A novel oil level monitoring sensor based on string tilted fiber Bragg grating*

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In this paper, we present a novel oil level monitoring sensor based on string tilted fiber Bragg grating (TFBG). The measurement range and sensitivity of oil level monitoring can be modulated via changing the length and number of string tilted fiber gratings. The transmission spectrum of string TFBGs immersed in oil changes obviously with the oil level variation. Experiments are conducted on three 2 cm-length serial TFBGs with the same tilted angle of 10°. A sensitivity of 3.28 dB/cm in the string TFBG sensor is achieved with good linearity by means of TFBG spectrum characteristic with peak-low value. The cladding mode transmission power and the amplitude of high order cladding mode resonance are nearly linear to the oil level variation. This kind of sensor is insensitive to temperature and attributed to be employed in extremely harsh environment oil monitoring.
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Oil level monitoring is very important in some industrial areas, such as fuel storage, petroleum product, textile industry, and bio-chemical processing. In the past, many different oil level sensors based on mechanical, electrical and optical fiber techniques were fabricated and employed. Among them, the optical fiber sensors are with advantages and prospective application market, so several kinds of optical fiber oil-level sensors have been developed quickly in recent years. Fiber Bragg grating sensors have been reported to be effective in monitoring various surrounding parameters, including temperature, strain, tilt, torsion, flow, humidity, chemicals and gas[1-3]. Tilted fiber Bragg grating (TFBG) possesses the merits of both FBG and long-period grating (LPG). Furthermore, this kind of sensor originated from TFBG is temperature independent and accurate to measure refractive index[4,5]. Binfeng Yun[6] proposed a liquid-level sensor based on etched fiber Bragg grating. But the oil-level sensor based on TFBG has not been reported by now.

In this letter, our proposed oil-level-sensor experimental system is composed of three serial TFBGs. The first TFBG is immersed in the oil and the other two TFBGs are also immersed gradually with the increasing of oil level. The testing results indicate that the string TFBG transmission spectra are decreased with the oil level increasing. If more TFBGs are fabricated and connected with the string sensor, the oil-level sensor measurement range becomes larger, but then the sensor sensitivity decreases.

The concept of using cladding mode resonances from a TFBG was originally proposed by Laffont and Ferdinand[7]. When the surrounding refractive index (SRI) increases, high order cladding modes of TFBG are cut off and become leaky modes. Accordingly, in transmission spectrum, the area enclosed by the envelope of the resonance decreases with the surrounding medium refractive index changing. As well known, the Bragg reflection and the cladding mode resonance wavelengths λ_B and λ^i_{clad} of TFBG are determined by a phase-matching condition and can be expressed as follows[8]:

$$\lambda_B = 2n_{eff}\Lambda/\cos\theta \ , \qquad (1)$$

$$\lambda^i_{clad} = (n^i_{eff} + n^i_{clad})\Lambda/\cos\theta \ , \qquad (2)$$

where n_{eff}, n^i_{eff} and n^i_{clad} are the effective indices of the core mode at λ_B, the core mode and the ith cladding mode at λ^i_{clad} respectively, Λ and θ are the period and the internal tilt angle of the TFBG, respectively. The string TFBG with many connected gratings can be considered as a long grating string from optical spectrum analysis view. When the string TFBG

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level sensor is immersed in oil, it will be regarded as two separated string gratings with different effective refractive indices. So, its total transmission spectrum contains two parts: one comes from air surrounding influence and the other is from oil surrounding medium influence. The oil level will be measured according to the effective lengths of the two separated string gratings.

Firstly, we use a 2 cm length TFBG with an internal tilt angle of 6° which is fabricated in hydrogen-loaded Corning SMF-28 fiber using a pulse KrF excimer laser and the phase-mask technique. The testing cladding mode spectra are depicted in Fig.1 and Fig.2.

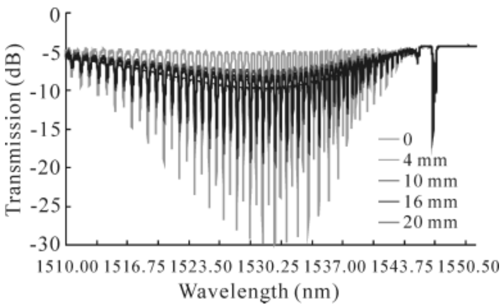

Fig.1 6° TFBG transmission spectra for different oil levels

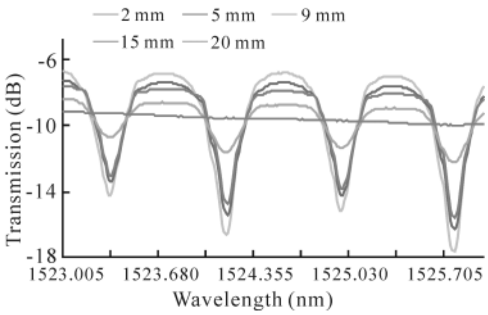

Fig.2 Cladding mode resonance changing with oil level

Here, we can notice the TFBG cladding mode spectra change sharply with the grating immersed in oil. The amplitude and peak to valley value of each cladding mode resonance are very different from the variation of oil level. The whole transmission spectrum power changes dramatically as well. So we will choose these characteristics as the representation of oil level measurement. To increase the measurement range of oil level, we need some serial TFBGs for experiment. Here, three 2 cm-long TFBGs with an internal tilt angle of 10° are fabricated by the same technique above mentioned. Their Bragg wavelengths are 1550 nm and the spacing is 5 cm. The testing setup is shown in Fig.3.

The three TFBGs signed as No.1 No.2 and No.3 are serially connected and mounted inside the cup with canola oil refractive index of 1.48. A broadband light source is coupled into the string TFBG and the transmission spectra are monitored by Ando 6317B optic spectrum analyzer with 0.01 nm resolution. Fig.4 shows the string TFBG transmission spectra measured with No.1, No.2 and No.3 TFBGs fully immersed at Bragg mode and different cladding mode resonances respectively.

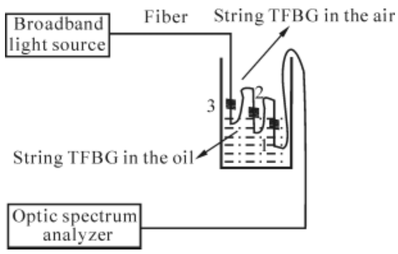

Fig.3 Experimental setup for oil level sensing based on string TFBG

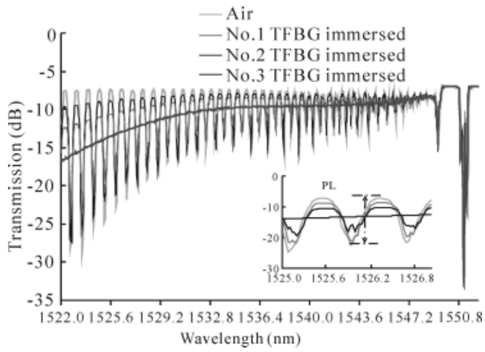

Fig.4 Transmission spectra of string TFBG with oil level increasing

It is obviously shown that the cladding mode transmission decreases sharply with the oil level increasing. Furthermore, we can conclude that the various trends of string TFBG transmission spectrum power with oil level changing are obtained. Because the canola oil refractive index is a little larger than that of the cladding material, the transmission loss will disappear and is close to zero from the TFBG coupling theory. So the total power transmitted through the string TFBG can be considered as a function of the oil level. We measure the main cladding mode power by calculating the cladding mode curve integral from 1522 nm to 1545 nm based on No.3 curve in Fig.4 and describe the relation between the cladding transmission power and the oil level in Fig.5.

The power can represent the oil level change linearly. We select the maximum amplitudes and the peak-valley values named PL (shown in Fig.4) of different order cladding modes (at some wavelength) and then compare their variations with oil level increasing.

Fig.6 depicts the relation between the amplitude of cladding mode resonance and the oil level. It shows that the amplitude is linear with the oil level increasing. The sensitivity of TFBG sensor by means of 1523.5 nm cladding mode amplitude is 2.13 dB/cm and that by means of 1540.1 nm cladding mode amplitude is 1.03 dB/cm.

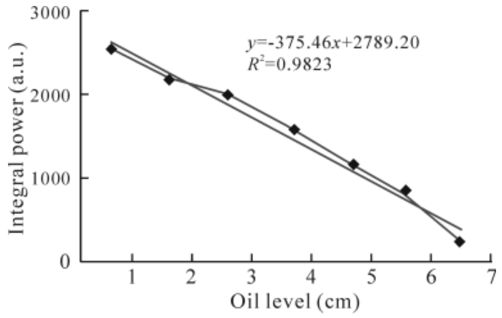

Fig.5 Cladding mode integral power vs. oil level

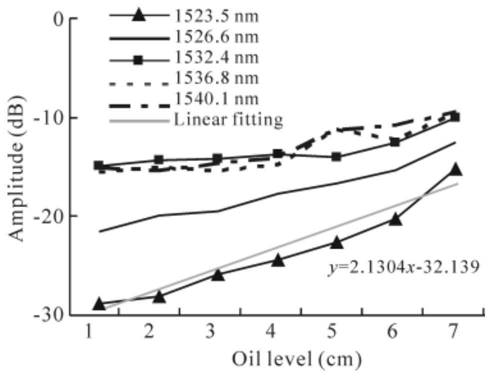

Fig.6 Amplitude of cladding mode resonance vs. oil level

Fig.7 describes the peak-valley value variation with the oil level increasing. It is obvious that the relation between the peak-valley value and the oil level is linear. Furthermore, the sensitivity of TFBG sensor by means of 1523.5 nm cladding mode peak-valley is 3.28 dB/cm and that by means of 1540.1 nm cladding mode peak-valley is 1.32 dB/cm. It indicates that the amplitude and peak-valley characteristics of the higher order cladding mode resonance are better than the lower order's.

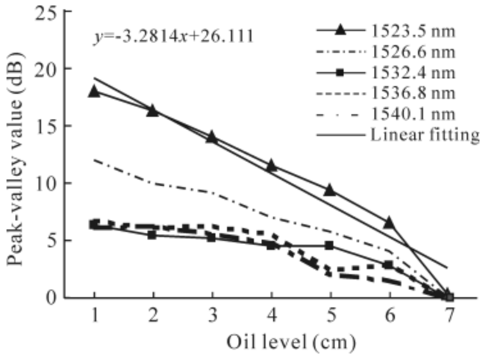

Fig.7 Peak-valley value of cladding mode resonance vs. oil level

By comparison, the peak-valley value is more effective to measure and estimate the oil level. Therefore, the string TFBG sensor output demonstrates a nearly linear variation with oil level rising. In practical monitoring system, it is necessary to serialize excessive TFBG sensors for a larger measurement range. Among them, each TFBG as a unit should be mounted continuously without spacing and all TFBG spectra are regarded as a very long grating transmission spectrum. Nevertheless, the sensitivity of the excessive string grating sensor will be influenced and becomes lower because more gratings share the long combined grating spectrum. In comparison with LPG and FBG[9], it is well known that TFBG is temperature-independent by means of grating core mode and cladding modes. Furthermore, these transmission characteristics which are used for oil level sensing do not change with the temperature variation. The oil refractive index here is 1.48, but the technology in the letter can be employed to measure different liquid levels with different refractive indices. What's more, the novel sensing method can be used to distinguish the interface of two different liquids with different refractive indices like water and oil (shown in Fig.8).

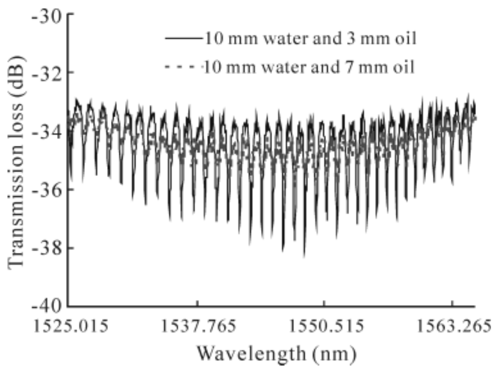

Fig.8 TFBG transmission spectra with the changing interface of water and oil

Here, a mixture with 10 mm thick water and 3 mm thick oil above water can be monitored via the transmission spectrum. Its transmission spectrum power is evidently different from that of the dot line that represents the oil-water interface with 10 mm thick water and 7 mm thick oil. As we all know, TFBG can be used to measure different surrounding refractive indices which are lower than that of the cladding material. For the oil whose refractive index is larger than or close to cladding index, the cladding mode wavelength shift is difficult to be extracted and can be ignored. We can make full use of the characteristics like transmission spectrum power, high order cladding mode amplitude and peak-valley value of each resonance given in the paper. However, for some liquids like water and alcohol whose refractive indices are lower than the cladding index, the cladding mode wavelength will also shift with the liquid level variation. Accordingly, the wavelength can be another characteristic for measuring the liquid level.

A novel oil level sensor based on string TFBG has been investigated in the paper. The experimental results show that the string TFBG oil-level sensor composed of three TFBGs can measure the oil level and water-oil interface. The level sensor sensitivities of different cladding mode resonances by transmission loss amplitude and peak-valley value are different. The sensitivity more than 3 dB /cm in its linear area is achieved as well. The oil level measurement method has low thermal sensitivity, especially compared with long period gratings, and offers simplicity and reliability for accurate oil level monitoring in hazard environment.

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References

[1] A. Iadicicco, A. Cusano, A. Cutolo, R. Bernini and M. Giordano, IEEE Photon. Technol. Lett. **16**, 1149 (2004).

[2] Wu Fei, ZHAO Jing, LIU Bin and ZHANG Ying, Optoelectronics Letters **6**, 98 (2010).

[3] YUAN Yin-quan, LIANG Lei and HANG Dong-sheng, Optoelectronics Letters **5**, 182 (2009).

[4] T. Guo, A. Ivanov, C. Chen and J. Albert, Opt. Lett. **33**, 1004 (2008).

[5] C-L Zhao, X. Yang, M. S. Demokan and W. Jin, J. Lightwave Technol. **24**, 879 (2006).

[6] N. Chen, B. Yun and Y. Cui, Appl. Phys. Lett. **88**, 133902 (2006).

[7] G. Laffont and P. Ferdinand, Meas. Sci. and Technol. **12**, 765 (2001).

[8] C. Chen, L. Xiong, C. Caucheteur, P. Megret and J. Albert, Proc. SPIE **6379**, 63790E1 (2006).

[9] S. Grice, W. Zhang, K. Sugden and I. Bennion, Liquid Level Sensor Utilizing a Long Period Fiber Grating, Photonics West, San Jose, California, USA, 2009.