On-line writing identical and weak fiber Bragg grating arrays

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We investigate the on-line writing identical fiber Bragg grating (FBG) arrays using the phase mask technique. Given the limitation of laser power, the energy density uniformity and the horizontal width of the writing spot cannot be further optimized. The results show that the FBG arrays obtained in the optimal process (drawing speed of 12 ± 0.15 m/min and average tension of 38.2 g) have a central wavelength bandwidth of less than 0.1 nm and an average reflectivity of 0.26%. Thus, the phase mask method is a promising alternative for on-line writing identical FBG arrays.

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On-line writing weak fiber Bragg grating (FBG) arrays is the process in which FBGs are directly inscribed into fiber during drawing. In this case, FBG writing must be performed before the fiber coating application because the fiber coating is usually not transparent to ultraviolet (UV) light. In traditional FBG preparation, the fiber needs to be decoated prior to FBG writing, and then recoated after the grating exposure. The conventional process is difficult to handle and degrades fiber strength, which causes damage to the engineering application. However, draw-tower FBGs can overcome these disadvantages because of simple operation and high mechanical stability[1,2]. Furthermore, such method can produce FBG sensor arrays without fiber splicing, which cannot be avoided in the traditional FBG array construction. Avoiding fiber splicing is important because splicing loss greatly reduces the multiplexing capacity of weak FBG arrays. These advantages have thus prompted researchers to investigate draw-tower FBGs[3,4].

The multiplexing capacity of traditional FBG sensor arrays is limited to dozens of FBGs although various multiplexing methods are used, e.g., wavelength-division multiplexing, time-division multiplexing, and so on[5−7]. Recently, several investigations have reported that identical weak FBG arrays can greatly improve the multiplexing capacity and sensing distance because of their narrow bandwidth and weak reflection characteristics[8−10]. However, these promising characteristics require that the weak FBG array should have good uniformity, especially in its wavelength. The draw-tower grating technique is a good option for preparing identical and weak FBG arrays.

Various factors of central wavelength separation, including fluctuations of drawing tension and core temperature, have been reported previously[3]. However, by detecting the surface temperature of bare fiber, we found that the core temperature of bare fiber at the writing spot was almost consistent at the stable drawing state. Several draw-tower FBGs are currently available in the market[11]. However, their wavelength accuracy of $\leqslant 0.4$ nm does not meet the requirements of high-quality FBG arrays, as shown in Table 1. In their FBG writing platforms, the interference fringes used for writing FBGs are easily influenced by air flow because of the long optical path of the Talbot interferometer[12]. Moreover, very small changes in the angle and position of the two reflecting mirrors decrease the grating wavelength accuracy. Therefore, the grating wavelength accuracy was not enough even if the phase mask technique was used in the FBG writing platforms. In our experiment, the triangle interference area of the phase mask was directly used for on-line writing identical FBG arrays to reduce the effect of the interferometer.

In this letter, we report on-line writing identical and weak FBG arrays using the phase mask technique. This study involves the preparation of a photosensitive fiber and experimental investigations on the drawing process. We focused on how to improve the uniformity of FBG arrays, and found that the tension fluctuations during drawing would greatly decrease the uniformity of FBG arrays. A suitable and stable tension was a key factor for on-line writing identical and weak FBG arrays.

For on-line writing weak FBG arrays, one production-type draw-tower, which could operate at speeds ranging from 3 to 200 m/min to a bare fiber diameter of 125 μm, was used. The drawing speed and drawing tension can be automatically controlled and displayed. A line-narrowed ArF excimer laser (OptoSystems CL5300), with a beam size of 4×12 (mm), pulse width of 10 ns, maximum pulse energy of 40 mJ, and maximum laser repetition rate of 300 Hz, was used in the FBG writing platform. The reflective spectra of FBGs were obtained using an

Table 1. Standard Specifications for Single Draw-tower Grating and Draw-tower Grating Chain

Center Wavelength (nm)	1 525...1 575 or 810...860
Wavelength Accuracy (nm)	$\leqslant 0.4$
Attenuation (dB/km)	8.6 at 1 550 nm 18.4 at 830 nm

optical analyzer (Yokogawa-AQ6370B) with a homemade LED source at 1.3-μm wavelength band. The spectra of the weak FBG arrays were obtained using an optical time domain reflectometer (OTDR, Yokogawa-AQ7260).

FBG was written via the phase mask method using periodic interference fringes of the $\pm$1st diffraction light to irradiate photosensitive fiber. Thus, the refractive index of the fiber core was periodically changed. In this method, the interference fringes were determined by the structure of the phase mask and not influenced by light source coherence, which ensured the good wavelength consistency of the FBG array. The laser beam was as large as possible to ensure uniform energy density in a wider writing spot. Moreover, the FBG writing platform was mounted on the draw tower near the first coating to reduce fiber vibration, as shown in Fig. 1. In our experiment, draw-tower FBG arrays were generally performed under the relatively stable pulse energy of 25 mJ. The laser beam was focused from a 4×12 to a 0.7×10 (mm) line using three cylindrical lenses. The distance between the phase mask and bare fiber was controlled at 0.50 mm.

Draw-tower FBG arrays require that the fibers possess high single-pulse photosensitivity because the single laser pulse used in this study has limited energy and irradiation time. A previous report indicated that co-doping Ge/B can greatly improve the photosensitivity of the optical fiber[13]. In the present study, a Ge/B co-doped preform was fabricated at the Optical Fiber Research and Development Department, Fiber-Home Communication Science and Technology Co., Ltd. The obtained fiber, with a B-doped concentration of approximately 10 mol%, showed excellent single-pulse photosensitivity and acceptable attenuation of 2.8 dB/km at 1 300 nm. Compared with the traditional hydrogen-loaded fiber (immersed in 9 Mpa hydrogen for 1 month), the Ge/B co-doped fiber showed a 15-fold grating reflectivity, or 2.1%, under the same conditions of a laser pulse energy of 29 mJ and beam size of 0.4×10 (mm). The Ge/B co-doped fiber was suitable for on-line writing FBG arrays.

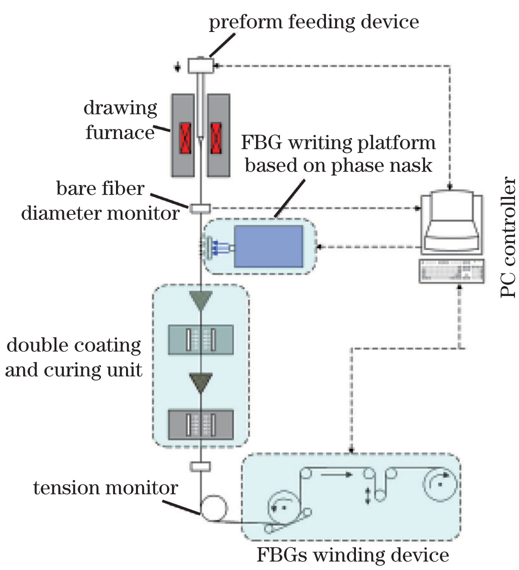

Fig. 1. Diagram of the on-line writing FBG system.

Table 2. Drawing Conditions of the two FBG Arrays

Drawing Conditions	300-FBG Array (A) 200-FBG Array (B)
Drawing Speed (m/min)	12±0.15 13±0.2
Average Drawing Tension* (g)	38.2 89.8
Furnace Temperature** (°C)	1 680±0.5 1 600 ±0.5

*Given that the drawing tension is small, the standard tension unit of Newton is replaced by gram.

**Furnace temperature is not accurate and is used only as reference, but furnace temperature is stably controlled.

In this study, two representative FBG arrays (array A and array B) were prepared under different drawing conditions, as shown in Table 2. The drawing tension in array B was significantly increased by lowering the furnace temperature.

Figure 2(a) shows the OTDR trace of continuous 200 FBGs in array A. Each FBG was written successfully. Figure 2(b) displays the local enlargement between 0.8 and 0.9 km. Therefore, the spatial separation within array A was fixed at 5 m. Under a drawing speed of 10 m/min, the system can achieve a spatial separation at the millimeter level with an accuracy of $\pm$1 mm.

Figure 3 shows the reflection spectra of array A and its single FBG (a) without tress. The overlapping spectrum of array A was almost similar to that of its single

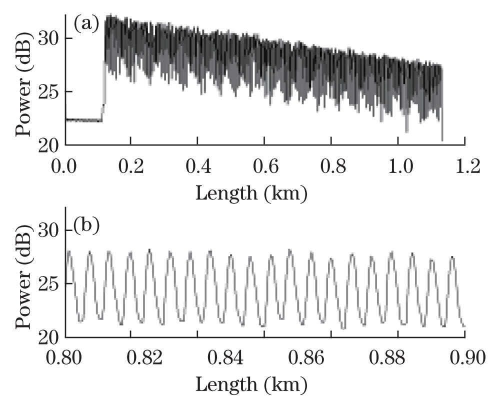

Fig. 2. (a) OTDR fragment from 200 FBGs of array A; (b) local enlargement between 0.8 and 0.9 km.

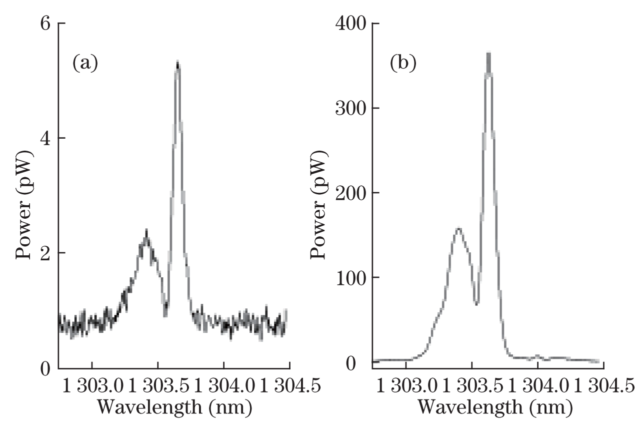

Fig. 3. Reflection spectra of array A and its single FBG, investigated with a light source power of 2.5 nW at 1 303.638 nm.

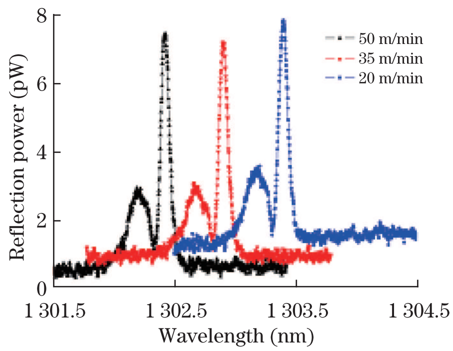

Fig. 4. Reflection spectra of three FBGs written at different speeds.

FBG. Thus, the results indicated that on-line writing FBG array using the phase mask method had a central wavelength with good uniformity.

The effect of drawing speed on the quality of FBG was first studied. Figure 4 shows the reflection spectra of FBGs obtained at different drawing speeds. The shape of the reflection spectra was unaffected by the drawing speed. In all the reflection spectra, the FWHM and reflection power of the main peak were 0.09 nm and ~7 pW, respectively. These findings indicate that FBGs can be written perfectly at specific drawing speeds of interest. Generally, the drawing tension is high at high drawing speeds, which would deteriorate the central wavelength uniformity of the FBG arrays. In addition, stabilizing the drawing process often took more than 1 h at high drawing speed. Therefore, in our experiment, on-line writing identical FBG arrays were conducted at the lower drawing speed of ~15 m/min.

The wavelength uniformity of FBG arrays is important because it is closely related to the data volume of terminal signal demodulation. Although the drawing process reached a stable work state, a small fluctuation in the drawing speed was always present to control fiber diameter in a qualified range. Thus, the fluctuation in the drawing tension was recorded to follow the change in the drawing speed. The central wavelength drifted reversely with an increase in drawing tension (Fig. 5), suggesting that the quality of the FBG arrays is highly sensitive to small fluctuations in drawing speed.

The central wavelength uniformity of on-line writing FBG array was investigated in the current study under different drawing tension values (the drawing tension increased by decreasing the furnace temperature), as shown in Fig. 6. In array A, the central wavelengths of 100 FBGs varied by ~0.1 nm from 1 303.608 to 1 303.686 nm. In array B, the fluctuation in the central wavelength reached up to 0.25 nm, which covered 302.000 to 1 302.250 nm. Moreover, the fluctuation in the adjacent wavelengths increased under high drawing tension. Notably, the change in the drawing speed was small for both FBG arrays, suggesting that high drawing tension was not a favorable condition. Our studies indicated that stable and proper drawing tension is a critical factor that can result in on-line writing FBG arrays with good wavelength uniformity.

Single FBG reflection power in array A was measured successively to investigate the uniformity of the reflection spectra. Figure 7 shows the reflection power of 100 FBGs in array A, in which relative deviation is approximately ±16%. During the draw-tower grating preparation, the output energy of the laser pulse had a fluctuation of ±8%. This finding suggests that the fiber vibration effect was not ignored with the fluctuation of FBG reflection power. Figure 8 shows the vibration of bare optical fiber in the exposed area. Given that the laser energy density is represented by Gaussian distribution in the horizontal direction, it became more uneven from the middle to both sides after spot focus. Therefore, the fiber vibration in the beam spot significantly affected the grating reflectivity.

The effects of drawing speed and drawing tension were investigated to reduce fiber vibration. When the drawing tension was smaller than 10 g, where the drawing speed was low, the lateral vibration of the optical fiber was distinct. The lateral vibration greatly improved with the increase in drawing tension up to 30 g. However, the reflectance consistency of the FBG array was difficult to improve by further decreasing fiber vibration. Thus, other methods for improving the reflectivity uniformity of draw-tower FBG arrays should be studied, e.g., by homogenizing the energy density and by further widening the horizontal dimension of the writing spot.

In conclusion, draw-tower FBG arrays are prepared based on the phase mask technique, and the uniformity of the obtained FBG arrays is investigated. The results indicate that the uniformity of the draw-tower FBG arrays greatly depends on the stability of the drawing process, especially the drawing tension.

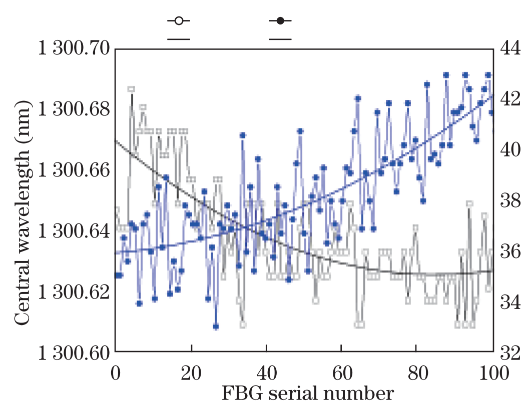

Fig. 5. Central wavelength and drawing tension traces of successive 100 FBGs in array A.

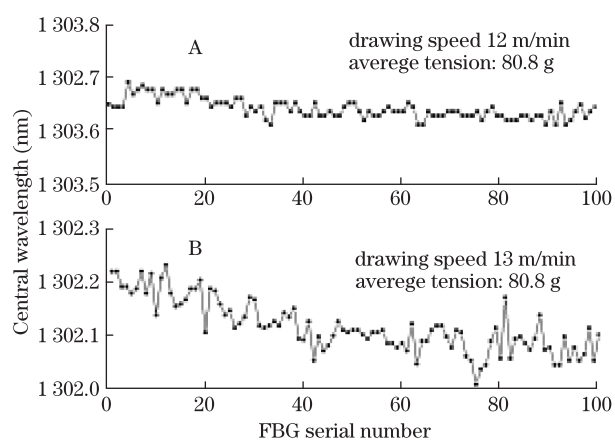

Fig. 6. Central wavelength distribution of successive 100 FBGs in array A and array B.

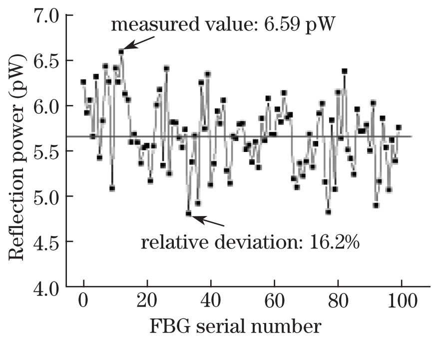

Fig. 7. Single FBG reflection power of 100 FBGs in array A investigated using a light source power of 2.5 nW at 1 303.638 nm.

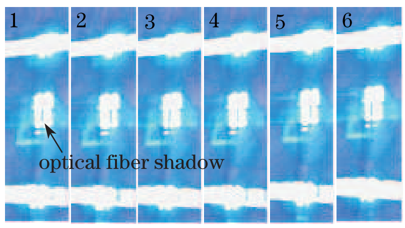

Fig. 8. Six images of the diffraction spot taken at a drawing speed of 12 m/min, average drawing tension of 38.2 g, and laser frequency of 50 Hz.

Under optimized conditions (drawing speed of 12 m/min and average drawing tension of 38.2 g), a 300-FBG array with an average reflectivity of approximately 0.26% is prepared. The array shows a central wavelength bandwidth of less than 0.1 nm, mean reflection power with a relative deviation of ±16%, and an excellent overlapping of peak shape. These results indicate that on-line writing FBG arrays using the phase mask technique results in a central wavelength with good uniformity. However, the uniformity of reflection power is not ideal because of unstable laser pulse energy, uneven distribution of writing energy density, and optical fiber vibration.

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References

1. C. G. Askins, M. A. Putnam, H. J. Patrick, and E. J. Friebele, Electron. Lett. **33,** 1333 (1997).
2. V. Hagemann, M. N. Trutzel, L. Staudigel, M. Rothhardt, H.-R. Mueller, and O. Krumpholz, Electron. Lett. **34,** 211 (1998).
3. L. Dong, J.-L. Archambault, L. Reekie, P. St. J. Russell, and D. N. Payne, Electron. Lett. **29,** 1557 (1993).
4. C. G. Askins, M. A. Putnam, G. M. Williams, and E. J. Friebele, Opt. Lett. **19,** 147 (1994).
5. S. Abad, F. M. Araúo, L. A. Ferreira, J. L. Santos, and M. Lóez-Amo, J. Lightwave Technol. **21,** 127 (2003).
6. Y. Dai, Y. Liu, J. Leng, G. Deng, and A. Asundi, Opt. Laser Eng. **47,** 1028 (2009).
7. X. Wan and H. F. Taylor, Opt. Lett. **18,** 1648 (2003).
8. M. Zhang, Q. Sun, Z. Wang, X. Li, H. Liu, and D. Liu, Opt. Commun. **285,** 3082 (2012).
9. Y. Wang, J. Gong, D. Y. Wang, B. Dong, W. Bi, and A. Wang, IEEE Photon. Technol. Lett. **23,** 70 (2011).
10. X. Li, Q. Sun, D. Liu, R. Liang, J. Zhang, J. Wo, P. P. Shum, and D. Liu, Opt. Express **20,** 12076 (2012).
11. http://www.fbgs-technologies.com/pagina.php?id=21366.
12. H. Bartelt, K. Schuster, S. Unger, C. Chojetzki, M. Rothhardt, and I. Latka, Appl. Opt. **46,** 3417 (2007).
13. D. L. Williams, B. J. Ainslie. J. R. Armitage, R. Kashyap, and R. Campbell, Electron. Lett. **29,** 45 (1993).