High channel-count comb filter based on multi-concatenated sampled chirped fiber Bragg gratings

Hongwei Yuan (苑红伟)[1], **Jun Zhou (周　骏)**[1,2*], **Weitao Ma (马伟涛)**[2],
Yongtang Sun (孙永堂)[1], and **Tiefeng Xu (徐铁峰)**[2]

[1]*Department of Optical Engineering, School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China*

[2]*Institute of Photonics, Faculty of Science, Ningbo University, Ningbo 315211, China*

*Corresponding author: ejzhou@yahoo.com.cn

A high channel-count comb filter based on multi-concatenated sampled chirped fiber Bragg gratings (MC-SCFBGs) is proposed and optimally designed by using several chirped gratings with different fundamental grating periods, instead of non-grating sections of SCFBGs. The numerical simulations of the reflection spectra show that the channel spacing and the channel bandwidth in MC-SCFBGs are smaller than those in multi-concatenated chirped fiber Bragg gratings (MC-CFBGs) and that the spectral bandwidth of MC-SCFBGs can be greatly broadened by increasing the cascade number of the grating sections in each sampling period.

OCIS codes: 060.2340, 060.3735, 350.2460.
doi: 10.3788/COL201109.080601.

In the last decades, fiber gratings as essential components in optical communication and fiber sensing systems have been rapidly developed[1−3]. The design and manufacturing of multi-channel filters based on the conventional sampled fiber Bragg gratings (SFBGs) have been largely investigated because of the increasing demand for higher number of wavelength channels in wavelength division multiplexing systems. The multi-channel operation of SFBGs is generated by the periodic sampling function, which is characterized by two parameters: the sampling period P and the length L_g of an individual grating section. The reflection spectrum of a SFBG has the following features: the overall reflection bandwidth, the channel spacing, and the channel bandwidth are inversely proportional to the respective grating section length, the sampling period, and the total length of the SFBG, respectively[4,5]. Nevertheless, in reality, in order to simultaneously realize broad bandwidth, dense channel spacing, and narrow channel bandwidth, the grating section length L_g has to be reduced, whereas the sampling period P and the total length of the SFBG have to be increased. Therefore, the sampling ratio, defined as $r = L_g/P$, has to be a small value (e.g., $L_g = 0.1$ mm, $P = 1.0$ mm, and $r = 0.1$)[6].

To make the channel spacing of SFBGs dense without changing the sampling period and the total length, some methods have been used in the design of SFBGs such as the multiple-phase-shift technique[5], the fractional Talbot effect[7], and the interleaved sampled Bragg gratings[8,9]. Although these methods are convenient and effective, concatenating several chirped gratings as one sampling period is rarely done to design SFBGs. Multi-concatenated chirped fiber Bragg gratings (MC-CFBGs) show the desired characteristics in the form of comb filters, such as broadening the total wavelength range, but both the channel spacing and the channel bandwidth are larger than those of sampled chirped fiber Bragg gratings (SCFBGs)[10]. In this letter, based on research on SCFBGs and MC-CFBGs, by replacing the non-grating sections with several chirped gratings with different fundamental grating periods, some structures for multi-concatenated SCFBGs (MC-SCFBGs) are proposed to realize high channel-count comb filters with broadened spectral bandwidth without changing the sampling period and the total length.

The schematic diagrams of the three kinds of grating structures are illustrated in Fig. 1. We assume that all the gratings have identical chirping coefficient c, and the chirped grating period can be expressed as $\Lambda(z) = \Lambda_0 + cz$ with $-L_g/2 < z < L_g/2$, where Λ_0 is the fundamental grating period at the center of the grating section. A SCFBG is a periodically sampled grating structure with chirped fiber Bragg gratings as its seeding gratings, as shown in Fig. 1(a). A MC-CFBG is shown in Fig. 1(b), where the chirped fiber Bragg gratings are the same as those in Fig. 1(a). By cascading several chirped grating sections with different fundamental grating periods Λ_{0i} as one sampling period, a MC-SCFBG is developed. The fundamental grating period of the ith grating section is given by $\Lambda_{0i}(i) = \Lambda_{01}[1 + c_g(i-1)]$, where $i \in (1, M)$ and the positive integer M is the cascade number of grating sections in one sampling period, c_g is the chirp coefficient of the grating period, and Λ_{01} is the first fundamental grating period. For simplified analysis, Fig. 1(c) shows an example of a MC-SCFBG with three different fundamental grating periods, Λ_{01}, Λ_{02}, and Λ_{03}. In our simulations, the three grating structures are assumed to have the same total length of $L_t = 12.0$ mm and the other parameters are as follows: the average refractive index is $n = 1.4568$, the peak refractive index modulation is $\delta n = 1 \times 10^{-3}$, $L_g = 1.0$ mm, $P = 3.0$ mm, $r = 1/3$, the sampling number $N_s = 4$ for the SCFBG and the MC-SCFBG, the cascade number $N_c = 12$ for the MC-CFBG, $c_g = 5.671 \times 10^{-3}$, $c = 1.2$ nm/mm, and $\Lambda_{01} = 529.0$ nm.

The fractional Talbot effect[7,11] in SCFBGs results in the channel wavelength spacing m (being a positive integer) being several times smaller than that of the uniform SFBGs, where the wavelength spacing $\Delta\lambda$ between
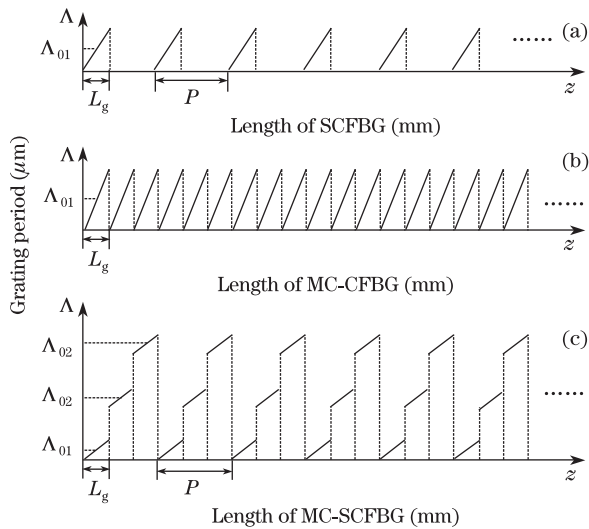
Fig. 1. Schematic diagrams of fiber grating structures: (a) SCFBG, (b) MC-CFBG, and (c) MC-SCFBG with periods of Λ_{01}, Λ_{02}, and Λ_{03}.

adjacent reflection bands is fixed by the sampling period P with the relationship of $\Delta\lambda = \lambda_B^2/(2nP)$[3]. However, it should be noticed that the influence of the fractional Talbot effect is not included in the following discussions.

The reflection spectra of the grating structures illustrated in Fig. 1 are calculated using the transfer matrix method[12], and the results are plotted in Fig. 2. As can be seen, the reflection spectra have the same characteristics: (i) the reflection peaks of the spectrum are uniformly distributed because the period of each grating section is linearly changed when c is a constant; (ii) the maximum reflectivity is located at the Bragg wavelength due to the Bragg condition $\lambda_B = 2n\Lambda$ (e.g., the wavelength is 1,541.3 nm for $\Lambda_{01} = 529.0$ nm); (iii) the other orders of reflection peaks can be derived from the Fourier analysis theory[13,14]. Figure 2 also shows that the –3-dB bandwidths are 4.02, 7.23, and 10.32 nm, and the channel numbers are 15, 9, and 37, corresponding to the SCFBG, the MC-CFBG, and the MC-SCFBG, respectively. Moreover, compared with Fig. 2(a), Fig. 2(c) shows that the reflection bandwidth of the MC-CFBG is widened greatly when the non-grating sections in each sampling period in Fig. 1(a) are replaced by identical chirped grating sections, and Fig. 2(e) shows that the reflection bandwidth of the MC-SCFBG is almost three times that of the SCFBG when more chirped grating sections are concatenated with different fundamental grating periods.

Furthermore, the details of the reflection spectra in the wavelength range of 1,541–1,546 nm are illustrated in Figs. 2(b), (d), and (f). Figures 2(b) and (f) show the bandwidths of SCFBG and MC-SCFBG, which are uniformly distributed with the channel spacing being equal to 0.2718 nm. In addition, in Fig. 2(d), the channel spacing of the MC-CFBG equals 0.8154 nm, which is exactly three times that of the SCFBG, mainly because the "equivalent" sampling period P_e and the grating section length L_g have the same value, resulting in the sampling period P_e being one-third that of the SCFBG (i.e., $P = 3.0$ mm for the SCFBG and $P_e = L_g = 1.0$ mm for the MC-CFBG). However, compared with the SCFBG and
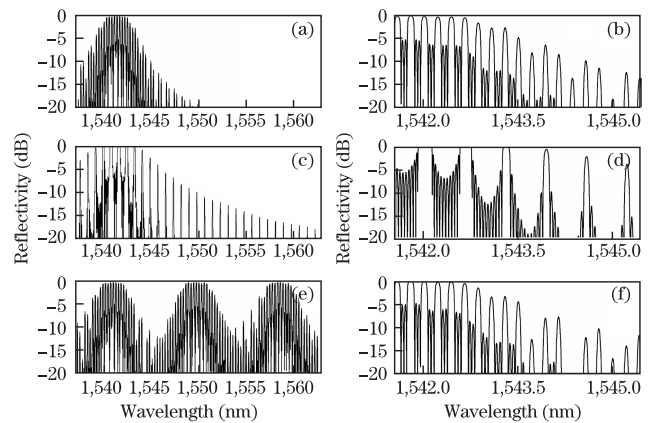

Fig. 2. Reflection spectra (with detail drawings) of fiber grating structures: (a) and (b) SCFBG structure; (c) and (d) MC-CFBG structure; (e) and (f) MC-SCFBG structure.
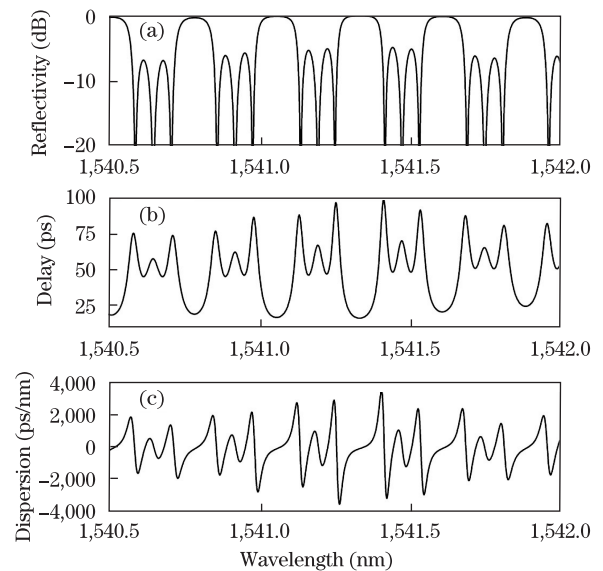

Fig. 3. (a) Reflection spectrum, (b) group delay, and (c) dispersion characteristics corresponding to the MC-SCFBG.

MC-SCFBG, the channel bandwidth of the MC-CFBG is non-uniform and reflection is very strong when the cascaded number of grating sections is relatively large. From Figs. 2(b) and (f), the reflection spectra of the MC-SCFBG is similar to that of the SCFBG, indicating that they have "equivalent" sampling period of $P = 3.0$ mm. Additionally, as shown in Figs. 2(a) and (e), the reflection spectrum of the three sets of SCFBGs with different fundamental grating periods is the same as that of the MC-SCFBG, although the former must be three times as long as the latter. The MC-SCFBG clearly seems to be "compressed", and its reflection spectrum bandwidth is broadened dramatically when the non-grating sections are replaced with several chirped gratings with different fundamental grating periods.

For the structure of MC-SCFBG, the group delay and dispersion properties are also investigated and shown in Fig. 3. Despite the concatenation and chirp effect, the in-band group delay characteristic of MC-SCFBG is still similar to that of SCFBG. In Fig. 3(b), the group delay curve has periodicity that corresponds to the uniformly distributed reflection channels, as shown in Fig. 3(a).
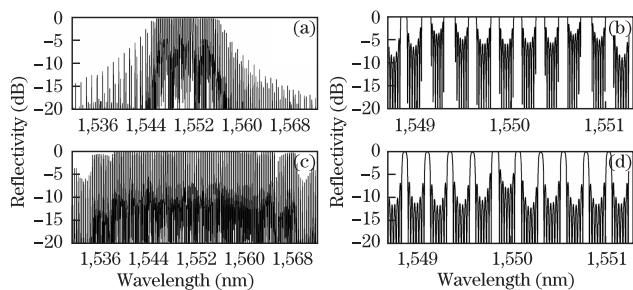
Fig. 4. Reflection spectra (with detail drawings) of two MC-SCFBGs: (a) and (b) $M = 3$, $\Lambda_{01} = 531.0$ nm, $L_{\mathrm{g}} = 1.0$ mm; (c) and (d) $M = 10$, $\Lambda_{01} = 528.0$ nm, $L_{\mathrm{g}} = 0.3$ mm.

Comparing Figs. 3(b) and (c), a quadratic and symmetric shape in each in-band group delay curve implies the following: (i) there is an approximately linear variation in the dispersion curve; (ii) the zero dispersion and small dispersion appear in the center and the edges of the reflection channel, respectively.

In order to confirm whether the bandwidth broadening effect is dependent on the number of grating sections with different Λ_{0i} in each sampling period, the reflection spectra of two MC-SCFBGs with different cascade number M are simulated and plotted in Fig. 4 for the same design parameters of $P = 3.0$ mm, $L_{\mathrm{t}} = 24.0$ mm, $N_{\mathrm{s}} = 8$, and $c_{\mathrm{g}} = 1.883 \times 10^{-3}$. It can be seen from Figs. 4(a) and (c) that the –3-dB bandwidths are 11.52 and 30.80 nm and the channel numbers are 41 and 108, respectively. This demonstrates that compared with that of SFBG, the bandwidth of MC-SCFBG is broadened due to the increase in the cascade number M of the chirped grating sections and the expandability of the filtering band by the strong chirp in each chirped grating section. In addition, it can be seen from Figs. 4(b) and (d) that the reflectivity of the main reflection peaks averages -1.7882×10^{-3} and -2.1450×10^{-1} dB, respectively, whereas the reflection spectra have the same channel spacing for different M. However, the average reflectivity and the channel bandwidths in Fig. 4(d) are smaller than those in Fig. 4(b) due to the different lengths of the grating section. In addition, when the channel spacing (inversely proportional to $P = M \times L_{\mathrm{g}}$) is small, the crosstalk between two adjacent channels will be relatively large because of the increase in the reflectivity of the side lobes, thereby decreasing the isolation between the two adjacent channels. Therefore, a trade-off for the length of the grating section between a necessary short size for obtaining the narrow channel bandwidth and a sufficiently long size for an efficient reflectivity of the peak must be determined.

Possible problem in practical fabrication for MC-SCFBGs, is difficult to ensure the distance between two adjacent grating sections to be zero, thus phase shift between the grating sections is induced inevitably. With the increase of random phase shift, the side lobes increase significantly and the reflection spectrum becomes worse. Nevertheless, apodization[12] can effectively reduce the side lobes and increase the isolation between channels.

In conclusion, MC-SCFBGs can serve as a positive reference for the design of fiber filters. Based on the analysis of SCFBGs and MC-CFBGs, when the non-grating sections of SCFBGs are replaced by several chirped gratings with different fundamental grating periods, the immediate advantage of MC-SCFBGs is realizing the broadening of the spectral bandwidth without changing the sampling period and the total length of the grating structure. Overall, MC-SCFBGs can provide a new application in optical communication systems.

References

1. M. Li, X. Chen, J. Hayashi, and H. Li, Opt. Express **17**, 8382 (2009).
2. J. Bland-Hawthorn, A. Buryak, and K. Kolossovski, J. Opt. Soc. Am. A **25**, 153 (2008).
3. S. Lu, O. Xu, S. Feng, and S. Jian, Chin. Opt. Lett. **7**, 469 (2009).
4. W. H. Loh, F. Q. Zhou, and J. J. Pan, IEEE Photon. Technol. Lett. **11**, 1280 (1999).
5. Y. Nasu and S. Yamashita, J. Lightwave Technol. **23**, 1808 (2005).
6. X. H. Zou, W. Pan, B. Luo, Z. M. Qin, M. Y. Wang, and W. L. Zhang, IEEE Photon. Technol. Lett. **18**, 1371 (2006).
7. J. Azaña, C. Wang, and L. R. Chen, J. Opt. Soc. Am. B **22**, 1829 (2005).
8. W. H. Loh, F. Q. Zhou, and J. J. Pan, Opt. Lett. **24**, 1457 (1999).
9. J. M. Castro, J. E. Castillo, R. Kostuk, C. M. Greiner, D. Iazikov, T. W. Mossberg, and D. F. Geraghty, IEEE Photon. Technol. Lett. **18**, 1615 (2006).
10. W. Ma, J. Zhou, T. Xu, L. Zhang, and H. Yuan, Chinese J. Laser (in Chinese) **37**, 1284 (2010).
11. C. Wang, J. Azaña, and L. R. Chen, Opt. Lett. **29**, 1590 (2004).
12. T. Erdogan, J. Lightwave Technol. **15**, 1277 (1997).
13. H. Li, M. Li, and J. Hayashi, Opt. Lett. **34**, 938 (2009).
14. H. Li, Y. Sheng, Y. Li, and J. E. Rothenberg, J. Lightwave Technol. **21**, 2074 (2003).