# Channel spacing halving and multi-channel apodisation of sampling fiber Bragg grating based on Moiré effect

**Ling Zhao (赵 岭), Ronghui Qu (瞿荣辉), Lin Li (李 琳),**
**Aiping Luo (罗爱平), and Zujie Fang (方祖捷)**

*Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Science, Shanghai 201800*

Received September 3, 2002

Channel spacing halving and multi-channel apodisation of sampling fiber Bragg grating (SFBG) based on Moiré effect are demonstrated, which are realized by stretching and double exposure in fabrication of the SFBG. The experiment and theoretical analysis showed that the channel spacing could be halved when the period of Moiré grating was four times of the period of sampling and the initial phase difference of two exposures was even times of $\pi$. The multi-channel apodisation could be realized when the period of Moiré fringe was twice the length of SFBG and the initial phase difference of two exposures was odd times of $\pi$. A novel method to control the initial phase difference of two exposures is presented in this paper. Using this technique, we fabricated two SFBGs with channel spacing of 50 and 100 G by a same phase mask and an apodized SFBG with channel spacing of 100 G.

*OCIS codes:* 060.2340, 060.2330, 050.2770.

UV induced sampling fiber Bragg gratings (SFBGs) have been an interesting subject as potential enabling technologies for multi-wavelength filtering[1], multi-channel optical add/drop multiplexing[2] and broad tuning in DBR fiber laser[3] because they offer multiple reflection peaks with precise control over the peak separation[4]. Dense channel spacing and high side lobe suppression are needed to improve efficiency of channels and ensure high channel isolation when the SFBG is used as multi-channel filter in DWDM system. N. Yusuke and S. Yamashita halved the channel spacing of SFBG by moving the phase mask or using uniform UV light as a post-process which introduced a $\pi$ phase shift every second sampled section[5]. R. Kashyap *et al.* apodized chirp and unchirp FBGs by Moiré effect caused by stretching and double exposure[6]. We demonstrated theoretically and experimentally that the channel spacing of SFBG could be halved when the period of Moiré grating was four times of the period of sampling and the initial phase difference of two exposures was even times of $\pi$ during stretching and double exposure. The multi-channel apodisation could be realized when the period of Moiré fringe was twice the length of SFBG and the initial phase difference of two exposures was odd times of $\pi$. A novel method to control the initial phase difference of two exposures is presented in this paper. Using this technique, we fabricated two SFBGs with channel spacing of 50 and 100 G by a same phase mask, respectively and an apodized SFBG with channel spacing of 100 G.

The channel separation of SFBG is given as[7]

$$\Delta\lambda = \frac{\lambda_{\mathrm{B}}^2}{2 \cdot n_{\mathrm{eff}} \cdot L_A}, \tag{1}$$

where $n_{\mathrm{eff}}$ is the effective refractive index in the grating and $L_A$ is the sampling period, and $\lambda_{\mathrm{B}}$ is Bragg wavelength determined by the period of phase mask. It has been proved that different channels appear more even under small sampling duty cycle[8]. During the fabrication of SFBG, the index modulation must increase to get high reflectivity and the UV source must have large spatial coherence when the sampling duty cycle is small.

For uniform-period gratings of equal refractive index amplitude $\delta n$ with period $\Lambda_1$ and $\Lambda_2$, the double exposures result in a spatial amplitude-modulated waveform with a rapid variation with period $\Lambda_c$ and a slowly varying envelope with period $\Lambda_s$[9]. That is so-called Moiré effect. At the envelope crossover points, the phase of the grating changes intrinsically by $\pi$. When the period of Moiré grating $\Lambda_s$ is four times of the sampling period $L_A$ and $\pi$-phase-shifted points overlap the area exposed through amplitude mask, the index modulation of the area near the $\pi$-phase-shifted points is suppressed, as shown as Fig. 1(a). In this case, the sampling period is doubled equivalently and the channel spacing of SFBG is halved. The initial phase difference $\varphi_1 - \varphi_2$ of two exposures must be even times of $\pi$ in order to ensure $\pi$-phase-shifted points to overlap the area exposed through amplitude mask. The advantage of the halving channel method is that the equalization of different channels is hardly affected because the sampling duty cycle does not change. The channel space halving is more obvious when the sampling duty cycle is small because the index modulation of the area near $\pi$-phase-shifted points could be more suppressed. When the period of Moiré fringe is twice the length of SFBG and the initial phase difference of two exposures is odd times of $\pi$, the average effective index of the grating remains constant, even though the index modulation becomes a varying function of grating length, as shown as Fig. 1(b). In this case, the SFBG is apodized.

We simulated the side lobe suppression and 3-dB bandwidth of center reflection peak of SFBG versus the sampling period and obtained the results, as shown in Fig. 2. The related parameters in simulation were: $\delta n = 1 \times 10^{-3}$, $\Lambda_1 = 535.5$ nm, $L_A = 1$ mm, $R = 1/10$, $L = 10$ mm, $n_{\mathrm{eff}} = 1.45$, $\lambda_{\mathrm{B}} = 1550$ nm, and $\varphi_1 - \varphi_2 = \pi$.

It is clear that the side lobes are suppressed evidently at different sampling period when the SFBG is apodized by Moiré effect. The 3-dB bandwidth of center reflection

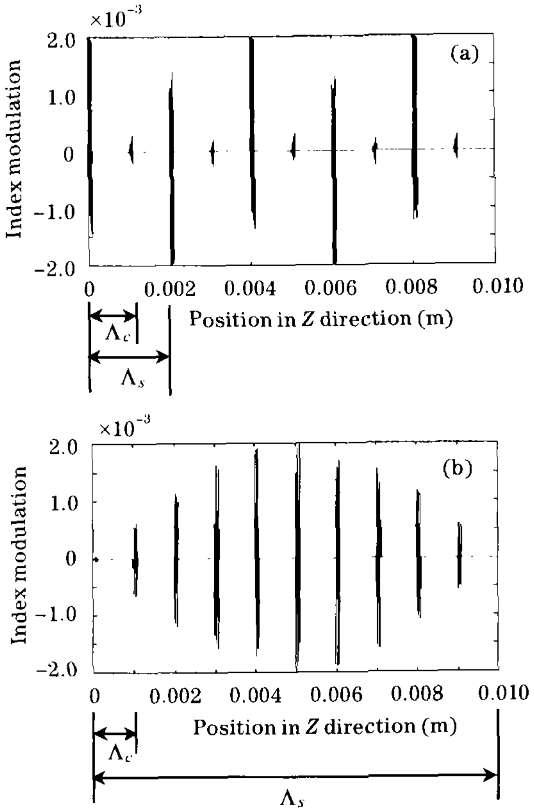


Fig. 1. Distribution of index for Moiré SFBG. (a) Channel spacing halving ($\Lambda_s$ = 4 mm, $\varphi_1 - \varphi_2 = 0$); (b) apodisation ($\Lambda_s$ = 2 cm, $\varphi_1 - \varphi_2 = \pi$).

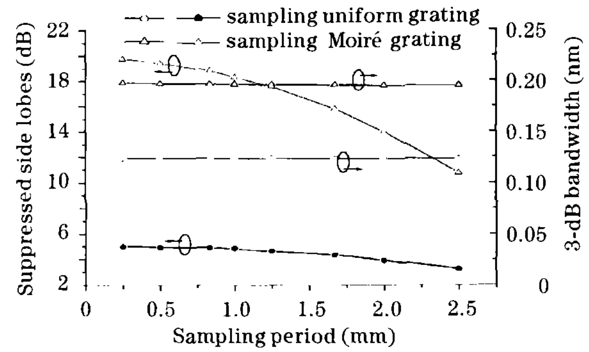


Fig. 2. Side lobe suppression and 3-dB bandwidth versus sampling period.

peak of SFBG was widened after apodisation. The other reflection peaks also had the same characteristics as the center reflection peak. So multi-channel of SFBG can be apodized simultaneously by Moiré effect.

The fiber used in the experiment was standard telecom fiber which had been hydrogen-loaded at a pressure of 140 atm at room temperature for several weeks in order to get high photosensitivity. The fiber was placed directly behind the 10-mm-long uniform-period phase mask on which there overlapped a metal sampling mask with rectangular slit and controlled by a one-dimension adjuster. The source was 193 nm ArF excimer laser with intensity of 100 mJ/cm$^2$. The sampling period was 1 mm and sampling duty cycle was 1 : 10. The experiment setup was shown in Fig. 3(a). Because the controlling of the initial phase difference $\varphi_1 - \varphi_2$ of two exposure is a key factor in forming Moiré fringe, we stretched the fiber to get the phase difference as shown in Fig. 3(b).

The fiber was fixed at the point of $A$ and $D$ during the first exposure. After the first exposure, the fiber was stretched at the point of $D$ while the point of $A$ was fixed at the original position. The length of grating ($BC$) was defined as $L_g$, which was decided by the length of phase mask. The length of $AB, CD$ and $AD$ were defined as $L_1, L_2$ and $L$, respectively. The total change of the fiber in stretching is

$$\Delta L = \Delta L_1 + \Delta L_g + \Delta L_2, \tag{2}$$

The initial phase difference $\varphi_1 - \varphi_2$ equals to odd times of $\pi$ when $\Delta L_1 = (2M+1)\Lambda_1/2$, where $\Lambda_1$ is the period of grating before stretching and $M$ is an integer. The strain of the whole fiber should be uniform, therefore a relation holds as

$$\frac{\Delta L}{L} = \frac{\Delta L_g}{L_g} = \frac{\Delta L_2}{L_2}. \tag{3}$$

From Eqs. (2) and (3) we get

$$M = \frac{\Delta L \cdot (L - L_g - L_2)}{L \cdot \Lambda_1} - \frac{1}{2}. \tag{4}$$

The initial phase difference $\varphi_1 - \varphi_2$ equals to even times of $\pi$ when $\Delta L_1 = M\Lambda_1$ and we get

$$M = \frac{\Delta L \cdot (L - L_g - L_2)}{L \cdot \Lambda_1}. \tag{5}$$

So we could choose proper $\Delta L$ and $L_2$ to meet the requirement of Eqs. (4) and (5) with known $L$, $L_g$ and $\Lambda_1$. The parameter $\Delta L$ can be precisely controlled because there exists the relation as

$$\frac{\Delta L}{L} = \frac{\Delta \lambda}{\lambda}, \tag{6}$$

where $\Delta\lambda$ is the Bragg wavelength of center reflection peak of SFBG. Using this technique, we fabricated two

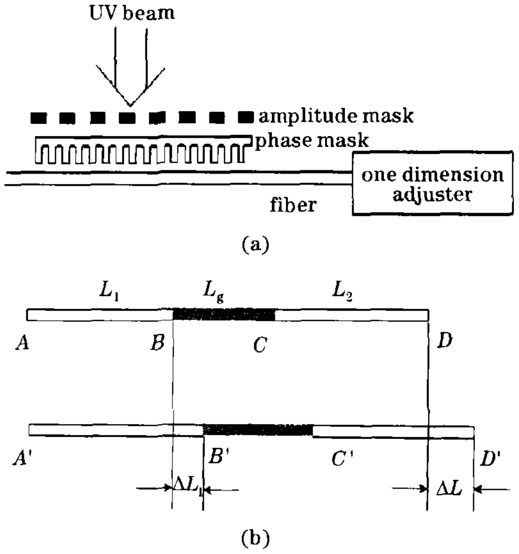
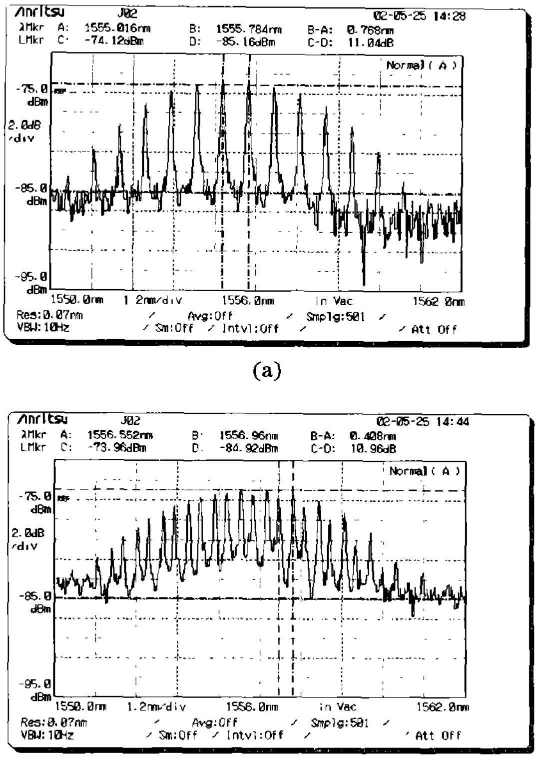


Fig. 3. Moiré SFBG fabrication. (a) Experiment setup; (b) controlling the initial phase difference $\varphi_1 - \varphi_2$ by stretching.



(a)

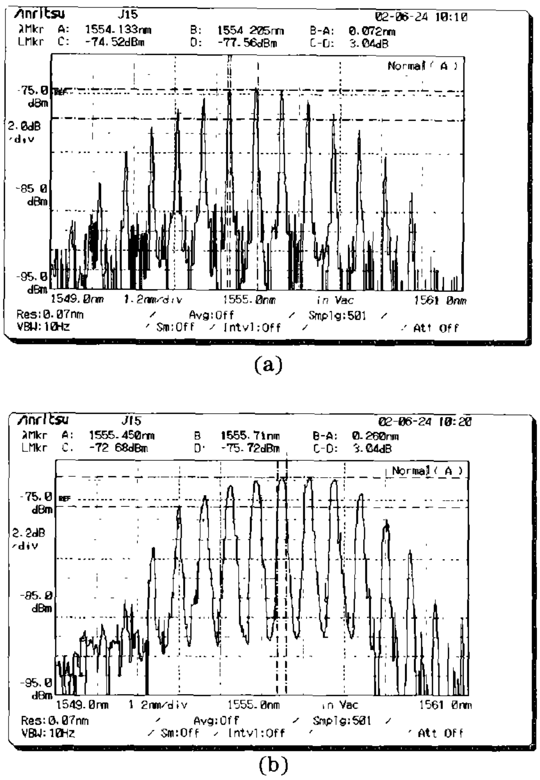
(b)

Fig. 4. Channel Spacing of SFBG halving by Moiré effect. (a) Before halving; (b) after halving.

kinds of SFBG whose channel spacing were 50 and 100 G by a same phase mask, respectively. The reflection spectra are shown in Fig. 4. The resolution of the optical spectra analyzer is 0.07 nm.

We fabricated an apodized SFBG whose channel spacing was 100 G. The reflection spectrum is shown in Fig. 5(b). It is clear that the side lobes of reflection peaks were suppressed simultaneously and the 3-dB bandwidth of reflection peaks were widened, that will help to improve the efficiency of channels.

In summary, we demonstrated that the channel spacing of SFBG could be halved when the period of Moiré grating was four times of the period of sampling and the initial phase difference of two exposures was even times of $\pi$ during stretching and double exposure. The multichannel apodisation could be realized when the period of Moiré fringe was twice the length of SFBG and the initial phase difference of two exposures was odd times of $\pi$. A novel method to control the initial phase difference of two exposures was presented in this paper. Using this technique, we fabricated two SFBGs with channel spacings of 50 and 100 G by a same phase mask, respectively and an apodized SFBG with channel spacing of 100 G.



(a)

(b)

Fig. 5. Apodisation of SFBG by Moiré effect. (a) Without apodisation; (b) with apodisation.

L. Zhao's e-mail address is lingzhaook@sina.com.cn.

## References

1. J. Hübner, D. Zauner, and M. Kristensen, IEEE Photon. Technol. Lett. **18,** 552 (1998).
2. W. H. Loh, F. Q. Zhou, and J. J. Pan, Opt. Lett. **24,** 1457 (1999).
3. M. Ibsen, B. J. Eggleton, M. G. Sceats, and F. Ouellette, Electron. Lett. **31,** 899 (1995).
4. B. J. Eggleton, P. A. Krug, L. Poladian, and F. Ouellette, Electron. Lett. **30,** 1620 (1994).
5. N. Yusuke and S. Yamashita, Proc. Optics and Fiber Commun. **TuQ3,** 110 (2002).
6. R. Kashyap, A. Swanton, and D. J. Armes, Electron. Lett. **32,** 1226 (1996).
7. M. Ibsen, M. K. Durtin, and M. J. Cole, IEEE Photon. Technol. Lett. **10,** 842 (1998)
8. L. Li, Z. J. Fang, and H. W. Cai, in *Proc. CLEO/Pacific Rim,* p. I-404 (2001).
9. D. C. J. REID, C. M. Ragdale, and I. Bennion, Electron. Lett. **26,** 10 (1990).