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## Fabrication of Dual-Wavelength Fiber Bragg Grating with a Longitudinal Stretch

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**Abstract** A method of fabricating dual-wavelength fiber Bragg grating with a uniform phase mask is demonstrated. Theoretical analysis and numerical simulation using Matrix method are given. The moving exposing technique is adopted. Good control over the grating's reflectivity and the separation of the two Bragg wavelengths is enabled by adjusting the stretch, the length of the grating, and the exposure. A grating with two equal transmission peaks of 19.5 dB is obtained by using this method, and the separation of the two Bragg wavelengths is 0.78 nm.

**Keywords** fiber Bragg grating (FBG), dual-wavelength fiber Bragg grating, Matrix method

**PACS numbers** 42.81.-i

### 1 Introduction

Fiber Bragg gratings (FBGs) have been broadly used in optical communication and sensor system after the photosensitivity of Ge-doped fibers was discovered in 1978 [1–4]. To satisfy more and more applications, various special gratings have emerged, one of which is the dual-wavelength FBG. This kind of grating can be used in multichannel OADMs, multiwavelength filters, and multiwavelength fiber lasers and for solving the problem of the temperature-strain cross sensitivity of FBG sensors [5]. The longitudinal stretch method can be used in fabricating Chirped gratings, morie

gratings, etc. [6–8]. Basing on this method and the moving exposing technique, the dual-wavelength FBGs can be fabricated with only one phase mask. The technique lends itself to writing gratings with controllable reflectivity and separating two resonant wavelengths. The method has many advantages, such as simple operation, flexible control, good repeatability.

### 2 Principle and numerical simulation

The experimental setup is shown in Fig. 1, which shows a fiber holder with a translation stage controlled by a stepper motor and a uniform phase mask fixed on the holder. The UV light from a KrF excimer laser operating at 248 nm is focalized on the photosensitive fiber behind the uniform phase mask by a cylindrical lens. The energy per pulse is 50 mJ, and the repetition rate is 30 Hz. A tunable slot is used to limit the width of the UV light beam (i.e., the length of the grating). We fabricated a fiber clamp with a spring, where the other end of the spring is fixed. When the photosensitive fiber with the phase mask is translated along the fiber's axis by operating the stepped motor, the spring is stretched, which induces a longitudinal stretch to the fiber. The spontaneous radiation emitted from erbium-doped fiber amplifier pumped by 980-nm LD is used as the broad band source (BBS). The transmission spectrum is displayed on an optical spectrum analyzer (OSA).

For a uniform Bragg grating, the relation between the Bragg wavelength and the grating period is  $\lambda_B = 2n_{\text{eff}}\Lambda$ , where  $n_{\text{eff}}$  is the effective index of the core mode. If we give a longitudinal stretch to a fiber before fabricating uniform FBG and withdraw the stretch after writing the grating,  $\lambda_B$  will have a short wavelength because  $\Lambda$  is smaller. The dual-wavelength FBG obtained in our method consists of two subgratings, which were made by using the moving exposing technique with only one phase mask. At the beginning, the spring is the original length, and the width of the slot is  $L_1$ . After the first exposure, we obtain the first subgrating, whose length is  $L_1$ , Bragg wavelength is  $\lambda_1$ , and transmission peak is  $T_1$ . We translate the fiber along its axis

Translated from *Chinese Journal of Quantum Electronics*, 2005, 22 (1) (in Chinese)

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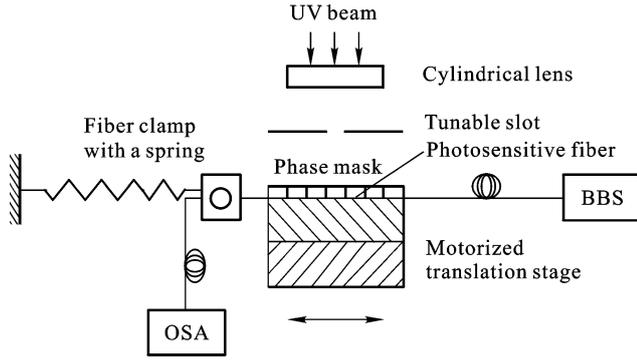


Fig. 1 Experimental setup

with the displacement  $L_1$ ; then, the spring is extended, and a longitudinal stretch is applied to the fiber. We set the width of the slot to be  $L_2$ . Next, we begin to fabricate the second subgrating, whose length is  $L_2$  and transmission peak is  $T_2$ . We withdraw the stretch, and thus, the period of the second subgrating gets smaller, which gives rise to a shorter resonance wavelength  $\lambda_2$ . We can make  $T_1 = T_2$  by appropriately controlling the number of pulses for the two exposures, when  $\lambda_1 \neq \lambda_2$ . Therefore, using this scheme, a

dual-wavelength FBG with a total length of  $L_1 + L_2$  is obtainable. By changing the stretch, the width of the slot, and the number of the two exposures, we can control the transmissivity of the dual-wavelength Bragg grating and the separation of the two resonant wavelengths.

Based on the analysis of the character of this kind of dual-wavelength FBG, we can perform some theoretical analysis and numerical simulation by using the Matrix method.

The dual-wavelength FBG obtained in our method consists of two subgratings that are produced by different exposures. The locations of the two subgratings are different. For simplicity, we assume that  $L_1 = L_2 = L$ ; therefore, there are two uniform subgratings with different periods in the fiber, whose length is  $2L$ . The interactions of the two subgratings and incident light field can be considered independent. With the Matrix method, the transfer matrix ( $F_D$ ) of the dual-wavelength FBG is given by [9]:

$$(F_D) = \begin{pmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{pmatrix} = (F_1) \cdot (F_2) \quad (1)$$

$$(F_1) = \begin{pmatrix} \cosh(\gamma_1 L) - i \frac{\hat{\sigma}_1}{\gamma_1} \sinh(\gamma_1 L) & -i \frac{\kappa_1}{\gamma_1} \sinh(\gamma_1 L) \\ i \frac{\kappa_1}{\gamma_1} \sinh(\gamma_1 L) & \cosh(\gamma_1 L) + i \frac{\hat{\sigma}_1}{\gamma_1} \sinh(\gamma_1 L) \end{pmatrix} \quad (2)$$

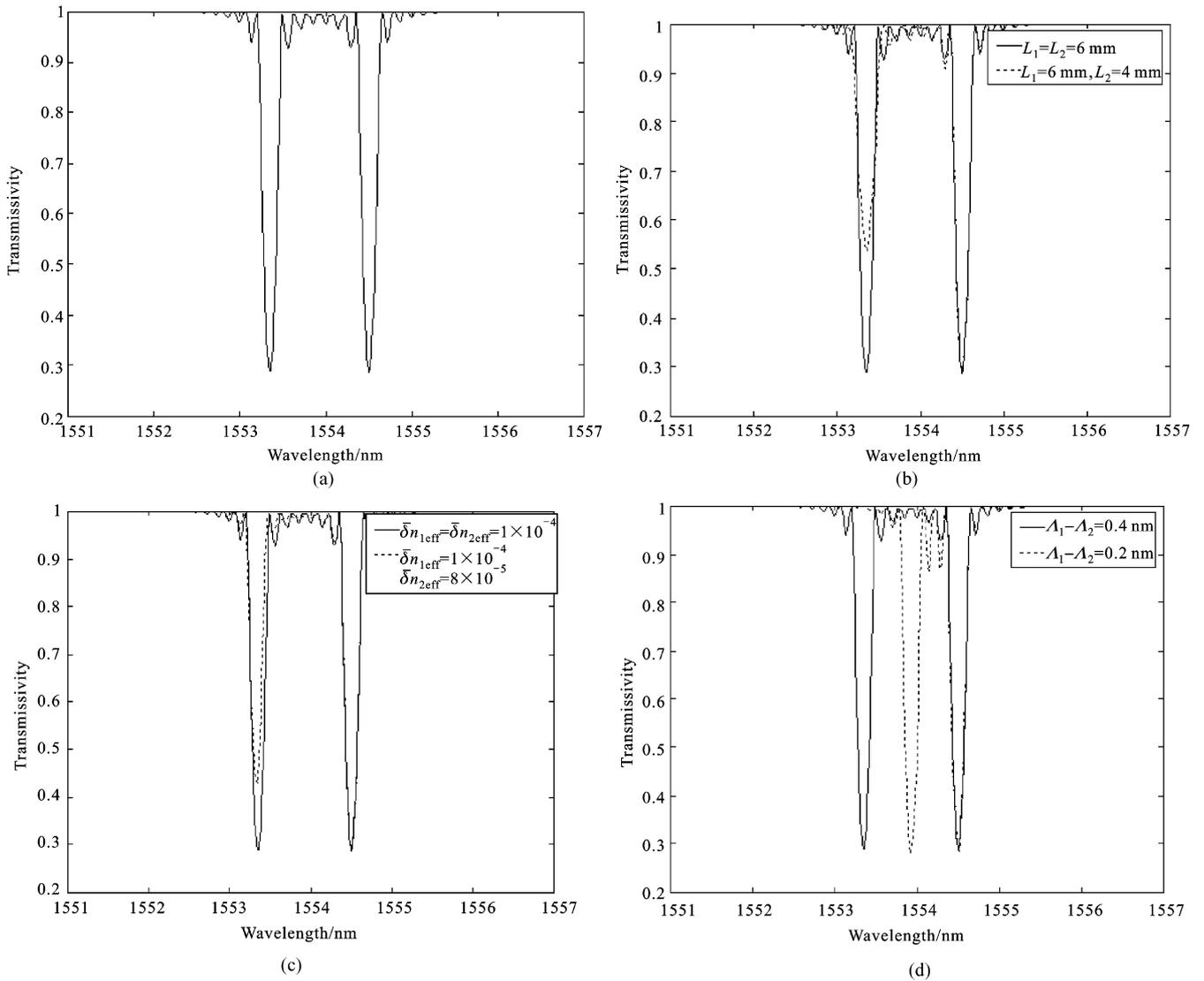
$$(F_2) = \begin{pmatrix} \cosh(\gamma_2 L) - i \frac{\hat{\sigma}_2}{\gamma_2} \sinh(\gamma_2 L) & -i \frac{\kappa_2}{\gamma_2} \sinh(\gamma_2 L) \\ i \frac{\kappa_2}{\gamma_2} \sinh(\gamma_2 L) & \cosh(\gamma_2 L) + i \frac{\hat{\sigma}_2}{\gamma_2} \sinh(\gamma_2 L) \end{pmatrix} \quad (3)$$

where  $(F_1)$  and  $(F_2)$  are transfer matrixes of the two subgratings;  $\kappa_1 = \pi \lambda^{-1} \nu_1 \bar{\delta} n_{\text{eff}1}$  and  $\kappa_2 = \pi \lambda^{-1} \nu_2 \bar{\delta} n_{\text{eff}2}$  are the ‘‘ac’’ coupling coefficients of the two subgratings ( $\nu_1$  and  $\nu_2$  are the index modulation coefficients and  $\bar{\delta} n_{\text{eff}1}$  and  $\bar{\delta} n_{\text{eff}2}$  are the ‘‘dc’’ index changes spatially averaged over the grating period);  $\hat{\sigma}_1 = \delta_1 + \sigma_1$  and  $\hat{\sigma}_2 = \delta_2 + \sigma_2$  are the general ‘‘dc’’ self-coupling coefficient, where  $\sigma_1 = 2\pi \lambda^{-1} \bar{\delta} n_{\text{eff}1}$ ,  $\sigma_2 = 2\pi \lambda^{-1} \bar{\delta} n_{\text{eff}2}$ . Here,  $\delta_1 = 2\pi \left( \lambda^{-1} - (2A_1 n_{\text{eff}})^{-1} \right)$  and  $\delta_2 = 2\pi \left( \lambda^{-1} - (2A_2 n_{\text{eff}})^{-1} \right)$  are the detuning from the Bragg wavelength  $\lambda_B$ . The relation between the field amplitudes of forward ( $R_0, R_{2L}$ ) and backward ( $S_0, S_{2L}$ ) propagating waves at the two ends of the dual-wavelength FBG is given by

$$\begin{pmatrix} R_{2L} \\ S_{2L} \end{pmatrix} = (F_D) \cdot \begin{pmatrix} R_0 \\ S_0 \end{pmatrix} = \begin{pmatrix} F_{11} & F_{12} \\ F_{21} & F_{22} \end{pmatrix} \begin{pmatrix} R_0 \\ S_0 \end{pmatrix} \quad (4)$$

With the boundary conditions, the amplitude reflection coefficient, power reflection coefficient, and power transmission coefficient can be shown to be  $\rho = F_{21}/F_{11}$ ,  $r = \rho \rho^*$ , and  $t = |F_{11}|^{-2}$ , respectively.

Figure 2 shows the calculated transmission spectra of the dual-wavelength FBG. Here,  $n_{\text{eff}} = 1.45$ ,  $A_1 = 536$  nm, and  $\nu_1 = \nu_2 = 1$ . In Fig. 2(a),  $L_1 = L_2 = 6$  mm,  $\bar{\delta} n_{\text{eff}} = \bar{\delta} n_{2\text{eff}} = 1 \times 10^{-4}$ , and  $A_1 - A_2 = 0.4$  nm. Figure 2(b) shows the calculated transmission spectra with different  $L_2$ , where  $\bar{\delta} n_{\text{eff}} = \bar{\delta} n_{2\text{eff}} = 1 \times 10^{-4}$  and  $A_1 - A_2 = 0.4$ . Figure 2(c) shows the calculated transmission spectra with different  $\bar{\delta} n_{2\text{eff}}$ , where  $L_1 = L_2 = 6$  mm,  $A_1 - A_2 = 0.4$ , and  $\bar{\delta} n_{\text{eff}} = 1 \times 10^{-4}$ . From Figs. 2(b),(c) we can ascertain that the transmissivity can be the same by adjusting the lengths of the subgratings and the numbers of the two exposures. Figure 2(d) shows the calculated transmission spectrum via the stretch, which makes the difference between the periods



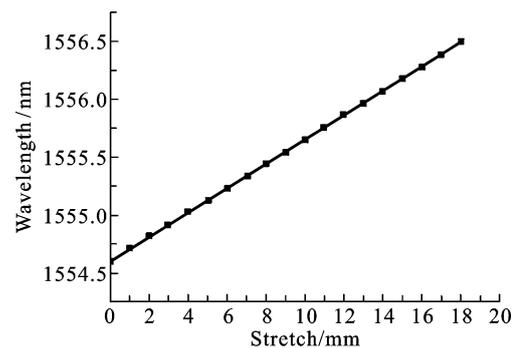
**Fig. 2** Numerical simulated transmission spectrum of the dual-wavelength FBG

of the two subgratings 0.4 and 0.2 nm, respectively. Here,  $L_1 = L_2 = 6$  mm and  $\bar{\delta}n_{1\text{eff}} = \bar{\delta}n_{2\text{eff}} = 1 \times 10^{-4}$ . Thus, we can obtain the needed dual-wavelength FBG with the proper wavelength separation by adjusting the value of the stretch.

### 3 Experiment

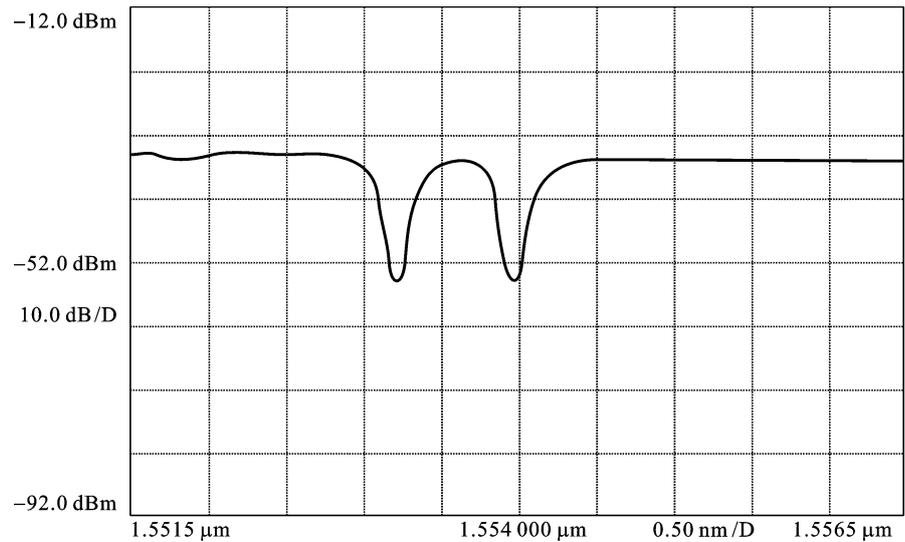
Next, we will fabricate a dual-wavelength FBG with a 0.8-nm wavelength separation using this scheme. In the experiment, we fabricate a fiber holder by selecting a proper spring. The period of the phase mask is 1 073.33 nm. We select the C598-302(s) photosensitive fibers, whose  $n_{\text{eff}}$  is 1.462 3, made by the No. 46 Institute of China's Information Industry. Firstly, we fabricate an ordinary FBG without stretch. Then, we applied longitudinal stretch to the grating. Figure 3 shows the Bragg wavelength variation

with the displacement of the fiber holder. We can see that the linear relation is good.



**Fig. 3** Plot showing Bragg wavelength variation with the stretch

**Fig. 4** Transmission spectrum of the experimentally obtained dual-wavelength FBG



With the data in Fig. 3, we set the width of slot as 7 mm, and the times of the two exposures are all 3000. Finally, we obtain a dual-wavelength FBG, whose length is 1.4 cm; the separation of the two resonant wavelengths is 0.78 nm, and the transmissivities are all about 19.5 dB. Figure 4 shows the transmission spectra, which are close to our expected target.

With this scheme, we can control the transmissivity of the dual-wavelength Bragg grating and the separation of the two resonant wavelengths by changing the stretch, the width of the slot, and the number of the two exposures. The advantages of the method are simple operation and good repeatability.

In the situation where only the longitudinal stretch scheme (without the moving exposing technique) is used, the two exposures will be in the same position and the second exposure will affect the first exposure, which causes the reduction of the index modulation of the first subgrating. Therefore, the reflectivity of the dual-wavelength FBG is low. With the moving exposing technique, the two exposures will be noninterfering, and then dual-wavelength FBG with high reflectivity can be obtained.

If we increase the exposed fiber section, we can get multiwavelength FBG with this scheme, while in the fabricating procedure, we must be aware that the stretch cannot exceed the maximum value that the fiber can bear.

#### 4 Conclusion

We fabricated dual-wavelength FBGs by using one phase mask. Theoretical analysis and numerical simulation were carried out using the Matrix method. The moving exposing technique was applied in our method. The transmissivity of the dual-wavelength FBG and the separation of the two resonant wavelengths can be flexibly controlled using this

method. A dual-wavelength FBG with two equal transmission peaks of 19.5 dB was obtained, and the separation of the two Bragg wavelengths was 0.78 nm. This method can also be used to fabricate FBG with more resonant wavelength.

**Acknowledgement** This study was supported by the National “863” high-technology project (No.2002AA313110).

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