Reflective Optical Fiber Refractometer Based on Long-Period Grating Tailored Active Bragg Grating

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***Abstract*— A reflective optical fiber refractometer based on a long-period grating (LPG) followed by an active fiber Bragg grating (AFBG) is proposed. The AFBG is inscribed in a short section of cobalt-doped optical fiber, which can be heated by pump laser and acts as a sensing signal indicator. The LPG functions as a bridge between the surrounding refractive index (RI) and the AFBG reflection, tailoring the power of pump laser for heating. Experimental results demonstrate that the wavelength response of this fiber grating-based reflective refractometer can be easily adjusted, and a significantly improved sensitivity within the RI range from 1.3403 to 1.4654 has been achieved.**

***Index Terms*— Reflective optical fiber refractometer, active Bragg grating, long-period grating.**

I. INTRODUCTION

IN RECENT years, optical fiber refractive index (RI) sensing has received a great deal of attention and various kinds of refractive index sensors have been developed based on different working principles [1]–[19]. Among these sensors, optical fiber gratings incorporated sensors are considered to be more competitive because of their wavelength encode property, easy fabrication and reproducibility, high sensitivity and remote operation capability. One well-known scheme is based on long-period grating (LPG) [5]. Many LPG based RI sensors have been demonstrated [6]–[9]. Although the refractive index sensitivities of these sensors can be relatively high, the large spectral widths limit their sensing resolution and the transmission readout type cripples the practicability in their applications for practical bio- and chemical sensing [10]. In another scheme, RI sensors incorporated with fiber Bragg grating (FBG) have also been widely investigated, owing to their compact size, high multiplexing potential and reflection mode operation. Since FBG is inherently not sensitive to the surrounding refractive index (SRI), some special postprocesses need to be employed to construct RI sensors, such as the etched FBG [11], the side polished FBG [12] and FBG written in D-shaped [13] or H-shaped fiber [14]. However, these processes not only significantly degrade fiber mechanical strength but also increase the complexity and cost of fabrication. Tilted FBG (TFBG) has also been proposed for SRI measurement [15], [16]. This scheme, however, causes the core mode to be coupled to a number of cladding modes in a large wavelength range with small wavelength intervals, thereby rendering not only the multiplexing difficulty but also potential coupling wavelength confusion. More recently, some cascade schemes, including single-mode-multimode-single-mode (SMS) fiber structure followed by FBG [17], LPG combined with FBG [18], and thin-core fiber tailored FBG [19], have been explored to realize the desirable reflective RI sensing. Although these techniques are attractive and promising, they suffer either low SRI sensitivity or weak reflective sensing signal which makes them not practical in real sensing applications.

In this letter, we propose a novel reflective optical fiber refractometer, which is based on the desired reflection mode operation by constructing an LPG followed by an active fiber Bragg grating (AFBG). The AFBG is inscribed in a cobalt-doped optical fiber (COF), which can be optically heated by the pump laser. The resonant wavelength of the LPG is appropriately designed to overlap the wavelength of the pump laser. Once the SRI changes, the LPG's resonant wavelength shifts and mismatches the pump laser, which leads to the temperature change of the AFBG and finally induces the red shift of the reflection wavelength. We demonstrated a temperature-insensitive refractometer based on active gratings earlier [20], which could be thermally stabilized through the pump light heating. However that refractometer was in the transmission readout type and its configuration was rather complicated. The sensor presented here is more compact and yields strong reflective sensing signal with significantly enhanced SRI sensitivity. More importantly, the SRI sensitivity can be easily adjusted by selecting different powers of the pump laser or the COFs with different absorption coefficients.

II. OPERATION PRINCIPLE

As shown in Fig. 1, a short section of the COF is fusion spliced to the leading single mode fiber (SMF). A LPG and

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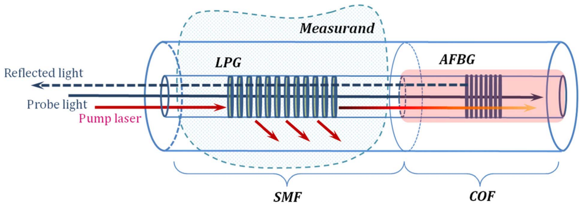

Fig. 1. The schematic diagram of the proposed optical fiber grating refractometer.

an AFBG are respectively inscribed in the SMF and the COF. The core of the COF is doped with photoabsorption medium cobalt. Therefore, the COF can nonradiatively absorb the pump laser propagating in its core and transfer the laser power into heat [21]–[23], which induces the temperature increase of the COF, as well as of the AFBG region. The resonant wavelength of the LPG is appropriately designed to overlap the wavelength of the pump laser. Thus part of the pump laser will be coupled to the cladding mode and fade away along the fiber. Once the SRI changes, the resonant wavelength of the LPG shifts [5], leading to the wavelength mismatch between the LPG and the pump laser. Thus the transmission loss of the pump laser induced by the LPG changes. As a result, the power of pump laser that reaches the COF part changes as well, inducing resulting in the temperature variation of the AFBG region. Due to the inherent sensitivity of the Bragg resonance wavelength to temperature [24], one can deduce the SRI change by monitoring the reflective Bragg wavelength shift of the AFBG.

III. Fabrication of the Reflective Refractometer

The refractometer has been implemented by using commercialized COF (ATN, CorActive High-Tech). The absorption wavelength of the COF ranges from 1250 to 1620 nm and the absorption coefficient of the used COF is 5 dB/cm. The AFBG with a length of $\sim$8 mm was written by using the phase mask method with a 193 nm ArF excimer ultraviolet laser (Coherent, Bragg Star S-Industrial). Before grating fabrication, the COF was hydrogen-loaded at 100 °C under 100 bar pressure for 4 days. The period of the used phase mask is 1070.0 nm. The LPG with a period of 470 μm and length of $\sim$20 mm was inscribed in the SMF by using the point-by-point fabrication technique. An erbium-doped fiber amplified tunable laser (81940A, Agilent Technologies) was used as the pump laser source.

Figure 2(a) shows the transmission spectrum of the fabricated grating sensor (in air) without pump laser injection. The transmission spectrum consists of two well-defined dips corresponding to the LPG at 1532.720 nm with transimission loss of ~ -16 dB and the AFBG at 1546.150 nm, respectively. Different resonant modes of the LPG will result in the different sensitivities of the sensor [25]. Here the observered transmission dip is corresponding to the coupling from the foundamental mode to the 5th high order mode [26]. The wavelength response to the SRI of the selected mode of LPG was measured in advanced. When the SRI increases, the resonant wavelength of the LPG shifts to a shorter wavelength. The relative position between the resonance wavelength of the LPG and operating wavelength of pump laser is the essential parameter which influences the sensitivity and accuracy of the sensor. Here the wavelength of the pump laser, denoted as λp in Fig. 2(a), was fixed at 1534 nm and is a little longer than the resonant wavelength of the LPG in air to ensure a large dynamic range, high sensivitiy and accuracy. Figure 2(b) shows the reflection spectrum measured from the lead-in fiber end. Only one peak is observed and it is equivalent to the reflection of a normal FBG.

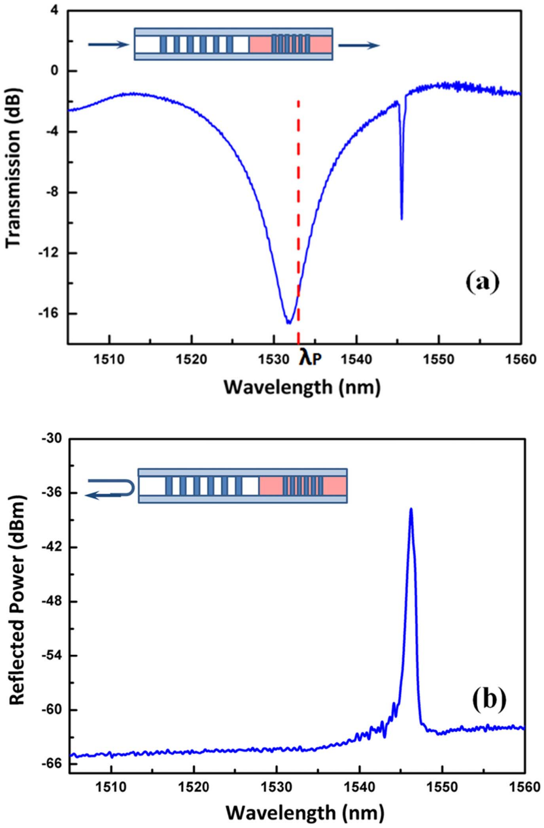

Fig. 2. Measured (a) transmission spectrum and (b) reflection spectrum of the proposed sensor in air.

IV. Results and Discussions

In order to evaluate the SRI sensing performance, the proposed reflective sensor was immersed into a series of sucrose solutions with different mass concentrations. The refractive indexes corresponding to the used solutions all refer to their values at the wavelength of 589 nm [27]. Figure 4 shows the experimental setup for testing of the proposed reflective sensor. A broadband light source (BBS) and optical spectrum analyzer (OSA, Ando AQ6317) were used as the FBG interrogation section. Only the LPG part was immersed into the liquid so that the generated heat in the COF makes no difference on the measurand. The amplified tunable laser with power of 500 mW as the SRI increases. This is due to the fact that as the SRI increases, the resonant wavelength of the LPG shifts to a shorter wavelength, was launched into the sensor through a WDM. Figure 3 shows the reflection spectra at different refractive index values, which indicates that the

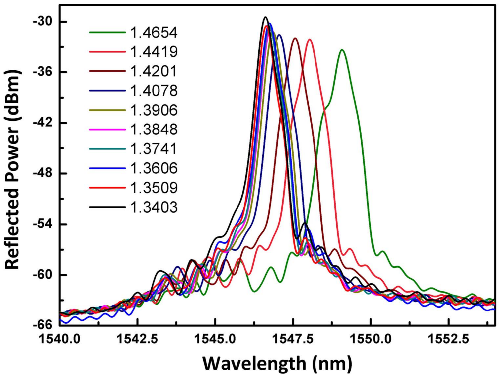

Fig. 3. Spectral response of the reflection spectrum at different SRIs with the pump power of 500 mW.

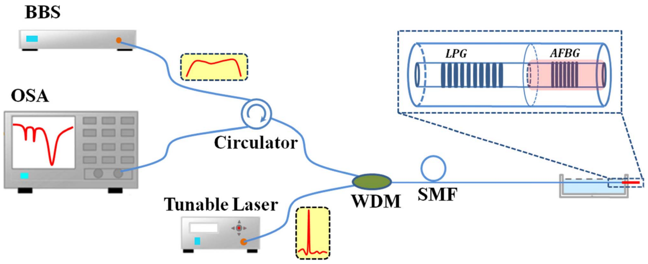

Fig. 4. The schematic diagram of the setup for testing of the reflective sensor.

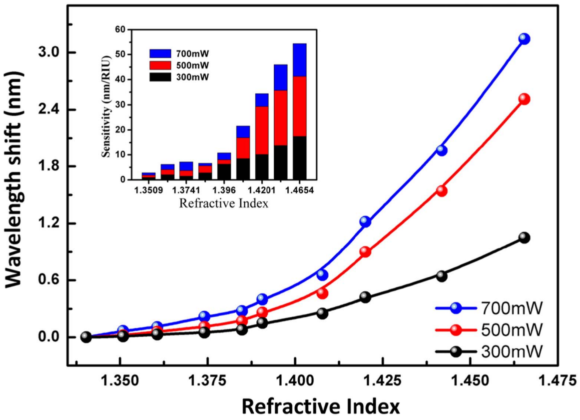

Fig. 5. The wavelength responses of the AFBG sensor versus SRI with different powers of pump laser. The inset shows the corresponding calculated refractive index sensitivities.

Bragg wavelength of the AFBG shifts to a longer wavelength thereby resulting in the increase of the pump laser power reaching the COF. Thus the temperature of the AFBG region increases and the Bragg wavelength experiences a redshift. Meanwhile, the reflection spectrum shows a slight chirp due to the non-uniform heating profile along the COF [19]. The wavelength shift as a function of the SRI is shown in Fig. 5. The inset shows the calculated RI sensitivities of the sensor at different RI values. The maximum sensitivity of 41.2 nm per refractive index unit (RIU) was achieved at the refractive index value of 1.4654, which is improved by nearly one order of magnitude compared with the sensitivities of the cascade structures proposed before [17], [19].

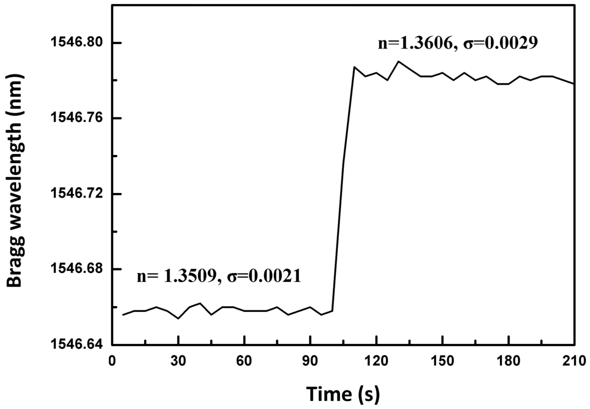

Fig. 6. The dynamic measurement in time for SRI change from 1.3509 to 1.3606.

The sensitivities with different pump powers were also measured and are shown in Fig. 5. When the power of the pump laser was adjusted to 300 mW and 700 mW, maximum sensitivities of 17.5 and 55.1 nm/RIU were respectively achieved. The inset clearly indicates that the sensor with higher pump power has higher sensitivity within the measured RI range from 1.3403 to 1.4654. Therefore, one can easily adjust the sensitivity of the refractometer by changing the power of pump laser. This suggests that a simple way to further improve the sensitivity is to increase the pump power. Considering the spectral resolution of OSA is 0.01 nm, one can deduce that the resolution of the proposed refractometer is up to$1.8 \times 10^{-4}\ RIU$.

In additional to resolution, the limit of detection is also an important parameter of sensors in biochemical sensing applications. The dynamic measurement in time for SRI step change is shown in Fig. 6, from which the standard deviation (σ) in detecting the wavelength has been calculated (see Fig. 6) [27]–[29]. Here we considered the limit of detectable signal as the average calculated standard deviation divided by the sensitivity in the measurement SRI range [27]. From this view, an average limit of detection of $\pm 6.0 \times 10^{-4}\ RIU$ was achieved. In the best measurement, a limit of detection of $\pm 3.8 \times 10^{-5}\ RIU$ could be achieved in the SRI range near 1.4654 and at pump power of 700 mW, when our device has the highest sensitivity of 55.1 nm/RIU. In a real biochemical applications, for more stringent statistics case, assuming a 3σ standard, it would yield a limit of detection of $\pm 1.2 \times 10^{-4} RIU$, which is comparable to the other reports [28], [29].

Sensors with the AFBG of identical grating parameters but inscribed in the COFs with different absorption coefficients were also fabricated and measured. As shown in Fig. 7, for the same pump power of 300 mw, sensors with different kinds of COFs show similar behavior as those shown in Fig. 4. And the sensor using the COF with absorption coefficient of 5 dB/cm possesses higher SRI sensitivity than the one using the COF with absorption coefficient of 3 dB/cm. This indicates that the sensitivity of the refractometer can be further improved by selecting the COF with higher absorption coefficient. Meanwhile, it should be pointed out that with the increase

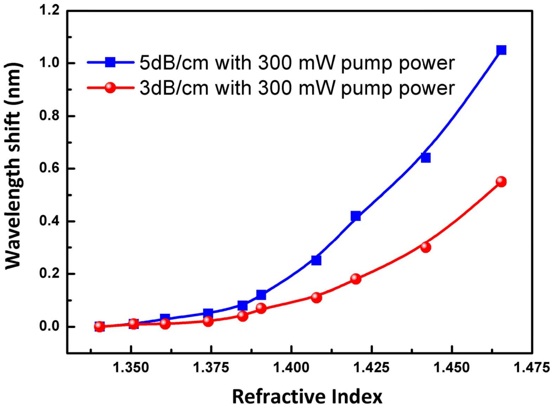

Fig. 7. Measured wavelength responses versus SRI with different absorption coefficients of the used COFs.

of COF's absorption coefficient, the loss of the reflective sensing signal also increases. Thus here comes a tradeoff between the SRI sensitivity and the quality of sensing signal. However, by properly choosing the COF with suitable absorption coefficient, the proposed refractometer can potentially achieve the desirable sensitivity and maintain the strong sensing signal.

V. CONCLUSION

In conclusion, we have proposed and demonstrated a novel reflective SRI sensor, showing significantly improved sensitivity based on a LPG tailored AFBG. This structure utilizes the SRI sensitive LPG to tailor the power of pump laser reaching the AFBG, which then transforms the SRI information into the Bragg wavelength shift of the AFBG. Experimental results show that this RI sensor with strong reflective sensing signal has achieved a maximum sensitivity of 55.1 nm/RIU within the refractive index range from 1.3403 to 1.4654. The sensitivity can also be easily adjusted by optimizing the pump power and the absorption coefficient of the COF. Such a good performance renders this SRI sensor as a great potential candidate for reflective remote single-point sensing in biochemical applications.

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