Optimal design of a multichannel fiber Bragg grating by using the DC sampling method

Hua Zhao[1], Miaomiao Zhanag[1], and Hongpu Li[2*]
[1]Key Laboratory of Optoelectronic Technology of Jiangsu Province, School of Physical Science and Technology, Nanjing Normal University, Nanjing 210023, P. R. China,
[2]Faculty of Engineering, Shizuoka University, 3-5-1, Johoku, Hamamatsu, 432-8561, Japan. *ri.kofu@shizuoka.ac.jp.

***Abstract*-A novel and flexible method for producing a multichannel filter from a single-channel fiber Bragg grating (FBG) is proposed and numerically demonstrated. The proposed method enables us to produce a multichannel filter from a single channel FBG just by using the direct UV exposure without the need of the expense and the complex phase mask. Moreover, the proposed method provides much more flexibilities to design any other new kinds of fiber gratings than ever before.**

I. INTRODUCTION

In the past decades, multichannel fiber Bragg gratings (FBGs) have recently attracted a lot of research interest and found versatile applications in the fields of fiber sensing, all-optical signal processing, and optical communications [1-6]. To date, various sampling functions have been used to produce the multichannel FBG, which mainly can be divided into two kinds, i.e., the amplitude-only and the phase-only modulations. For the first one, one typical example is utilization of a periodic rectangular function [1,2], which however will inevitably result in a large non-uniformity among channels. For the later one, the phase-only sampling method can reduce the index change required for the sampled FBG with even an 81-channel to a practical level [3-5]. However, the grating's pitches will be changed differently along the fiber direction due to the introduction of the phase sampling function. As result, a specially-ordered phase-mask with a fringe resolution better than several nanometers is generally demanded, which makes this kind of phase-masks extremely expensive and has few flexibilities to write any other kinds of FBG. In this study, a novel and flexible method named the DC-sampling method, is firstly proposed and numerically demonstrated. The proposed DC-sampling function acts equivalently like the previous phase-only sampling, which can be used to produce a multichannel FBG and meanwhile make the maximum utilization of the fiber as well.

II. PRINCIPLE AND OPTIMAL DESIGN FOR THE DC-SAMPLING FBG

The refractive-index distribution n_s in a single-channel FBG (the seed FBG) can be expressed as

$$n_s(z) = n_0 + \Delta n_1 \cos(2\pi z / \Lambda_0 + \phi_g), \tag{1}$$

where z is the position along the grating direction, n_0 is the effective index of the core, Δn_1 is the amplitude of the grating, Λ_0 is the central pitch, and ϕ_g is the local phase of the FBG. For simplicity, the linear phase term ϕ_g in Eq. (1) can be neglected, and the seed FBG is assumed to be a uniform one, thus, the AC-part of its index-modulation can be simply described as

$$\Delta n_{AC}(z) = \Delta n_1 \cdot \cos(2\pi z / \Lambda_0). \tag{2}$$

To produce multiple identical channels from the seed FBG, a new function called the DC-sampling one is utilized, which can be expressed by

$$\Delta n_{DC}(z) = A(z) \otimes \sum_{j=-\infty}^{\infty} \delta(z - j \cdot \Lambda_P), \tag{3}$$

where Λ_p is the period of the DC-sampling function Δn_{DC}. $\otimes$ represents the convolution operation, $\delta(z)$ is a Dirac delta function and $A(z)$ is a base function within one period of the Λ_p. Here the idea to produce a multichannel FBG is that the seed FBG and an additional slowly-varied index-modulation which is exactly represented as the DC-sampling function in Eq. (3) are superimposed each other in a same length of the fiber, meanwhile the condition of that the Λ_p is much longer than Λ_0 is satisfied. Therefore, the total index-modulation distribution for the proposed multichannel FBG can be expressed by the equation of $\Delta n_M(z) = \Delta n_{DC} + \Delta n_{AC}$. As indicated before in Refs. [6, 7], the slowly varied DC-part index-modulation can be equivalent to the differential of the grating's phase ϕ_M, since they make the same contribution to the grating's DC coupling coefficient. In another word, the change of the grating's phase ϕ_M is then given by

$$\phi_M(z) = 2\int_0^z \frac{2\pi}{\lambda} \Delta n_{DC}(z) dz, \tag{4}$$

where λ is the central wavelength. The index-modulation distribution $\Delta n_M(z)$ in Eq. (4) can be equivalently expressed as

$$\Delta n_M(z) = \Delta n_1 \cdot \cos\{(2\pi z / \Lambda_0) + \phi_M(z)\}. \tag{5}$$

Since ϕ_M is a periodic function with a period Λ_p, one can expand Eq. (6) in Fourier series as:

$$\Delta n_M(z) = \Delta n_1 \cdot \sum_{n=-\infty}^{\infty} F_n \exp\left\{i2\pi z\left(\frac{1}{\Lambda_0} + \frac{n}{\Lambda_p}\right)\right\}, \tag{6}$$

where $\Delta n_1 F_n$ is the Fourier series. From Eq. (6), it is clearly seen that $\Delta n_M(z)$ consists of an infinite number of the newly obtained FBGs (channels) with constant channel spacing (in units of the wavenumber domain) $1/\Lambda_P$, where each of these gratings has its own amplitude $\Delta n_1 F_n$ and a pitch $\Lambda_n = 1/(1/\Lambda_0 + n/\Lambda_P)$ in terms of the different order number n. The above results are exactly the same as those obtained by using the phase-only sampling methods [3]. In order to obtain high-channel-count FBG with ideal channel uniformity, the phase function ϕ_M must be optimally selected. For simplicity, the phase function $\phi_M(z)$ is

978-1-7281-1647-1/19/$31.00 ©2019 IEEE

assumed to include a certain number of sinusoid functions with frequency n/Λ_P (n=1, 2, 3, …, J), which is given by

$$\phi_M(z)=\sum_{n=1}^{J}\alpha_n\sin\left(2\pi nz/\Lambda_P+\theta_n\right), \quad (7)$$

where J is the number of the harmonic terms, the minimum value of which is determined by the channel number what we demand for the multichannel FBG. The free parameters α_n and θ_n in (8) need to be optimally selected later. To substitute the Eq. (7) into Eq. (5), the index-modulation $\Delta n_M(z)$ can be rewritten as

$$\Delta n_M(z)=\Delta n_1\cdot\cos\left\{\frac{2\pi}{\Lambda_0}z+\sum_{n=1}^{J}\alpha_n\sin\left(2\pi nz/\Lambda_P+\theta_n\right)\right\}, \quad (8)$$

where the terms α_n and θ_n in (8) are optimally selected such that the F_n in Eq. (6) are identical within the desired channels. By using the simulated annealing algorithm, optimization for the 9-channels phase function $\phi_M(z)$ was obtained, which is expressed by

$$\begin{aligned}\phi_M(z)=&-2.935\sin(W)+0.758\cos(2W)-0.420\sin(3W)\\&-0.318\cos(4W)+0.171\sin(5W)\end{aligned}, \quad (9)$$

where $W=2\pi z/\Lambda_P$ and five harmonic terms are included. Distributions of the phase $\phi_M(z)$ within one sampling period and the corresponding Fourier series $|F_n|$ are shown in Figs. 1 (a) and (b), respectively. From the Fig. 1 (b), it can be found that the in-band energy efficiency is larger than 97%, and the non-uniformity through the central 9 channels is less than 0.8%. By substituting the Eq. (9) into Eq. (4) and performing the differential operation on both sides, the DC-sampling function Δn_{DC} is then obtained as

$$\begin{aligned}\Delta n_{DC}(z)=\frac{\lambda}{2\Lambda_P}\{&-2.935\cos(W)-1.16\sin(2W)\\&-1.26\cos(3W)+1.272\sin(4W)+0.855\cos(5W)\}\end{aligned}. \quad (10)$$

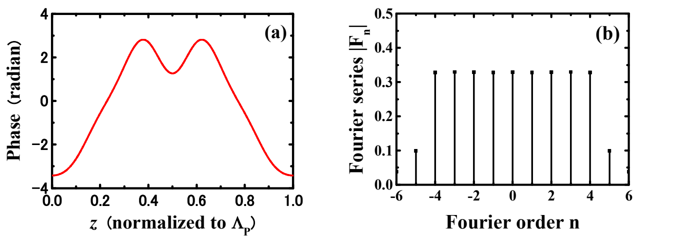

Fig. 1. The optimized 9-channel phase function. (a) the phase function and (b) the corresponding Fourier series |Fn|.

Figure 2(a) shows the distribution of the optimized DC-sampling function along the grating position, where the sampling period Λ_P and the grating's central wavelength λ are particularly adopted as 0.2 cm and 1550 nm, respectively. The total length of the grating is chosen as 1 cm. The above results indicate that if we can make the DC-part of the induced index-modulation in a seed FBG exactly like the one shown in Fig. 2(a), then it means that the phase function $\phi_M(z)$ shown in Eq. (9) can be equivalently inserted into the seed grating. As a result, a 9-channel FBG with an identical channel amplitude and spacing is expected to obtain.

To prove the above conceptual principle, we have calculated both the transmission and reflection spectra of the DC-sampled 9-channel FBG by using the transfer matrix method [7]. The results are given in Fig. 2(b), where the period Λ_0 and the maximum index-modulation Δn_1 of the seed grating are assumed to be 0.55 μm and 8×10^{-4}, respectively. Period of the sampling function and total length of the seed grating are assumed to 0.2 mm and 1 cm, respectively, which are the same as what we utilized in Fig. 2(a). From Fig. 2(b), it can be obviously seen that there exist nine nearly identical channels/notches in the reflection/transmission spectrum and each of them has a strong depth larger than 18 dB in transmission. In addition, the channel spacing is 0.42 nm. All the above results are exactly the same as those obtained by directly inserting the phase-sampling function into the Eq. (5), which in return means that the proposed DC-sampling method acts exactly like an equivalent phase-only sampling function.

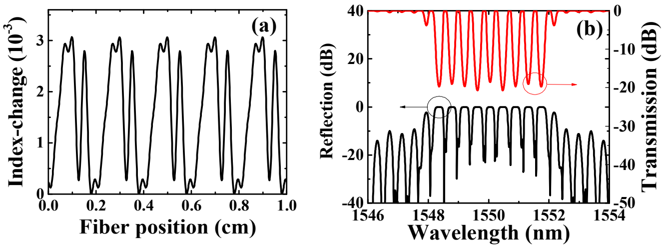

Fig. 2. (a) The optimized DC-sampling function for 9-channel FBG. (b) The calculated spectra for the DC-sampling 9-channel FBG.

III. CONCLUSIONS

A novel DC-sampling method enabling to produce a multichannel FBG is firstly proposed and numerically demonstrated. The proposed method would provide us much more flexibilities to fabricate any other new kinds of fiber gratings than ever before.

ACKNOWLEDGMENT

This work is partly supported by KDDI Foundation for Research Grant Program, and Jiangsu Provincial Natural Science Research Projects for Higher Education Institutions (18KJB510020).

REFERENCES

1. F. Oullette, P. Krug, T. Stephens, G. Dhosi, and B. Eggleton, "Broadband and WDM dispersion compensation using chirped sampled fibre Bragg gratings," Electron. Lett. 31(11), 899-901 (1995).
2. M. Ibsen, M. Durkin, M. Cole and R. Laming, "Sinc-sampled fiber Bragg gratings for identical multiple wavelength operation," IEEE Photon. Tech. Lett. 10(6), 842-844 (1998).
3. H. Li, Y. Sheng, Y. Li, and J. Rothenberg, "Phased-only sampled fiber Bragg gratings for high channel counts chromatic dispersion compensation," IEEE J. Lightwave Technol. 21(9), 2074-2083 (2003).
4. H. Li, M. Li, K. Ogusu, Y. Sheng, and J. Rothenberg, "Optimization of a continuous phase-only sampling for high channel-count fiber Bragg gratings," Optics Express 14(8), 3152-3160 (2006).
5. H. Li, M. Li, Y. Sheng, and J. Rothenberg, "Advances in the design and fabrication of high-channel-count fiber Bragg gratings," IEEE J. Lightwave Technol. 25(9), 2739-2750 (2007).
6. C. Zhu, S. Ishikami, H. Zhao, and H. Li, "Multichannel long-period fiber grating realized by using the helical sampling approach," IEEE J. Lightwave Technol., DOI: 10.1109/JLT.2019.2897314, In Press, (2019).
7. T. Erdogan, "Fiber grating spectra," IEEE J. Lightwave Technol. 15(8), 1277-1294 (1997).