A novel fiber-laser-based fiber Bragg grating strain sensor with high-birefringence Sagnac fiber loop mirror

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A novel fiber-laser-based strain sensor is proposed and experimentally demonstrated. The laser cavity is composed of a high-birefringence Sagnac fiber loop mirror (HiBi-SFLM) and a fiber Bragg grating (FBG) which also acts as a strain-sensing element. In the linear region of the HiBi-SFLM reflection spectrum, when the strain applied on the FBG makes the Bragg grating wavelength shift, the laser output power changes due to reflectivity variation of the HiBi-SFLM. Experimental results show that the laser output power varies almost linearly with the applied strain. The measurement of the output power can be performed by a conventional photo-detector.

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Fiber Bragg gratings (FBGs) have attracted considerable attention in recent years and been applied in a diversity of sensor systems to measure different kinds of physical variables[1,2]. This is because of their unique advantages such as the ease in handling, the wavelength-encoded measurement information, and the potential multiplexing capability over a single optical fiber[3−7]. FBG-based sensors can be classified into two types: passive sensors which are fabricated only using standard fiber, and active sensors that are fabricated with fiber doped with rare earth materials such as erbium as the active gain medium. In passive FBG-based sensor systems, a spectrally broadband source is required to cover the wavelength range over which the Bragg grating is measurand-tuned. This method is inefficient because only a small fraction of the total light launched into the fiber will be reflected as the sensor signal due to the narrow-band nature of the Bragg reflection[8]. The output power reflected from this type of source is often quite weak, leading to a poor signal-to-noise ratio (SNR) of the measurement system, especially in noisy environments. Thus the potential accuracy is reduced. In contrast with passive sensors, the advantages of a laser-based sensor system include the significant improvements in SNR and high resolution for wavelength shift, with the signal amplification occurring in the optical domain[9,10].

In this letter, we present and demonstrate a novel fiber-laser-based strain sensor. The laser cavity is formed by a high-birefringence Sagnac fiber loop mirror (HiBi-SFLM) and a FBG which also acts as sensing probe. When the FBG sensing probe was subject to an external physical parameter, such as strain in our paper, the Bragg wavelength changed and the laser output power varied due to the variation of reflectivity of the HiBi-SFLM. Thus, the wavelength-encoded signal can be converted to the laser output power change. The sensitivity of detection or the measurement range can be adjusted by changing the HiBi fiber length.

Figure 1 shows the schematic diagram of the FBG strain sensor based on a fiber laser. A HiBi-SFLM and the FBG form the linear cavity of the fiber laser. The FBG acts as both the laser wavelength selective element and the sensing probe. A 980/1550 nm wavelength division multiplexer (WDM) is used as the wavelength combiner. The gain is provided by a 5-m-long home-made erbium-doped fiber (EDF) with an absorption coefficient of 16 dB/m at 1530 nm and pumped by a laser diode with a maximum output of 110 mW at 980 nm through the WDM.

The HiBi-SFLM is constructed by incorporating a piece of high birefringence fiber between the two coupling arms of the 3-dB coupler. For the HiBi-SFLM, the input optical field is split into counter-propagating fields that interfere at the 3-dB coupler. The phase difference between the polarization components propagating along the fast and slow axes over a length L of birefringent fiber is given as $\Delta = \frac{2\pi L(n_{\text{fast}}-n_{\text{slow}})}{\lambda}$, in which n_{fast} and n_{slow} are the effective refractive indices for the fast and slow polarization states, respectively, and λ is the wavelength. As Δ is wavelength dependent, the transmitted or reflected power is a periodic function of the wavelength. The wavelength spacing is inversely proportional to the length and birefringence of the polarization maintaining fiber as $\delta\lambda = \frac{\lambda^2}{(n_{\text{fast}}-n_{\text{slow}})L}$[11]. Obviously, for small wavelength spacing, a larger fiber birefringence or longer fiber length is required. The reflection function are related to the phase difference Δ as[12]

$$R(\lambda) = \cos^2(\Delta/2). \quad (1)$$

A polarization controller and a 5-m-long high-birefringence fiber are used in the fiber loop mirror.

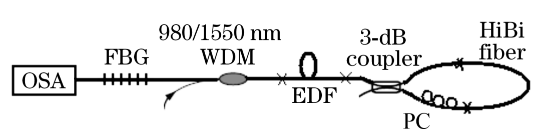

Fig. 1. Schematic diagram of the proposed sensor system. PC: polarization controller.

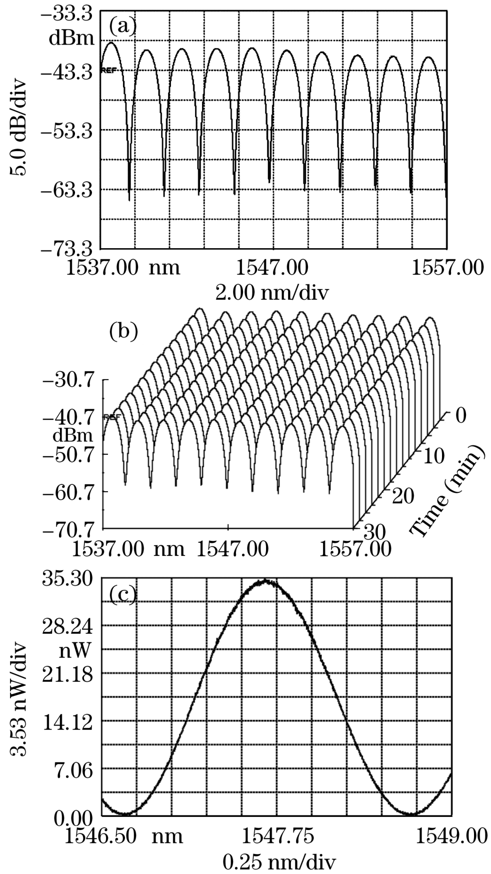

Fig. 2. (a) Reflection spectrum of the HiBi-SFLM in decibel scale; (b) repeated scans of the reflection spectrum for half an hour; (c) one period of the reflection spectrum in linear scale.

Figure 2(a) shows the measured reflection spectrum of the HiBi-SFLM in decibel scale. The wavelength spacing of the peaks is found to be about 2 nm, and the peak-to-notch contrast of the spectrum is larger than 22 dB. Figure 2(b) shows the repeated scans of the reflection spectrum for half an hour with a scan interval of 2 min under ordinary laboratory conditions without any temperature stabilization. It is clear that no significant change appears in the whole scanning process. Thus, the HiBi-SFLM here is more stable than the unbalanced Mach-Zehnder interferometer (MZI), which is very sensitive to environmental changes. This is because in the HiBi-SFLM, the two optical paths that induce the interference are in the same fiber rather than two different fiber arms of MZI. Figure 2(c) shows the reflection spectra of the HiBi-SFLM in linear scale. It can be seen that there are nearly linear regions on both sides of the reflection peak. If the strain is applied to the FBG, the central wavelength of the FBG will be shifted to the longer wavelength. When the Bragg wavelength of the FBG shifts in the linear region of the reflection spectrum of the HiBi-SFLM, the variation of the reflectivity of HiBi-SFLM with wavelength is nearly linear, and it could be expected that there exists a relationship between the laser output intensity and the magnitude of the physical variable that causes the shift of central wavelength.

The FBG with a length of about 6 cm written in a hydrogen loaded single-mode fiber (SMF) was fabricated with a uniform phase mask (with a period of 1068 nm) using KrF excimer laser. The central wavelength of the FBG is 1547.727 nm with a 3-dB bandwidth of 0.052 nm and a reflectivity of 93.8%. The transmission spectrum of the FBG is shown in Fig. 3.

The FBG sensor probe was bonded to a fiber stretcher. In the experiment, we applied an axial strain to the FBG by fixing both ends of the FBG and stretching it with a translation stage. When the strain was applied to the FBG, the fiber laser output was measured using an optical spectrum analyzer (OSA, ANDO AQ6317, Japan) with 0.01-nm resolution. Figure 4 shows the output spectra of the laser operating at different stretching values with a fixed pump power of 60 mW. With the strain increased, the laser wavelength shifts towards the longer wavelength side of the spectrum and the intensity decreased, which results from the decreasing reflectivity of the HiBi-SFLM in the range of 1547.75 − 1549 nm (see Fig. 2). Since the Bragg wavelength of the FBG shifts in the linear region of the reflection spectrum of the HiBi-SFLM, it can be seen that the laser intensity changes almost linearly. And the linewidth of laser output is kept about 0.027 nm in the measurement.

In order to evaluate the optical power behavior, the intensity variation of the laser output at different strain values are measured, as shown in Fig. 5. The change of the output power of the whole measuring range is about 0.17−0.34 mW. Considering a linear fitting to the experimental data, the laser output power P can be expressed as a function of strain ε through

$$P = 0.35148 - 2.52444 \times 10^{-4}\varepsilon. \quad (2)$$

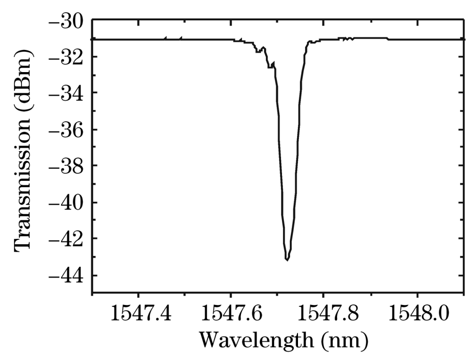

Fig. 3. Transmission spectrum of the FBG.

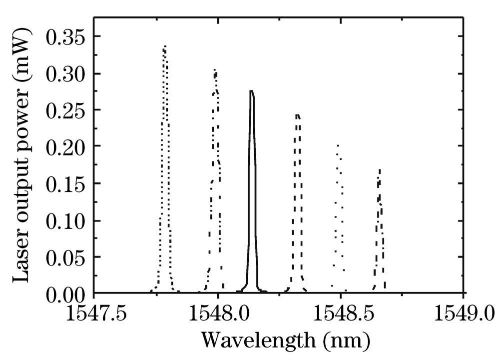

Fig. 4. Variation of the laser output power with different applied strains on the FBG. The applied strain is increasing for the curves from left to right.

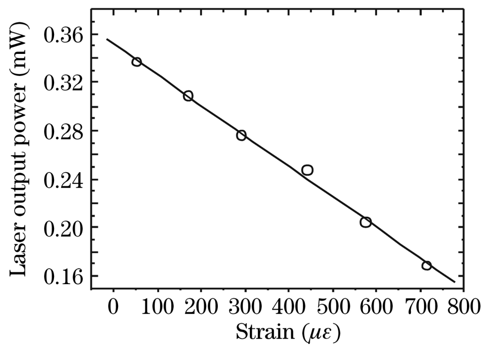

Fig. 5. Laser output power versus applied strain on the FBG.

In Eq. (2), P is in the unit of milliwatt, and ε is in the unit of μstrain ($\mu\varepsilon$).

The results showed that the relationship between the laser output power and the applied strain is quite linear ($R^2 = 0.998$). The sensitivity was found to be 0.25 μW/$\mu\varepsilon$.

The dynamic measuring range, which is determined by the peak spacing of the intensity pattern, can be increased or decreased by shortening or lengthening the HiBi fiber, but there is a trade-off between the measurement sensitivity (or resolution) and the peak spacing (or unambiguous measurable range). The wider the dynamic range is, the worse the resolution of the sensor system will be, and *vice versa*.

It is worth to mention that, when the strain applied to the FBG is changed, the laser wavelength and intensity both change in the real-time measurement. During the first few minutes (about 1 or 2 min) after a different laser wavelength appears, the output laser power is very unstable. However, after that period, the output power presents constant fluctuations of approximately 5 μW. Such fluctuations are probably owing to the pump source noise combined with the intrinsic noise of the system. Considering the power fluctuations and the linear fitting in Fig. 5, it is determined that the sensor error is about 20 $\mu\varepsilon$. To reduce the power fluctuation and obtain the higher sensing resolution, the structure of the laser should be further optimized, for example by increasing the reflectivity of the FBG, shortening the length of EDF, etc.

In the experiment, the entire strain measurement cycles were repeated using both ascending and descending values. As a result, the response of the active-sensor was found to be repeatable with small power fluctuation especially in the longer wavelength range, which is expected to be minimized by increasing the pump power. It is worth to note that although the measurement was performed using an OSA, it is possible to measure the laser output power by means of a much cheaper conventional photo-detector.

In conclusion, we proposed and experimentally demonstrated a fiber-laser-based strain sensor composed of a FBG and a HiBi-SFLM. The proposed sensor scheme can convert the wavelength shift into the laser output power change. Experimental results showed that when the Bragg wavelength shift of the FBG is within the linear region of reflection spectrum of the HiBi-SFLM, the relationship between the laser output power and the applied strain is nearly linear. Appropriately changing the HiBi-fiber length can adjust the sensor resolution and measurement range. There is a trade-off between these two parameters. This system is simple, polarization independent, and manufacturable using standard and readily available all-fiber components.

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