A strain-induced birefringent double-clad fiber Bragg grating

Lijun Li (李丽君), Lei Sun (孙 磊), Wande Fan (范万德), Zhi Wang (王 志), Jianhua Luo (罗建花), Shenggui Fu (付圣贵), Shuzhong Yuan (袁树忠), and Xiaoyi Dong (董孝义)

Institute of Modern Optics, Nankai University, Tianjin 300071

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A strain-induced birefringence double-clad (DC) fiber Bragg grating (FBG) is proposed and demonstrated. The grating is fabricated in the core of rectangular inner cladding double clad fiber by using phase mask method. By applying lateral strain on the grating, the birefringence is induced. In order to detect the birefringent effect of the grating, we use it as the output mirror of a laser. When lateral strain is applied, the grating becomes birefringent. Therefore, one reflection peak of double-clad fiber Bragg grating becomes two peaks and the laser also lases in two wavelengths. The wavelength spacing of the laser can be tuned from 0 to 0.8 nm. The absolute wavelengths for the two polarizations can be tuned 1.2 and 2.0 nm, respectively.

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Fiber birefringence plays an important role in complex polarization dynamics of rare-earth-doped fiber lasers[1]. Recently some novel lasers and double-clad (DC) fiber lasers (DCFL), have attracted much interest for high power lasers. Such lasers have a second cladding area to facilitate pumping with semiconductor lasers. Different cladding structures, such as rectangular, star-shape, and circular, are all in use to provide an efficient absorption of pump energy by the fiber core. It raises new questions about laser dynamics, stabilities, and polarization properties. In particular, the asymmetric structure of such fibers, with, typically, a rectangular inner cladding surrounding a circular core, prompts these birefringence properties. As shown in Refs. [2] and [3], the birefringence in double clad fiber was measured, and the presence of intrinsic and induced birefringences was demonstrated. Recently, Jeffrey and Dahv *et al.*[4,5] reported polarization-maintaining DC fiber amplifier by using external stress-induced birefringence DC fiber.

In this letter a strain-induced birefringence in rectangular inner cladding Yb^{3+}-doped DC fiber Bragg grating (FBG) is reported experimentally. Applying lateral strain on the grating, birefringence is induced. In order to detect the birefringent effect of the grating, we use it as the output mirror of a laser. When lateral strain is applied, the grating may become birefringent. Therefore, one reflection peak of DC FBG becomes two peaks and the laser also lases in two wavelengths. For the reason of the laser with two orthogonal polarization states, it can avoid the wavelength competition from homogeneous gain broadening, ensuring stable room-temperature operation. When lateral strain is applied, the wavelength spacing can be tuned from 0 to 0.8 nm, at the same time, the absolute wavelengths of the two polarizations can be tuned 1.2 and 2.0 nm, respectively.

The rectangular inner cladding DC fiber with elliptical cladding has been studied[2,3]. The slow and fast axes of the core coincide with those of the cladding. We apply stress on the DC FBG along the short axis of the inner cladding. The refractive index of FBG changes and the FBG becomes birefringence. Two plane-polarized waves propagate in line with two directions, one is parallel and the other is perpendicular to the direction of the applied load. We assume the principal optical axis align with x-, y-, and z-Cartesian axes. The induced birefringence B of the light propagating along the z-axis is given by

$$B = B_0 + \frac{|\Delta n_y - \Delta n_x|}{n_0}, \tag{1}$$

where B_0 is the intrinsic birefringence induced by the elliptical inner cladding; n_0 is the initial core refractive index of the undisturbed optical BGF; and Δn_x and Δn_y are the refractive index changes for the x- and y-polarizations respectively due to the applied loads. The refractive index changes due to the photo-elastic effect and developed to the first order are given by[6]

$$\Delta\left(\frac{1}{n_m^2}\right) = p_{mn}\varepsilon_n, \quad m,n = (1,2,3,4,5,6), \tag{2}$$

where p_{mn} is photo-elastic coefficient, and ε_n is the strain tensor.

The Bragg grating reflection wavelength is given by $\lambda = 2\Lambda n_{\mathrm{eff}}$, where n_{eff} is the initial effective refractive index, λ the Bragg wavelength, and Λ the grating period. When the FBG is subjected to a disturbance P, the Bragg wavelength shifts. Under isothermal condition, the shift is given by

$$\mathrm{d}\lambda = \left[2\Lambda\left(\frac{\partial n_{\mathrm{eff}}}{\partial P}\right) + 2n_{\mathrm{eff}}\left(\frac{\partial\Lambda}{\partial P}\right)\right]\mathrm{d}P, \tag{3}$$

where P is the applied disturbance. From calculating the core refractive index changes and the FBG periodicity deformation caused by the applied disturbance the Bragg wavelength changes can be deduced.

With Eqs. (1), (2), and (3), the Bragg wavelength shifts can be given by

$$\Delta\lambda_x = 2n_x\Lambda\left[-\frac{n_x^2}{2}\left(p_{11}\varepsilon_x + p_{12}\varepsilon_y\right) + \left(1-\frac{n_x^2}{2}\right)p_{12}\varepsilon_z\right]$$

for $x-$polarization, (4)

$$\Delta\lambda_y = 2n_y\Lambda\left[-\frac{n_y^2}{2}\left(p_{12}\varepsilon_x + p_{11}\varepsilon_y\right) + \left(1-\frac{n_y^2}{2}\right)p_{12}\varepsilon_z\right]$$

for $y-$polarization. (5)

It is obvious that two wavelengths shift synchronously with axial strain ε_z, and wavelength space changes when lateral strains ε_x, ε_y are applied.

The FBG is directly fabricated in the rectangular inner cladding DC fiber with phase mask method. The ultraviolet light source is a narrowband KrF excimer laser operated at 248 nm, the typical energy per pulse was 80 mJ, and the phase mask period is 724.86 nm. The reflectivity of DC FBG is about 30%, whose reflection peak wavelength is 1055.2 nm. In order to detect the birefringence, we use this rectangular inner cladding DC fiber as active fiber and this grating as the output mirror of an Yb^{3+}-doped DC fiber laser. When lateral strain is applied, the FBG becomes birefringent. Therefore, the reflection peak of the FBG becomes two peaks and the laser also lases in two wavelengths. The laser wavelength spacing can be tuned by the perspex and screw. When screwed, the perspex will apply a lateral strain to the FBG, which can produce birefringence in fiber through strain-optic effect. The stress in the fiber can be estimated by $\sigma = 8.3 \times 10^5 \times \theta$, where θ is the screwed angle[6]. We apply the lateral strain in line with the slow axis in order to increase the birefringence[1]. With increasing the wavelength spacing, the two wavelengths shift to longer wavelength synchronously.

The laser configuration is shown in Fig. 1. The pump source is a laser diode (LD), whose maximum output power from the pigtail is about 1 W. A couple system is used to pump the rectangular inner cladding of ytterbium-doped DC fiber, with a length of 20 m, a diameter of 100 × 85 μm, and a core diameter of 5 μm. The linear cavity is formed between a dichroic mirror and a DC FBG. A polarization controller (PC) is inserted in the cavity, through which we can control the state of polarization of the wave in the cavity. The strain is applied to the DC FBG by using tuning frame. The FBG is placed between two pieces of perspex, and lateral strain is applied through screw. An optical spectrum analyzer with the resolution of 0.1 nm is used to monitor the laser output spectra.

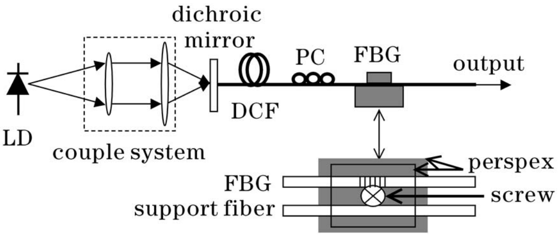

Fig. 1. Experimental setup of tunable dual-wavelength DCFL.

Three lasing states can be observed, when the PC is adjusting. In two states, only one polarization can oscillate. These two states are orthogonal polarized each other. Therefore, only one wavelength can be observed lasing in one state. In the third state, both orthogonal linearly polarized modes co-exist. The three kinds of states are shown in Fig. 2. Two wavelengths are 1055.7 and 1056 nm, respectively, and the side-mode suppressive ratio (SMSR) is over 40 dB. Figure 3 shows the output spectrum of the laser with FBG when the screwed angle is 100°. Two wavelengths are 1056.4- and 1057.2-nm, respectively, and SMSR is 29 dB. The laser outputs at room temperature are stable. Figure 4 shows the dependence of the wavelength spacing $\Delta\lambda$ on lateral strain, where linear responses are observed. The wavelength space can be tuned from 0 to 0.8 nm. Following these, Fig. 5 shows the dependence of Bragg reflection wavelength variation $\Delta\lambda_{\mathrm{B}}$ on screwed angle for two polarized directions. The absolute wavelengths of the two polarizations can be tuned 1.2 and 2.0 nm, respectively. When strain is applied, the Bragg reflection wavelength variation of the x-polarization is larger than that of the y-polarization because of photoelastic property of the optical fiber's material[6].

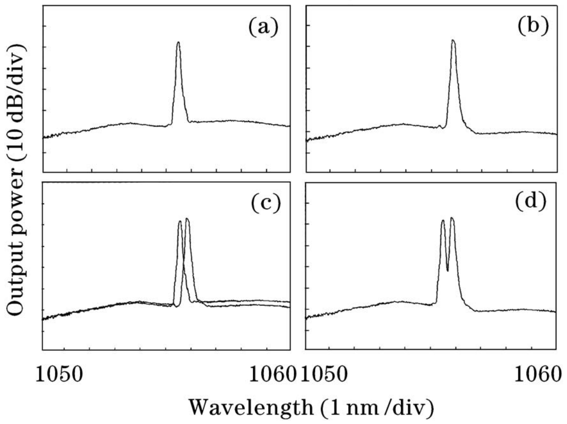

Fig. 2. Output spectra of tuned dual-wavelength DCFL with the screwed angle of 40°. Outputs of single-polarization mode operation spectra in 1055.7 nm (a) and 1056 nm (b); Output of two single-polarization mode operation spectrum overlaid to dual-mode operation spectrum (c); Output of dual-wavelength operation spectrum (d).

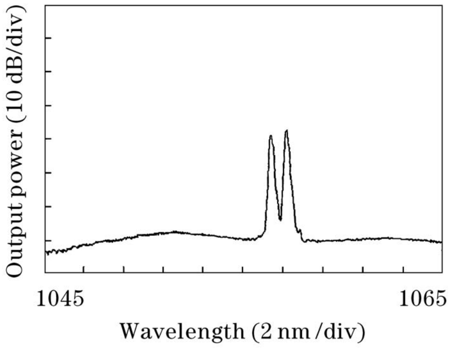

Fig. 3. Output spectrum of tuned dual-wavelength DCFL with the screwed angle of 100°.

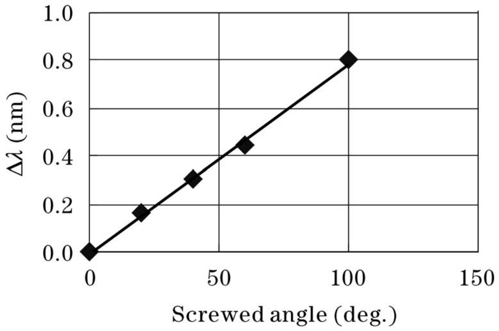

Fig. 4. Dependence of lasing wavelength spacing on screwed angle.

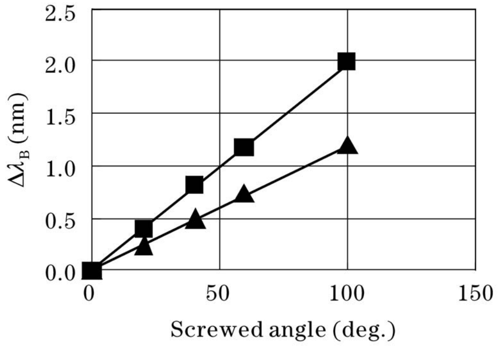

Fig. 5. Dependence of Bragg reflection wavelength variation on screwed angle for two polarize directions.

In summary, we have presented a strain-induced birefringence of rectangular inner cladding DC FBG. The birefringent effect is detected. By applying lateral strain on the grating, one reflection peak of DC FBG becomes two peaks. The wavelength spacing of the grating can be tuned from 0 to 0.8 nm. The absolute wavelengths of the two polarizations can be tuned 1.2 and 2.0 nm, respectively. By applying lateral strain on FBG, two lasing wavelengths can be controlled. This simple and low cost configuration also can be used in Er^{3+}/Yb^{3+}-codoped DC fiber. This technology can be utilized to reduce the wavelength competition. Accordingly, this method may have numerous applications in optical communications and sensing.

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