation is then required, and the required index modulation will be between $\sqrt{\tilde{N}} \times \Delta n_s$ and $\tilde{N} \times \Delta n_s$.

As a conclusion, we have proposed a novel approach to designing a multi-channel grating based on a largely-chirped structure. We have defined a new measure, called DGC, to characterize the difficulty in realizing a multi-channel grating, which is associated with the beam finesse of the FBG fabrication system. We have shown that the DGC of a multi-channel grating designed based on the previous techniques is too high to be fabricated by a conventional FBG fabrication system. In our proposed design, the DGC of a multi-channel grating is reduced significantly thanks to the use of a largely chirped structure, as can be seen from (18). In addition, if the length of a grating is increased, the index modulation is decreased, which also simplifies the fabrication. Four gratings having 51-channels with a channel spacing of 100 GHz were designed and numerically evaluated. The advantages of the proposed technique: 1) different multi-channel gratings can be fabricated using a single commercially available chirped phase mask; 2) no out-of-band channels are generated; 3) multi-channel response with non-identical sub-channel responses and non-identical channel spacing can be achieved; and 4) the multi-channel gratings can be fabricated by a conventional FBG fabrication system that has a practically achievable beam finesse and low index modulation.

### References


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