

Highly sensitive bending sensor based on Er³⁺-doped DBR fiber laser

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Abstract: A short cavity Er³⁺-doped distributed-Bragg-reflector (DBR) fiber laser with a low polarization beat frequency has been demonstrated for bending measurement. The polarization beat frequency of the DBR laser is extremely sensitive to bending and can measure curvature changes as small as $1.8 \times 10^{-2} \text{ m}^{-1}$. Excellent agreement between experimental and theoretical results was obtained for bending curvatures from 0 m^{-1} to 58.8 m^{-1} with corresponding changes in beat frequency from 18.6 MHz to 253 MHz. The sensor is insensitive to temperature fluctuations and has a temperature coefficient of the beat frequency of $-25.4 \text{ kHz}/^\circ\text{C}$, making the temperature compensation unnecessary in most practical applications. The very low beat frequency of the DBR fiber laser makes frequency down-conversion unnecessary. This can greatly simplify the demodulation scheme and thus, allow the realization of low-cost but highly sensitive optical bending sensor systems.

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1. Introduction

Fiber-optic devices such as fiber gratings and fiber lasers have been developed as powerful sensors in various industrial applications, particularly in structural health monitoring [1–3]. Along with temperature and strain measurements, mechanical bending is an important parameter for structural health diagnosis and plays an important role in modern smart structure monitoring. Reported fiber-optic bending sensing schemes include the use of long period fiber gratings (LPFGs) [4,5] and fiber Bragg gratings (FBGs) fabricated in multicore fibers [6,7]. Other methods based on intensity detection of the bending loss of high order guided modes [8], and cladding mode [9] were also reported. However, fiber gratings based bending sensors are generally sensitive to temperature and normally also require expensive wavelength demodulation. On the other hand, intensity based bending sensors suffer from power fluctuations of light sources.

Single-longitudinal-mode distributed-Bragg-reflector (DBR) fiber lasers are relatively easy to fabricate and their applications for sensing [10–13] and microwave generation [14,15] have been reported and have generated much interest recently. In this paper, we propose and demonstrate a temperature-insensitive bending sensor based on the measurement of the polarization beat frequency shift of a short cavity DBR fiber laser written in an Er^{3+} -doped fiber. Its bending characteristics in both frequency domain and in optical spectrum domain are analyzed in details. The high orientation-dependent bending sensitivity of the sensor is also investigated. Excellent agreement between theoretical and experimental results is achieved. Experimental results show that the polarization beat frequency of the laser is extremely sensitive to the bending curvature over a large bending range with orientation-recognizable ability, and at the same time insensitive to temperature. More important, the DBR laser operates at a low beat frequency (~ 20 MHz) and thus permits direct electronics detection using simple and inexpensive low-speed electronic devices.

2. Principle

A DBR fiber laser composed of a pair of wavelength-matched FBGs written in an active fiber usually operates in two orthogonal polarization modes. The wavelengths of the two orthogonal polarization lasing modes are given by

$$\lambda_{x,y} = 2n_{x,y}\Lambda, \quad (1)$$

where Λ is the grating pitch, n_x and n_y are the refractive indices of the fast and slow axes of the fiber along the fiber laser, respectively. The slight difference between the values of n_x and n_y is due to the asymmetry index modulation in the core of the fiber caused by side UV irradiation during the FBG fabrication process. The frequency difference between the two orthogonal polarization modes is

$$f_0 = cB_{\text{FBG}} / (n_{\text{eff}}\lambda), \quad (2)$$

where c is the speed of light in vacuum, $B_{FBG} = n_x - n_y$ is the birefringence, $n_{eff} \approx n_x \approx n_y$ is the effective refractive index of the core mode of the fiber, and the average lasing wavelength $\lambda = 2n_{eff}\Lambda \approx \lambda_x \approx \lambda_y$.

Additional birefringence will be introduced to the fiber laser when it is bent. The bending induced birefringence is mainly caused by stress [16]. Assuming the fiber is elastically homogeneous and isotropic, for a weak curvature of $\kappa a \ll 1$, (where a is the fiber radius, and κ is the curvature of the fiber bending), the bending induced birefringence can be expressed as [17]

$$B_{bend} = 0.25n^3 (p_{11} - p_{12})(1 + \nu)\kappa^2 a^2, \quad (3)$$

where p_{11} and p_{12} are the components of strain-optical tensor of the fiber material, ν is Poisson's ratio, n is the average refractive index of the fiber material. The typical values for fused silica are $p_{11} = 0.12$, $p_{12} = 0.27$, $\nu = 0.17$, $a = 62.5 \times 10^{-6}$ m, and $n = 1.444$ (at 1550 nm) [18]. Inserting these values into Eq. (3) we obtain

$$B_{bend} = -5.16 \times 10^{-10} \kappa^2. \quad (4)$$

Equation (4) indicates that the bending induced birefringence is proportional to the square of the bending curvature imposed on the fiber. The negative sign in Eq. (4) indicates that the fast axis of the bending induced birefringence coincides with the radius of curvature and the slow axis is normal to the plane of the curvature. When the DBR fiber laser is bent, the total birefringence should be the vector addition of the birefringence induced by FBG inscription (B_{FBG}) and that by bending (B_{bend}), and can be expressed as

$$B_{total} = \sqrt{(B_{bend}^2 + B_{FBG}^2 + 2B_{bend}B_{FBG} \cos 2\theta)}, \quad (5)$$

where θ is the angle between the fast axis of the bending induced birefringence and the fast axis of the FBG inscription induced birefringence, as shown in Fig. 1. From Eqs. (2), (4) and (5) we obtain the following polarization beat frequency of the bent DBR fiber laser

$$f = \sqrt{\left(f_0 \cos 2\theta + 5.16 \times 10^{-10} \kappa^2 \cdot c / n_{eff} \lambda\right)^2 + f_0^2 \sin^2 2\theta}. \quad (6)$$

Equation (6) indicates that the polarization beat frequency is dependent on both the bending curvature κ and the bending orientation θ . Therefore, the DBR fiber laser can work as an orientation-recognizable bending sensor when it is attached onto a flat surface with its fast (slow) axis normal to the surface and subsequent bending in the plane normal or parallel to the surface will result in decreasing (increasing) or increasing (decreasing), respectively, in the beat frequency.

3. Experiment and results

Figure 1 shows our experimental setup used to investigate the bending sensor based on DBR fiber laser. The DBR fiber laser was inscribed in a short length of a commercial Er^{3+} -doped fiber (Corning Er1600L3) which has a peak absorption of 18.0 to 29.0 dB/m at 1530 nm and a core diameter of about 4.2 μm . The FBGs were fabricated using phase-mask grating-writing technique with a 193 nm ArF excimer laser. A phase-mask with a pitch of 1068 nm was employed and FBGs with Bragg wavelength of ~ 1550 nm were obtained, which gives an effective refractive index of 1.4513 for the Er^{3+} -doped fiber. The lengths of the two FBGs are 6 mm and 8 mm, and are separated by 12 mm. Thus the DBR fiber laser has a total length of 26 mm and a nominal cavity length of ~ 19 mm.

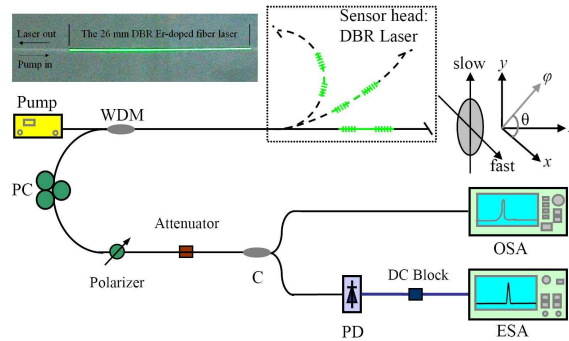


Fig. 1. Experimental setup of the bending sensor based on a short cavity DBR fiber laser. The insert is the photograph of the DFB fiber laser when it is pumped.

The DBR fiber laser was pumped by a 980 nm laser diode with an output power of ~ 80 mW through a 980/1550 nm wavelength division multiplexer (WDM). The laser output was split into two parts by a 3-dB coupler (C): one part was monitored by an optical spectrum analyzer (OSA, Yokogawa AQ 6370), and the other was injected to a photodetector (PD, Newfocus 1811-FC, 25 kHz - 125 MHz) which is connected to an electrical spectrum analyzer (ESA, Agilent Technologies E8247C, 250 kHz - 40 GHz). By adjusting the polarization controller (PC) and the polarizer, the two orthogonal polarization lasing modes can be turned to the same polarization state so that strong beating signal can be achieved at the PD. The attenuator was employed to protect the PD whose continuous-wave saturation power is -13 dBm at 1550 nm. At room temperature (20°C), the lasing wavelength measured by the OSA was 1549.794 nm with an optical signal to noise ratio of over 60 dB, as shown in Fig. 2(a). Figure 2(b) shows the superimposed spectra of the polarization beat signals of the DBR fiber laser under different bending curvatures, measured by the ESA. When the DBR fiber laser was kept straight, we observed a polarization beat frequency of $f_0 = 18.6$ MHz, which is much lower than the beat frequency of ~ 1 GHz reported previously for a DBR fiber laser written in Er/Yb co-doped double-cladding fiber [10–12]. The very low beat frequency of the present DBR fiber laser makes frequency down-conversion unnecessary. The value of the birefringence introduced by the FBG inscription process calculated using Eq. (2) is about 1.4×10^{-7} . The frequency of the polarization beat signal shifts significantly when the DBR fiber laser was bent, as shown in Fig. 2(b). The 3-dB bandwidth of the polarization beat frequency signal was measured to be less than 1 kHz and the frequency drift is observed to be ~ 50 kHz in the free-running mode at room temperature.

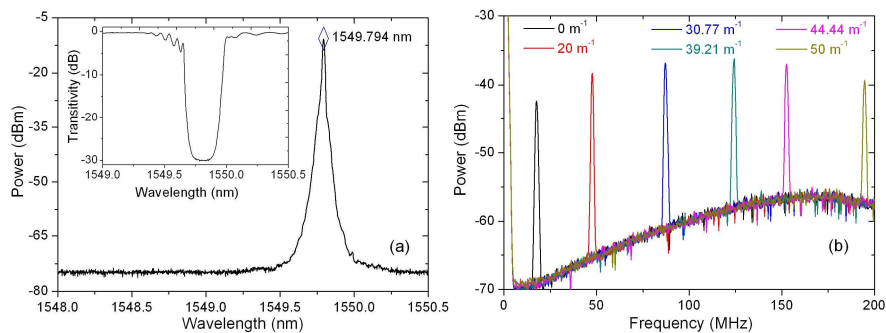


Fig. 2. (a) Optical spectrum of the DBR fiber laser and (b) superimposed electrical spectra of the polarization beat frequency of the proposed DBR fiber laser subjected to bending of different curvatures with $\theta = 0^\circ$. The inset in (a) shows the transmission spectrum of the high reflection FBG of the DBR fiber laser.

Figure 1 shows that the direction of the z -axis is parallel to the fiber axis, the x - and y -axis (the fast and slow axes) are the fiber eigen-axes defined by the UV-induced birefringence introduced during the FBG fabrication process and φ is the direction of the fiber curvature in x - y plane (the radial plane of the fiber). We measured the beat frequency as a function of the bending curvature applied to the fiber at various angles θ ($= 0^\circ, 90^\circ, 180^\circ$ and 270°) between the x and φ axes. The curvatures of the fiber bending are introduced by attaching the DBR fiber laser on the surface of cylinders with different diameters. The results of these measurements together with the corresponding theoretical curves of the birefringence calculated using Eq. (5) and the beat frequency calculated using Eq. (6) for different fiber bending curvatures are shown in Fig. 3.

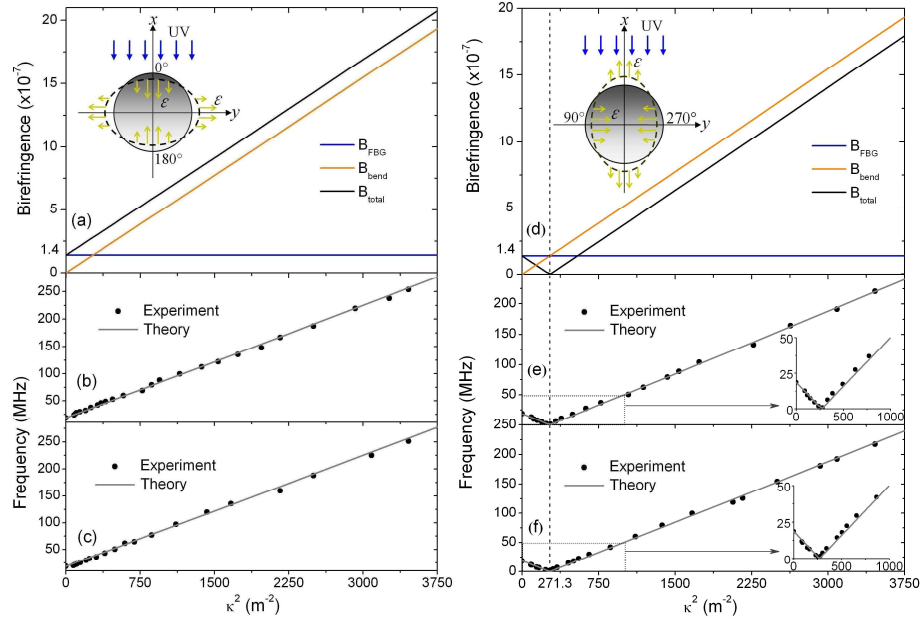


Fig. 3. Birefringence of the DBR fiber laser versus bending curvature for $\theta = 0^\circ$ or 180° (a), and 90° or 270° (d), and the corresponding polarization beat frequency of the DBR fiber laser versus bending curvature for $\theta = 0^\circ$ (b), 180° (c), 90° (e), and 270° (f). Inserts of (a) and (d) show the cross section of the bent DBR fiber laser along the plane of the fast and slow axes, respectively. The blue arrowheads indicate the direction of UV light during FBG inscription. The arrows on the fiber indicate the force (ϵ) exerted on the fiber when it is bent, introducing stress and deformation to the fiber laser.

When $\theta = 0^\circ$ or $\theta = 180^\circ$, the x eigen-axis (fast axis defined by FBG inscription process) of the fiber is aligned with the applied bending axis (φ). Equations (5) and (6) can be simplified to $B_{bend} + B_{FBG}$ and $f = f_0 + 5.16 \times 10^{-10} \kappa^2 c / (n_{eff} \lambda)$, respectively. The highest bending sensitivity can be achieved in this bending direction. Figures 3(b) and 3(c) show the experimental results when the bending curvature of the DBR fiber laser increases from 0 m^{-1} to 58.8 m^{-1} on the x - z plane (as shown in Fig. 1) with $\theta = 0^\circ$ and $\theta = 180^\circ$, and the corresponding polarization beat frequency of the DBR laser increases from 18.6 MHz to 253 MHz ($\theta = 0^\circ$) and 251 MHz ($\theta = 180^\circ$), respectively. The measured beat frequency shows a linear response to κ^2 with almost same slope for $\theta = 0^\circ$ ($67.1 \text{ kHz} \cdot \text{m}^2$ with a mean square error of $R^2 = 99.92\%$) and $\theta = 180^\circ$ ($68.1 \text{ kHz} \cdot \text{m}^2$ with $R^2 = 99.90\%$). However, when $\theta = 90^\circ$ or $\theta = 270^\circ$ [then the y eigen-axis (slow axis) of the fiber is aligned with the applied bending axis (φ)] and for small bending curvatures, Eqs. (5) and (6) are simplified to $B_{bend} - B_{FBG}$ and $f = |f_0 - 5.16 \times 10^{-10} \kappa^2 c / (n_{eff} \lambda)|$. This is because the refractive index of the fiber laser along the fast axis increases and eventually reaches a value equal to that of the slow axis, resulting in zero beat frequency. Therefore, the beat frequency first decreases to a small value ($f = 0.89 \text{ MHz}$

when the bending curvature is $\sim 16.67 \text{ m}^{-1}$ for $\theta = 90^\circ$ and $f = 0.8 \text{ MHz}$ when the bending curvature is $\sim 16.13 \text{ m}^{-1}$ for $\theta = 270^\circ$) and then starts to increase with the same slope ($67.8 \text{ kHz}\cdot\text{m}^2$ with $R^2 = 99.90\%$ for $\theta = 90^\circ$ and $67.2 \text{ kHz}\cdot\text{m}^2$ with $R^2 = 99.93\%$ for $\theta = 270^\circ$) as that for $\theta = 0^\circ$ and $\theta = 180^\circ$. The measurement results show very good agreement with theoretical results for all the above four bending directions.

Previous reported fiber gratings based bending sensors [4–7] have shown that the wavelength shift is proportional to the bending curvature, whereas the beat frequency of the DBR fiber laser reported in the present work is proportional to the square of the bending curvature. This means the present type of bending sensor exhibits higher sensitivity when the bending curvature is large. For example, when the bending curvature is 20 m^{-1} , the bending sensitivity of our sensor is $2.75 \text{ MHz}\cdot\text{m}^{-1}$. The resolution of the sensor is limited by the beat frequency drift of the DBR fiber laser, which was observed to be $\sim 50 \text{ kHz}$ in the free-running mode. The bending sensor is therefore capable to detect small bending curvature change of $1.8 \times 10^{-2} \text{ m}^{-1}$ at bending curvature of 20 m^{-1} , which is much more sensitive than previously reported results, e.g., the results in [6] show a curvature resolution of $\pm 0.31 \text{ m}^{-1}$.

The temperature response of the polarization beat frequency is shown in Fig. 4. For a temperature change from 17.8°C to 74°C , the lasing wavelength varied by 0.6 nm (i.e. $10.7 \text{ pm}/^\circ\text{C}$) but the beat frequency shifts is less than 1.5 MHz (i.e. $-25.4 \text{ kHz}/^\circ\text{C}$ from 18.88 MHz to 17.45 MHz), demonstrating a relatively small thermal response in comparison to the bending response of the DBR fiber laser (hundreds of MHz). This characteristic is very useful for practical applications where temperature change is not too large and thus temperature effect can be ignored. The negative change of the beat frequency with temperature is believed to be caused by stress relaxation in the fiber [19].

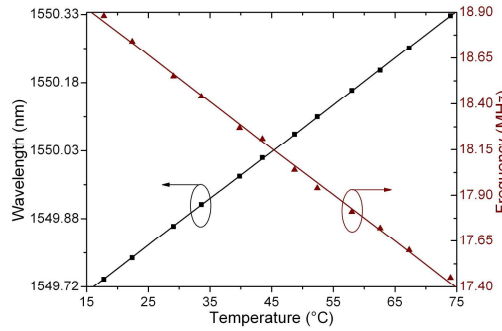


Fig. 4. Polarization beat frequency and lasing wavelength response of the DBR fiber laser versus temperature.

We also investigated the wavelength and power responses of the DBR fiber laser with applied bending and the experimental results are shown in Fig. 5. When the bending curvature increases from 0 to 58.8 m^{-1} , fluctuations of the laser wavelength and power were measured to be less than 0.02 nm and 0.16 dB , respectively, indicating that the proposed DBR fiber laser could be employed as a dual-frequency laser source with tunable frequency separation (by bending as shown in Fig. 3) and orthogonal polarization lasing modes.

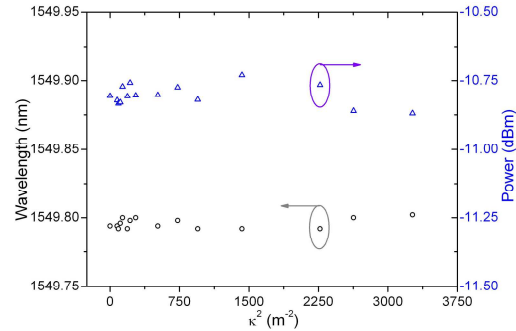


Fig. 5. Wavelength and power responses of the DBR fiber laser versus bending curvature.

4. Conclusion

The feasibility of using a short cavity DBR fiber laser fabricated in a conventional Er^{3+} -doped fiber as a bending sensor has been demonstrated. The laser operates in two orthogonal polarization modes and produces a beat frequency that varies with the square of the bending curvatures. Excellent agreement between experimental and theoretical results was obtained for bending curvatures from 0 m^{-1} to 58.8 m^{-1} with corresponding changes in beat frequency from 18.6 MHz to 253 MHz. The sensor exhibited very high bending sensitivity and can measure bending curvature changes as small as $1.8 \times 10^{-2} \text{ m}^{-1}$. The bending sensor is insensitive to temperature with a very small thermal beat frequency coefficient of $-25.4 \text{ kHz}/^\circ\text{C}$, making temperature compensation unnecessary in most practical applications. The DBR fiber laser also exhibits orientation dependence, and is short and can be multiplexed along a single fiber, making them a potential candidate for shape sensors. Furthermore, the low beat frequency allows inexpensive photodetectors and low-speed electronics to be used to demodulate the sensing signals.

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