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A fiber twist sensor based on the surface plasmon resonance (SPR) effect of an Au-coated tilted fiber Bragg grating (TFBG) is proposed. The SPR response to the twist effect on an Au-coated TFBG (immersing in distilled water) is studied theoretically and experimentally. The results show that the transmission power around the wavelength of SPR changes with the twist angle. For the twist ranging from 0° to 180° in clockwise or anti-clockwise directions, the proposed sensor shows sensitivities of 0.037 dBm° (S-polarized) and 0.039 dBm° (P-polarized), which are almost 7.5 times higher than that of the current similar existing twist sensor. © 2014 AIP Publishing LLC.

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Twist/torsion measurement has been attracted considerable research interests for its potential applications in health monitor of the bridge, dam, building, and so on. So far, a number of optical fiber twist sensors have been demonstrated, which include the use of high- or low-birefringence photonic crystal fibers (HB- or LB-PCF) in Sagnac loops,1–3 corrugated long period fiber grating (LPGs),4 integrated single-mode fiber (SMF), polarization-maintaining fibers (PMFs),5–6 fiber ring lasers, FBGs,7–9 and some special fibers.10,11 However, the Sagnac-based twist sensors usually suffer from temperature dependence and require relatively complex signal interrogation that often involves high-resolution optical spectrum analysis, which might limit such sensors’ potential applications. The LPGs-based twist sensors have relative long device size and broad spectral width, thus giving low stability and poor spectral resolution. Chen et al.12 reported an in-fiber twist sensor based on a fiber Bragg grating with 81° tilted structure. However, the large tilt angle tilted fiber Bragg grating (TFBG) is not commonly used and difficult to fabricate and control. TFBGs (tilt angle ranging from 0° to 10°) are of benefit to a wide range of sensing modalities: the grating planes are slightly tilted from the fiber axis, which enhance the coupling of light from the core mode to a large number of counter propagating cladding modes. They are widely used in external refractive index, bending, modern biological analysis, and others. As the TFBG was coated with a thin film of metal, the surface plasmon resonance (SPR)13,14 will be excited and enlarged. Consequently, some Au-coated TFBG based SPR sensors were demonstrated.15–17

In this Letter, an Au-coated TFBG twist sensor based on the SPR effect was demonstrated. Using the polarization properties of the Au-coated TFBG and the cladding modes (evanescent wave on the Au surface), the evolution of SPR properties of the Au-coated TFBG and the cladding modes was studied, and the obtained sensitivity of 0.037 dBm° is almost 7.5 times higher than that of the current similar existing twist sensor.12

A TFBG with a tilt angle of 10° and total length of 10 mm was written in hydrogen-loaded photosensitive Corning SMF-28 fiber with a pulsed KrF excimer laser by using the phase-mask method. The Bragg wavelength is 1602.5 nm. A gold coating with a thickness of 50 nm was deposited on the surface of the TFBG by a sputtering method. Fig. 1 shows the side view of the index perturbation pattern and the light propagating of the Au-coated TFBG. The grating couples the core mode to a multitude of cladding modes (each at a different wavelength, as determined by the grating period and mode effective index) and these couplings show up as loss peaks in the transmission spectrum. Because the thickness of the Au layer is only 50 nm, some of the light guided by the cladding tunnels will transmit to the outside surface of the Au layer. When this light is phase matched with a possible plasmon mode of the interface between the gold and the outer medium (for example, water or oil), such plasmon wave can be excited efficiently. The phase matching condition is relatively narrowband and involves only a small subset of cladding modes. When this occurs, the resonance becomes lossy and disappears from the transmission spectrum.15 and the position of the missing resonances reveals the wavelength of SPR. From the previous researches,16,17 we know that the SPR of the Au-coated TFBG mainly depends on following factors:

(i) For a TFBG, its Bragg wavelength λBragg and cladding mode resonance wavelengths λclad are determined by the following phase matching condition:

\[
\lambda_{\text{Bragg}} = 2N_{\text{eff}}(\text{core}) \cdot \Lambda / \cos(\theta),
\]

\[
\lambda_{\text{clad}} = (N_{\text{eff}}(\text{core}) + N_{\text{eff}}(\text{clad})) \cdot \Lambda / \cos(\theta),
\]

where \( N_{\text{eff}}(\text{core}) \) and \( N_{\text{eff}}(\text{clad}) \) are the effective indices of the fiber core and cladding.

(ii) Surface plasmon with effective index \( N_{\text{sp}} \) can be expressed by the dielectric constant of the metal (\( \varepsilon_{\text{m}} \)) and the refractive index of surrounding (\( n_s \)).
From Ref. 15, for a gold film thickness near 50 nm, the plasmon has an effective index, that is, very close to the gold water boundary calculated using Eq. (3). As the $N_{\text{eff}}$ is matched with the $N_s$ to some extent (and polarized matched), the cladding mode will be excited to a SPR.

(iii) The SPR signal depends strongly on the polarization of the input light: for P-polarized light, it is maximized, which corresponds to the complete extinction of a small subset of cladding mode resonances. For S-polarized light, the SPR effect cannot be excited and the spectrum is similar to that of the normal TFBG without Au coating.

Therefore, for an Au-coated TFBG, if its length of $L$, tilt angle of $\theta$, period of $A$, and the thickness of gold film were determined, the SPR is only decided by the polarization of the input light. The experimental setup is shown in Fig. 2. A broad band source (BBS) (JDS Uniphase), polarization controller (PC) (JDS Uniphase), and optical spectrum analyzer (OSA) (AQ6317B, ANDO) were used to achieve spectra with precise S- and P-polarized input light. The PC contains one polarizer, a half-wave plate, and a quarter-wave plate. This combination allows the preparation of arbitrary polarization states at the fiber input, which can compensate for any change of polarization state induced by fiber loops and twists in the optical path leading to the TFBG. The filter (Yenista, Xtm-50) and power meter (PD, JDS Uniphase, PS3) were used to monitor the light power of the SPR wave-lengths. For the twist measurement, the TFBG-SPR sensor positioned in the middle was fixed by a clamp on one side and a fiber rotator on the other end. The whole Au-coated TFBG was placed in distilled water. The Au-coated TFBG is used as the twist sensing head. In order to eliminate measurement errors from axial-strain and bending effects, we applied a small axial tension to the fiber maintaining it straight. The experiments were carried out over a twist angle range of 0° to 180° in steps of 15° on clockwise and anticlockwise directions.

The operation of the proposed sensor can be explained by Fig. 3. For the no twist condition, as shown in the coordinate system of Fig. 3(a), the input E-field vector $E_{1}$ (on the $x$-axis direction) is P-polarized for the TFBG (the polarization direction parallels to the grating plane). According to the cladding mode property of the TFBG, the excited cladding mode of $E_{c}$ is P-polarized too, and the SPR signal is maximized. When the TFBG is exposed to a twist around the longitudinal axes, as shown in Fig. 3(b), under the same input condition as Fig. 3(a), $E_{1}$ will be no longer parallel with the grating plane, since the grating plane will twist with the fiber’s torsion. In addition, the modes coupling from core to cladding occurred mostly in the front end of the TFBG (about 1 mm). So here the angle of twist refers to the twist angle of the front end of the TFBG. Assumed the front end of the TFBG is twisted to an angle of $\theta$, the polarization direction of excited cladding mode of $E_{c}$ will deviate from the $x$-axis with an angle of $\theta$. That means the $E_{c}$ can be decomposed as $E_{cx}$ and $E_{cy}$ with the expressions of $E_{cx} = E_{c} \cos \theta$ and $E_{cy} = E_{c} \sin \theta$, where $E_{cx}$ is P-polarized and the $E_{cy}$ is S-polarized. As a result, with the twist angle increasing to 90°, the amplitude of the $E_{cx}$ decreases to minimize, and the SPR signal will disappear, as shown in Fig. 4a-C. On the other hand, as the input light is the S-polarized (the polarization direction of $E_{1}$ is on the $y$-axis), the results are just the opposite: without any twist on the TFBG, there is no SPR, and as the twist angle increasing to 90°, the SPR signal is maximized, as shown in Fig. 4b-b. We can use a narrow filter to monitor the changing of the transmission power near the SPR resonance wavelength for different twist angles. The transmission power of $P_{\text{out}}^{\text{FBG--SPR}}$ near the SPR resonance wavelength has the following expression:

$$P_{\text{out}}^{\text{FBG--SPR}} = T_P \cos^2 \theta + T_s \sin^2 \theta,$$

where $T_P$ and $T_s$ are the initial transmission intensity of P- and S-polarized input without twist, respectively. $\theta$ is the twist angle in clockwise or anticlockwise. In our experimental, $T_P$, and $T_s$ have the values of −8.18 dB and −13.76 dB, respectively.

Fig. 4 shows the measured transmission spectra of an Au-coated TFBG-SPR sensor at (a) P- and (b) S-polarized states (in distilled water). A, B, C, D, and E represent spectra with the angle of 0°, 45°, 90°, 135°, and 180° in clockwise
Before the fiber was twisted, we can set the pre-polarization state at P- or S-polarization by adjusting the PC, and the SPR signal is maximized or minimized, as shown in Fig. 4(a–A) or Fig. 4(b–A). From Fig. 4(a), we can see that as the Au-coated TFBG-SPR sensor was twist in clockwise from 0° to 90°, the SPR signal become weak gradually. And as the twist angle reaches 90°, the SPR signal disappeared totally. As the twist angle was increased from 90° to 180°, the SPR signal become strong gradually. And as the twist angle reaches 180°, the SPR signal is maximized again. For S-polarization, as shown in Fig. 4(b), the evolutionary process of the SPR signal was opposite to that of the P-polarization input light. In the experiment, we then repeated this process by twisting the fiber in anticlockwise direction for P-and S-polarization input, and we saw clearly a repeating spectral evolution process, as shown in Fig. 4.

To obtain the relationship between the twist angle of the Au-coated TFBG and the SPR, a narrow filter (bandwidth = 0.5 nm, insertion loss = 5 dB) and a PD were used to monitor the light power around the SPR wavelength in transmission spectrum. As shown in Fig. 5, in the transmission spectrum of the Au-coated TFBG under the P-polarization and twist of 0°, the transmission power around a SPR wavelength of 1543.05 nm was monitored. Fig. 6 plots the normalized measured transmission power around the selected SPR signal for P- and S-polarizations in clockwise (0° to 180°) and anti-clockwise (0° to 180°) directions. Taking a quasi-linear range from 0° to 90° as an example, linear fit with a high value of 0.9987 and 0.9997 for P- and S-polarizations were obtained. And the normalized sensitivities are 0.0108/° and 0.0111/° (equivalent to 0.037 dBm/° and 0.039 dBm/°) were obtained for S- and P-polarization. In practical application, the sensor can be pre-twisted to this linear range for achieving a high sensitivity measurement.

The Au-coated TFBG SPR based sensor is capable of detecting both direction and amplitude of the twist if the initial operation state is set at 45° condition, where P- and S-polarizations have the same SPR strength. In this situation, relative variations of the two loss peaks give a clear indication of the twist direction. Moreover, the resolution of the twist sensor is calculated as 0.025° at the limit resolution of the PD of 0.001 dBm. Benefited from the using of intensity demodulation method, the proposed sensor has an application advantage in marked contrast with other grating based twist sensors which usually employ wavelength-shift means.
The temperature dependence was observed by heating the Au-coated TFBG (with a 90° angle of twist for S-polarization input) in a distilled water bath provided with a temperature controller. The experiments were carried out over a temperature range of 24–80 °C, as shown in Fig. 7. It can be seen that the observed SPR shift towards longer wavelengths as the temperature increases, which has a fitted linear slope equal to about 10 pm/°C for the device configuration studied here. This sensor’s temperature dependence is caused by the following three reasons: the water’s refractive index (RI) changed by the temperature, the twist induced the fiber circular birefringence, and the thermo-optic effect of the gold film. However, the temperature dependence caused by the twist induced circular birefringence and the thermo-optic effects of the gold film are small.17,18 Therefore, we think that the temperature dependence for this sensor is mainly caused by the distilled water’s RI changing, which leads to a shift of the SPR wavelength. For the purpose of our sensor, this shift can be lifted by proper calibration of the sensor prior to use because the TFBG-SPR sensor has an internal thermometer provided by the absolute value of the Bragg wavelength of the core mode back reflection.17

In addition, from Fig. 7, we can see that the intensity of the SPR wavelength changes with the increasing of temperature too, which seems to affect the measurement accuracy. However, as shown in Fig. 8, through calculating each SPR spectrum’s power (using a filter with a bandwidth of 0.5 nm), we found that each SPR has almost the same power. (The averaged normalized power error is about 1.7387E-5/C.) Therefore, the intensity changing of the SPR wavelength induced by the temperature changing is almost no influence to the proposed sensor’s measurement accuracy. Furthermore, the measurement accuracy is easily disturbed by the light source power fluctuation as using light intensity demodulation method. However, in our previous work, a difference arithmetic demodulation method has been demonstrated.19 Because the light source power fluctuations result in the same variation tendency for the spectra patterns of the two orthogonal polarization modes (S- and P-polarization), so we can use the similar method to eliminate the impact of the light source fluctuation on measurement accuracy.

In conclusion, this letter has presented a simple and effective SPR-based Au-coated TFBG twist sensor. This sensor is suitable for the measurement of twist within the range of ±180°. And the sensitivities of 0.037 dBm/°C (S-polarized) and 0.039 dBm/°C (P-polarized) were obtained. Benefits from TFBG-SPR sensor’s internal thermometer provided by the absolute value of the Bragg wavelength of the core mode back reflection, temperature dependence SPR wavelength shift of 10 pm/°C can be lifted by proper calibration of the sensor prior to use.

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FIG. 7. Measured spectra of the TFBG-SPR twist sensor for the SPR resonance wavelength and its shift against temperature change in distilled water.

FIG. 8. Normalized SPR power against temperature change in distilled water.