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Temperature- and strain- insensitive transverse load sensing based on optical fiber reflective Lyot filter

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For the first time to our knowledge, we propose and experimentally demonstrate a transverse load sensor using an optical fiber reflective Lyot filter. Such an optical fiber reflective Lyot filter consist of a fiber polarizer, a segment of polarization-maintaining fiber and a single mode fiber based fiber reflector. By demodulating the wavelength of the interference dip, the proposed device exhibits a desirable high transverse load sensitivity of 64.72 nm/(N/mm) without temperature and strain confusion, which provides a new option for the transverse load measurement and further expands the application of the fiber Lyot filter.

Recently, optical fiber sensors have gained increasing research interest due to their inherent particular advantages of high sensitivity, light weight, compact size, and electromagnetic immunity. A number of optical fiber sensors have been presented and demonstrated for different sensing applications including temperature,[1,2] torsion,[3–5] transverse load[6–9] and so on. Among above-mentioned optical fiber sensors, the fiber transverse load sensor with the ability to fulfil the measurement of transverse load plays an important role in the area of modern smart structure monitoring.

Up to now, a considerable amount of optical fiber transverse load sensors have been developed utilizing different fiber devices.[6–19] The most common fiber device used to construct the transverse load sensor is fiber grating. Liu et al. first reported a long period grating (LPG) in B/Ge co-doped fiber based transverse load sensor.[6] Zhang et al. presented and developed a fiber-optic transverse load sensor by measuring the polarization mode-splitting of the LPG induced by the transverse strain.[7] The above two LPG based transverse load sensors exhibit extremely high transverse load sensitivities and the maximum sensitivity is up to 50 nm/(N/mm). LeBlanc et al. realized a temperature-insensitive fiber transverse load sensor with a sensitivity of ~73 pm/(N/mm) based on a pi-phase-shifted fiber Bragg grating (PSFBG).[8] Chehura et al. presented transverse load sensors with a sensitivity of ~23 pm/(N/mm) by use of FBGs fabricated in a range of commercially available stress and geometrically induced high birefringent (HiBi) fibers.[9] However, the transverse load sensitivities of the two sensors are severely limited. To further improve the sensitivities of the FBG based transverse load sensors, FBGs fabricated in multicore fibers,[10] microstructural fibers[11] and suspended-core fibers[12] have been employed to construct the transverse load sensor. In addition, some special FBGs have been used to develop optical fiber load sensors, such as sampled fiber Bragg gratings (SFBGs),[13] chirped fiber Bragg gratings (CFBGs)[14] and tilted fiber gratings (TFGs).[15,16] Recently, Wang et al. applied the microwave photonics filtering technique into a FBG sensor for high-resolution transverse load measurement.[17] In addition, fiber based interferometers have also been used to measure the transverse load. Ma et al. established an optical fiber transverse load sensor by the use of a Fabry–Perot interferometer (FPI) with a fiber-tip micro-cavity.[18] Then, Wu et al. substantially enhanced the sensitivity of the transverse load fiber sensor by employing a special air cavity.

Lyot filter, which is generally made up of a birefringent element placed between two parallel polarizers, has been known for a long time and is extensively investigated.[20] Nowadays, a wide variety of Lyot filters have been built, such as bulk Lyot filters,[21–23] bulk-fiber mixed Lyot filters[24–26] and all fiber Lyot filters.[27–29] However, the main application of the Lyot filter is restricted to the field of spectral imaging,[21,23] laser[22,25,26,29,30] and optical communication.[27,28] For a single mode fiber (SMF) under transverse load, the stress-induced refractive index distribution along the two perpendicular directions of the fiber is different, resulting in the fiber birefringence. The induced fiber birefringence varies with the applied transverse load. As it is well known, the Lyot filter, as a birefringent filter, is sensitive to the variation of the birefringence, which makes it become a very promising candidate for fiber transverse load sensor. In this letter, we extend the application of the Lyot filter into the field of fiber sensing. Here, for the first time to our knowledge, a novel optical fiber transverse load sensor is proposed and demonstrated by employing the Lyot filter in a reflective way. The proposed sensor is mainly formed by a fiber polarizer and a segment of polarization-maintaining fiber (PMF). The principle of fundamental operation is to convert the applied transverse load induced fiber birefringent varies into the wavelength change of the interference spectrum for the Lyot filter. By monitoring the wavelength variation of the interference dip, the applied transverse load can be demodulated. The responses of the reflective Lyot filter to transverse load, temperature and strain are theoretically and experimentally investigated, respectively. The transverse load sensitivity of the reflective Lyot filter is up to 64.72 nm/(N/mm), however, the temperature and strain sensitivity are low to 4.5×10^{-4} nm/°C and 1.8×10^{-4} nm/$\mu\varepsilon$, which makes the proposed device attractive to transverse load measurement.

Unlike the conventional design ideas, we do not expect to demonstrate the fiber Lyot filter in a transmissive way, as the transmissive fiber Lyot filter is comprised of two fiber polarizers and a segment of PMF. Here, we present a fiber Lyot filter in a reflective way by employing only one fiber polarizer, a segment of PMF and a fiber reflector relying on the Fresnel reflection effect of the SMF, as illustrated in Fig. 1. Here, the fiber polarizer plays two roles

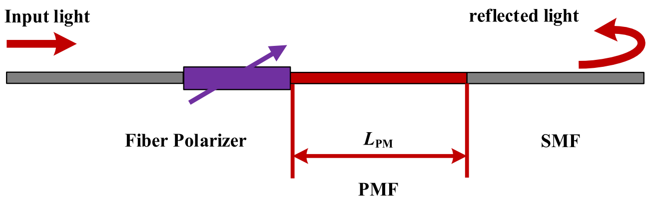

Fig. 1. (Color online) Diagram of the proposed optical fiber reflective Lyot filter.

simultaneously: serving as a fiber polarizer for the input light and acting as a polarization analyzer for the reflective light. The birefringent element used in the Lyot filter is a segment of PMF and the fast axis (or slow axis) of the PMF is aligned at an angle α to the optic axis of the fiber polarizer. After passing through the fiber polarizer, the input light is converted into linearly polarized light and subsequently propagates along the PMF. A small segment of standard SMF with a well-cleaved end is spliced to the PMF. Thus, the input light is reflected at the cleaved end of the SMF and then re-propagates into the PMF. Compared with the input light, the polarization state of the reflected light is changed by the Fresnel reflection, which is equal to a change in the angle β of the PMF with respect to the optic axis of the polarization analyzer. For the input light and the reflected light, the angle α, β must be properly pre-set to ensure that linearly polarized light can be resolved into two orthogonally polarized beams of light, co-linearly propagate separately along the two orthogonal polarization axes of the PMF. Because of the refractive index difference between the two polarization axes of the PMF, namely the birefringence of the PMF, a wavelength-dependent phase difference can be induced between the two co-linearly propagating polarized beams of light, and its magnitude is only depended on the birefringence and the length of the PMF. Finally, the two polarized beams of light are combined in the fiber polarizer, bringing about the interference of polarized light. In brief, the working principle of this all-fiber reflective Lyot filter is as follows: the input light is converted into linearly polarized light by the fiber polarizer and subsequently propagates twice along the PMF, resolved into two orthogonally polarized beams of light with a relative wavelength-dependent phase difference of $\Delta\varphi$, and then the two orthogonally polarized beams of light meet at the fiber polarizer, generating interference of polarized light.

For the reflective Lyot filter, the normalized reflectivity, R, as a wavelength-dependent filter transmission function can be expressed as:[5)]

$$R = \sin^2\alpha \sin^2\beta + \cos^2\alpha \cos^2\beta + \frac{1}{2}\sin 2\alpha \sin 2\beta \cos \Delta\varphi \tag{1}$$

where

$$\Delta\varphi = \frac{2\pi}{\lambda} \cdot B \cdot L_{equiv-\mathrm{PMF}}. \tag{2}$$

Here, B is the fiber birefringence in the PMF, $L_{equiv\text{-}PMF}$ represents the equivalent length of the PMF in the reflective Lyot filter.

The free spectrum range, namely the separation of adjacent dips (or peaks) in interference fringes is given by:[28)]

$$\Delta\lambda_m = \frac{{\lambda_m}^2}{B \cdot L_{equiv-\mathrm{PMF}}}. \tag{3}$$

The wavelength for the dip of the interference spectrum can be expressed as[28)]

$$\lambda_{\min}^m = \frac{2 \cdot B \cdot L_{equiv-\mathrm{PMF}}}{2m+1} \tag{4}$$

where m is a non-negative integer. From Eq. (4), we can find that the wavelength of the interference dip is related to the value of $B \cdot L_{equiv\text{-}\mathrm{PMF}}$. For the fiber Lyot filter under transverse load, the applied transverse load changes the fiber birefringence contributing to the filtering function directly, and then resulting in the variation of the wavelength for the dip of the interference spectrum. This provides a mechanism to deduce the value of the applied transverse load by real-time monitoring the wavelength of the interference dip.

Figure 2 shows the experimental setup for the transverse load measurement employing the reflective Lyot filter based sensor. A supercontinuum source (YCL-SC-5) with a stable output spectrum ranging from 800 nm to 1700 nm is connected to port 1 of an optical circulator (OC) as the input light. The reflective Lyot filter is connected to the port 2 of the OC. A ~10-cm-long PMF with a birefringence B of about 4×10^{-4} is employed as the birefringent element in the Lyot filter. An optical spectrum analyzer (OSA) with the highest resolution of 0.02 nm is connected to port 3 of the OC to real-time monitor the reflective spectrum. To apply a known transverse load on the fiber, we use the loading configuration shown in lower-right-hand inset of Fig. 2. A segment of SMF connected to the PMF in the reflective Lyot filter is used as the test fiber, with a fiber of the same diameter placed aside as the support fiber. The test fiber and the support fiber are laid between two flat-surface aluminum plates and kept straight by fixed on the aluminum plate with a small axial strain. Different transverse load is directly applied on the test fiber

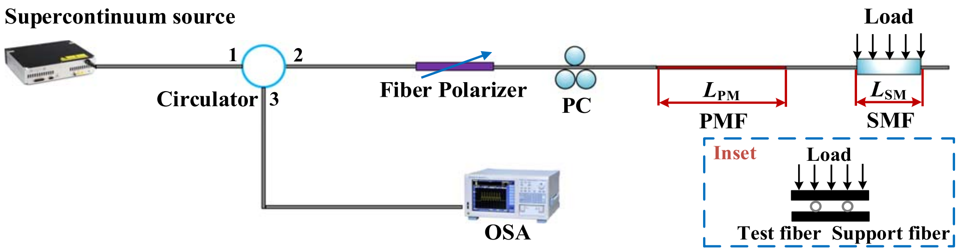

Fig. 2. (Color online) The experimental setup of the transverse load measurement with the proposed reflective Lyot filter based sensor.

by putting a number of standard weights on the top of the aluminum plate. For each value of the loading, the corresponding reflective spectrum is measured in real-time by the OSA. The active loading length L_{SMF} is ∼13 cm and the maximum loading applied is 6.975 kg.

Additionally, to get a desirable original reflective spectrum, a fiber polarization controller (PC) is employed in the Lyot filter. It should be pointed out that the PC is not essential for the practical application, as the desirable original reflective spectrum could be easily obtained by simply presetting a suitable angle α. Further, the original reflective spectrum measured in a spectrum range from 1500 nm to 1600 nm is shown in Fig. 3. It can be seen that the transmittance of the reflective Lyot filter is a wavelength-dependent filter transmission function, and the obtained original fringe contrast is up to ∼25 dB. What is more, the free spectrum range of the interference fringes is ∼29.2 nm near the wavelength of 1550 nm, corresponding to the $L_{equiv\text{-}PMF}$ of 20 cm.

In order to characterize the sensor in the transverse load, transverse loads ranging from 0 to 0.537 N mm^{-1} are directly applied on the sensor by putting a number of standard weights on the top of the aluminum plate at a constant environment temperature of ∼20 °C, and the corresponding wavelength evolution of the dip at the original wavelength of 1564.1 nm is shown in Fig. 4(a). It is shown that the fringe contrast of the interference dip varies with the applied transverse load, and the maximal variation of the fringe contrast is ∼16 dB. The variation of the fringe contrast is resulted from the conversion of polarization state induced by the applied transverse load. At the same time, we can find that the wavelength of the dip shifts to the longer-wavelength direction with the transverse load increasing, namely "red shift." The wavelength position of the interference dip at 1564.1 nm shifts to 1599.1 nm when the transverse load applied on the sensor increases from 0 to 0.537 N mm^{-1}, corresponding to the wavelength variation of 35 nm.

When the transverse load is applied on the SMF, the refractive index distribution in the two orthogonal axes of the SMF is different, resulting in the fiber birefringence ΔB. So the SMF under transverse load can be regarded as a segment of PMF with the birefringence of ΔB. So the wavelength for

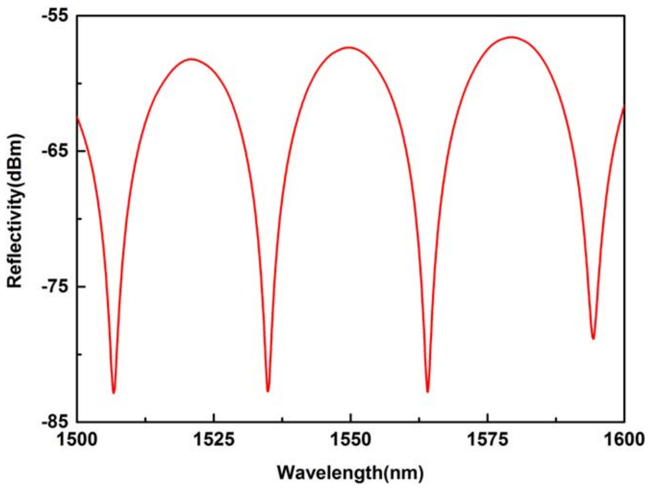

Fig. 3. (Color online) Measured original reflection spectrum of the proposed Lyot filter.

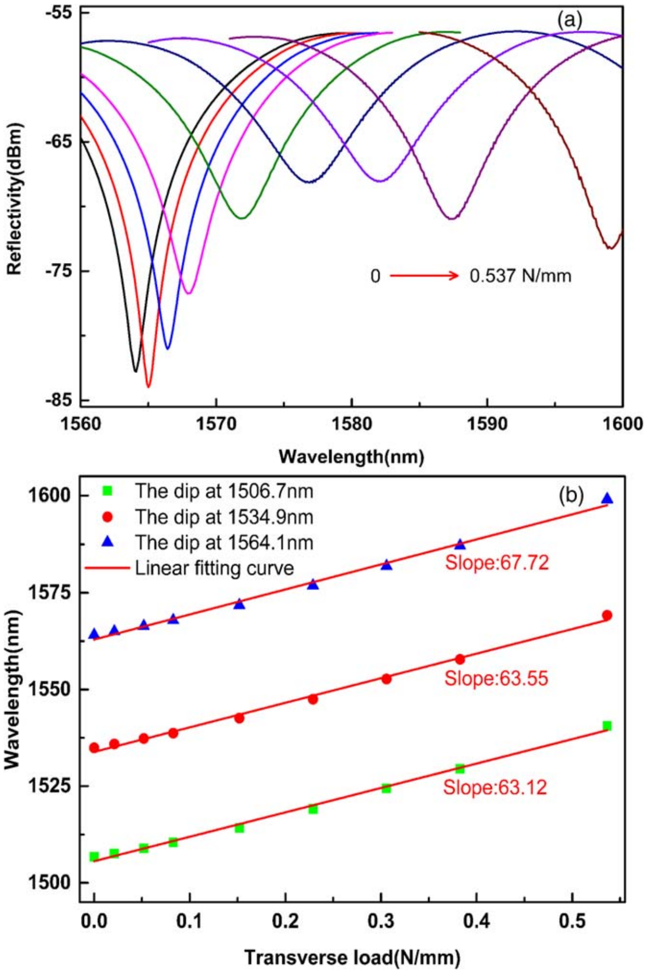

Fig. 4. (Color online) (a) The wavelength evolution of the dip with different applied transverse loads. (b) Transverse load response of the proposed reflective Lyot filter.

the interference dip of the Lyot filter under transverse load can be given by:

$$\lambda_{\min}^{m} = \frac{2}{2m+1}(B \cdot L_{equiv-PMF} + \Delta B \cdot L_{equiv-SMF}). \quad (5)$$

Here, ΔB represents the fiber birefringence of the SMF induced by the transverse load, and $L_{equiv\text{-}SMF}$ is the equivalent length of the SMF. With the increase of the transverse load applied on the SMF, the transverse load induced fiber birefringence ΔB is changed, resulting in the variation of dip wavelength. According to the Eq. (5), the increasement of the birefringence ΔB induced by the variation in the transverse load will bring about the red shift of the dip wavelength, which agrees well with the experimental result presented in Fig. 4(a). Then, the relationships between the wavelengths of the selected dips at 1506.7 nm, 1534.9 nm, 1554.1 nm and the applied transverse load are demonstrated in Fig. 4(b), where the symbols represent the experiment data and the red line are the linear fitting curves. It is shown that the wavelength shift of the selected dip pattern as a linear function of the applied transverse load with the maximal coefficient of 67.72. So the maximal transverse load sensitivity achieved in our experiment is 67.72 nm/(N/mm).

Then, the influence of temperature and strain on the proposed fiber transverse load sensor are investigated,

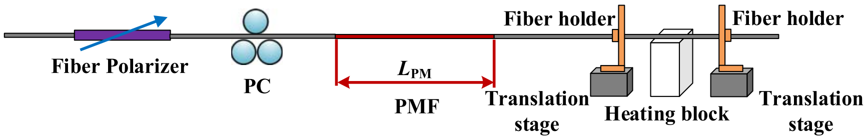

Fig. 5. (Color online) The experiment setup for the temperature and strain measurement.

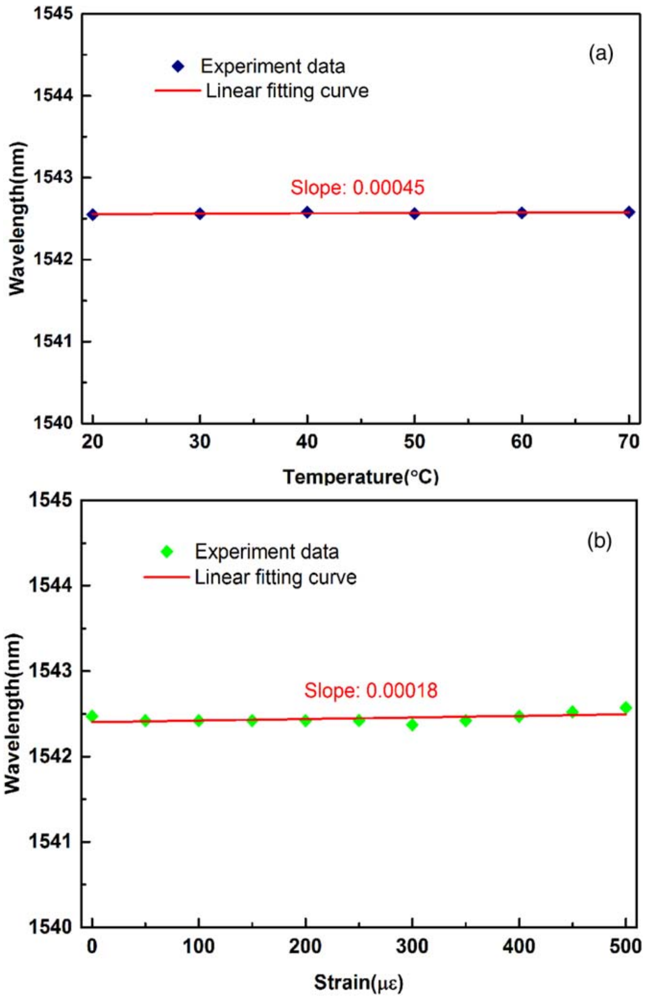

Fig. 6. (Color online) (a) Temperature response and (b) Strain response of the proposed reflective Lyot filter.

respectively. The experiment setup for temperature and strain measurement is illustrated in Fig. 5. Both ends of a ~20 cm long SMF are fixed by a pair of fiber holders. And the two fiber holders are mounted on two translation stages, respectively. So the strain can be applied to the sensor by moving one of the two translation stages. For the temperature measurement, a heating block controlled by a temperature controller is employed to heat a segment of SMF with the length of ~6 cm.

The temperature response of the sensor is investigated by gradually heating the sensor from 20 °C to 70 °C with an interval of 10 °C. For each measurement point, the temperature is maintained ~10 min, and the corresponding temperature response of the reflection spectrum is recorded by the OSA in real time. The selected reflection dip wavelength via temperature are demonstrated in Fig. 6(a). It can be clearly found that the selected reflection dip wavelength has little fluctuations with temperature. According to the coefficient of the linear fitting curve, we can obtain that the temperature sensitivity of the sensor is low, 4.5×10^{-4} nm/°C; that is to say, the sensor is temperature-insensitive. Then the strain response of the sensor is also investigated by varying the strain within the range from 0 to 500 $\mu\varepsilon$ with a step of 50 $\mu\varepsilon$, and the selected reflection dip wavelength via strain are demonstrated in Fig. 6(b). The obtained strain sensitivity is only 1.8×10^{-4} nm/$\mu\varepsilon$, vividly confirming that the proposed sensor is immune to strain. It is worth noting that, when temperature and strain are applied on the SMF uniformly, the refractive index difference between the two perpendicular directions of the SMF almost remain the same, resulting in the birefringence of the SMF being constant. As there is no birefringence change induced by temperature and strain, the sensor is insensitive to temperature and strain. Such a theoretical analysis is in good agreement with the results obtained in the experiment.

In conclusion, a novel optical fiber transverse load sensor is proposed and demonstrated by employing the Lyot filter in a reflective way for the first time. The applied transverse load changes the local birefringence of the SMF, and then results in the dip wavelength shift of the interference fringes. By monitoring the wavelength variation of the interference dip, the applied transverse load can be demodulated. The responses of the reflective Lyot filter to transverse load, temperature and strain are theoretically and experimentally investigated. The transverse load sensitivity of the reflective Lyot filter is up to 67.72 nm/(N/mm), however, the temperature and strain sensitivity are low to 4.5×10^{-4} nm/°C and 1.8×10^{-4} nm/$\mu\varepsilon$. Such sensing characteristics allow us to achieve a temperature- and strain-insensitive transverse load sensor, which provides a new option for the transverse load measurement and further exp ands the application of the fiber Lyot filter.

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