High-sensitivity pressure sensor based on tilt fibre Bragg grating radial load effect

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Abstract In this paper, a simple and novel optical fibre pressure sensor with tilt fibre Bragg grating is put forward. The radial compression and rebound on tilt fibre Bragg grating (TFBG) cause grating angle and length change, meanwhile, its cladding mode spectra decrease sharply. Some transmission spectrum characteristics, such as amplitude, extinction ratio value, wavelengths of cladding and Bragg modes, are extracted and analyzed. It shows that they are nearly linear with the radial pressure on surface of bare TFBG. Among them, the extinction ratio value with high sensitivity of 0.7 dB/N can keep consistent with pressure. The max amplitudes of some cladding mode resonance are good linear with radial press with sensitivity of 0.18 dB/N. The relation between each mode resonance wavelength shift and radial press on TFBG keeps good linearity with 0.8-pm/N sensitivity. By means of choosing tygon elastic pad material imposed on bare TFBG, the pressure sensitivity with amplitude of 0.21 dB/N and extinction ratio of 0.25 dB/N is obtained in order to use in practical engineering.

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1 Introduction

Fibre Bragg grating (FBG) sensors have attracted considerable interest owing to their unique properties[1]. Compared with currently used FBGs, a weakly tilted fiber Bragg grating (TFBG) shows a strong coupling from the core mode to azimuthally and non azimuthally symmetric contra-propagating cladding modes and to the contra-propagating core mode because of its grating planes slanted with respect of the fiber axis by a certain tilt angle [2]. TFBGs have also been employed in many significant sensing applications, such as mechanical macro-bending [3], dynamic vibration measurement [4], chemical and biochemical sensor [5] and so on. In this work, a novel small-range pressure sensor with high accuracy is presented and described. With thin textile pad around TFBG, the TFBG transmission spectra decrease sharply with the radial increasing load on TFBG. The pressure sensitivity and range can be varied with different TFBG coating material such as tygon polymer mentioned in this paper. By means of cladding mode resonance and Bragg wavelength shift, the pressure sensor based on TFBG can be compensated with external temperature influence well [6,7]. This study supplies a pressure measurement method which will be a significant and advanced technology in many practical engineering fields including oil-gas, power, construction and so on.

2 Principles of operation

As is well known, the Bragg reflection and cladding mode resonance wavelengths λ_B and λ^i_{clad} clad of TFBG are determined under a phase-matching condition and can be expressed as[6]

$$\lambda_B = 2n_{eff}\Lambda/\cos\theta, \tag{1}$$

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

where n_{eff}, n^i_{eff}, and n^i_{clad} are the effective indices of the core mode at λ_B and the core mode and the ith cladding mode at λ^i_{clad}, respectively, and Λ and θ are the period along the fiber axis and the internal tilt angle of the TFBG. For weakly TFBG, when it is pressed by radial direction load, its structure can vary similar to sketch from Fig. 1(a) to (b). The axial length of grating is lengthened from l to $l+\Delta l$ and the angle of grating is enlarged from θ to β. The load induced index change from n_{eff}, n^i_{eff} and n^i_{clad} to n'_{eff}, $(n^i_{eff})'$ and $(n^i_{clad})'$. Accordingly, Eqs. (1) and (2) will become Eqs. (3) and (4),

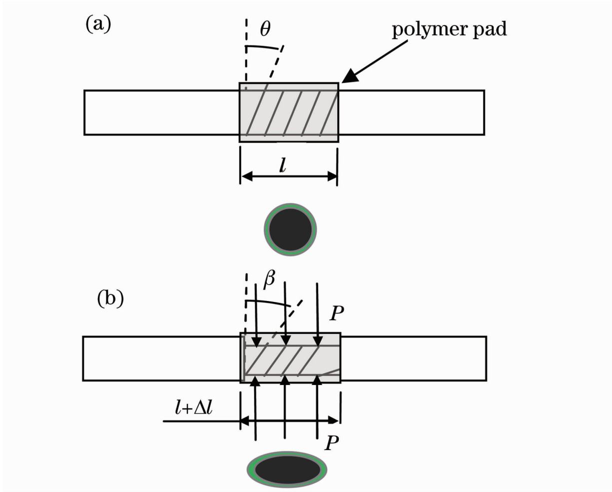

Fig. 1. Schematic diagram of TFBG pressed by radial load. (a) Without external radial load; (b) with external radial load

respectively. Here, the radial load P (shown in Fig. 1 (b)) should be applied to the surface of TFBG diameter direction along the laser beam of fabricating grating. The reason is that the direction compression can cause the obvious loss of cladding modes transmission. It can be easily concluded that the transmission spectra power will decrease due to the tilted angle of TFBG increase. Meanwhile, the TFBG wavelength including cladding modes, ghost mode and Bragg mode will shift owing to the grating period Λ lengthening. Therefore, the radial pressure on TFBG can be considered as the demodulation function of grating period, index and tilted angle parameters.

$$\lambda_{B} = 2n'_{eff}\Lambda \frac{l+\Delta l}{l}/\cos\beta, \quad (3)$$

$$\lambda^{i}_{clad} = [(n^{i}_{eff})' + (n^{i}_{clad})']\Lambda \frac{l+\Delta l}{l}/\cos\beta. \quad (4)$$

3 Experiment

We chose one-centimeter-long TFBG with an internal tilt angle of 8° and it was fabricated in hydrogen-loaded Corning SMF-28 single-mode fiber using a pulse KrF excimer laser and the phase-mask technique. The Bragg wavelength of the TFBG is 1550 nm and the original transmission spectrum is given in Fig. 2. The experimental setup used to test the characteristics of TFBG pressure sensor is made up of broadband light source, optical source analysis (OSA), Lloyd instruments Ltd company tunable press machine. During the process of experiment, we put thin elastic polymer pad on the above and bottom of bare TFBG for the purpose of protecting bare TFBG and deformation restoration. The universal testing machine can be operated manually and automatically. The transmission spectra of TFBG were monitored and measured with a optical spectrum analyzer (Ando 6317B) with 0.01-nm wavelength resolution and high sensitivity[8,9]. Some experimental results are depicted in Fig. 2 as well. Comparing them, we can easily notice that the cladding modes go down sharply with the increasing of 15 and 115 N loads on TFBG. The characteristics of the cladding modes are analyzed and extracted for the purpose of obtaining a good relation between each resonance mode and radial pressure. From the transmission spectra with different pressure experiments shown in Fig. 3, we can conclude that the amplitude, extinction ratio value (peak-low value), and wavelength shifts of each cladding mode resonance have some relations with the increasing

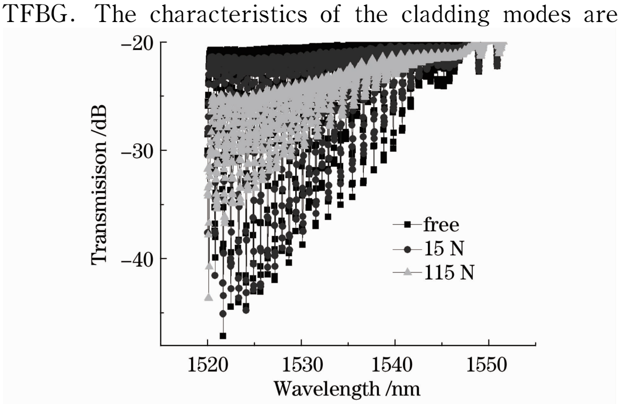

Fig. 2. Transmission spectra of 8° TFBG with different radial pressures

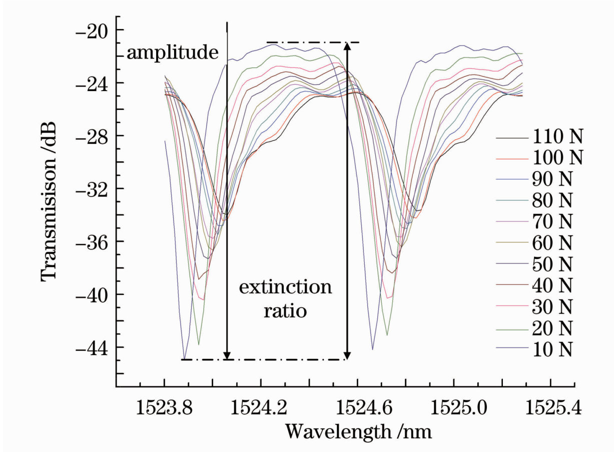

Fig. 3. Characteristics of each cladding mode resonance

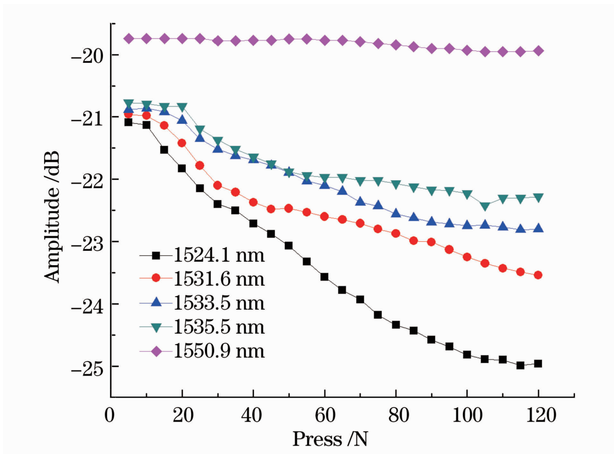

Fig. 4. Cladding mode amplitudes versus the radial pressure on TFBG

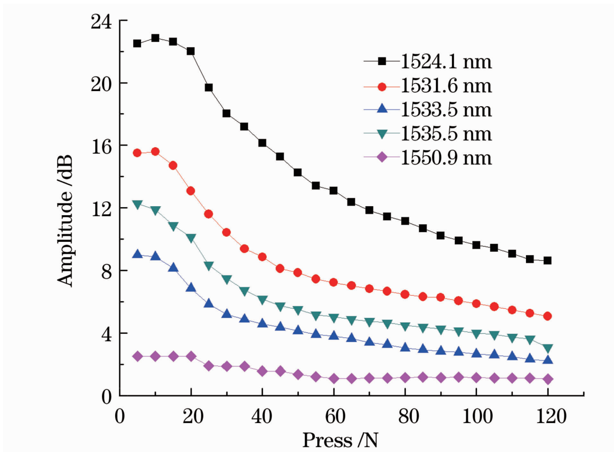

Fig. 5. Cladding mode extinction ratio value versus radial pressure

pressure effect on TFBG. Some characters of TFBG transmission spectra are extracted and their relation descriptions are presented in Fig. 4—6 respectively. These amplitudes of some cladding modes show good linear relation with the pressure changing from 0 to 120 N. The amplitude sensitivity of 1524.1-nm cladding mode is 0.18 dB/N and the amplitude sensitivity of 1535.5-nm cladding mode is 0.08 dB/N. The more cladding mode amplitude sensitivity is high, the more cladding mode is far from Bragg central wavelength. However, the amplitude sensitivity of Bragg mode is low and only 0.01 dB/N. The 1524.1-and 1535.5-nm cladding mode extinction ratio characteristics with sensitivity 0.7 and 0.35 dB/N, respectively, are more outstanding and significant than their amplitudes′ s. The more extinction ratio value sensitivity of cladding mode is high, the more cladding mode is far from Bragg central wavelength[10,11]. It indicates that the cladding mode wavelength and the Bragg mode wavelength are good linear with the radial pressure on TFBG in Fig.6, although it seems that some data points deviate the linear fit line, owing to small vertical axis scale with 0.02 nm. They both own the near consistent sensitivity with 0.8 pm/N. In the experiment, we implemented experiments on bare TFBG with only 0.1-mm-thick tissue fiber pad. So the pad influence on pressure sensitivity can be neglected. We employed the Tygon R-3603 as the 1.5-mm-thick pad on the top and bottom of another TFBG. The TFBG with 1600-nm Bragg wavelength and 10° was tested in the same procedure as mentioned above. The experimental results were shown in Fig. 7. Here, we can notice that the relation between amplitude and pressure ranging from 0 to 50 N with sensitivity of 0.21 dB/N is near linear. However, the relation changes slowly and keeps nearly constant from 60 to 120 N. The extinction ratio value character with sensitivity of 0.25 dB/N is a little better than the amplitude character at the same measurement range. The press and release load experiments were repeated and described in Fig.8. In these experiments, the pad material with tensile strength of 11.4 MPa and tensile modulus of 4.5 MPa owns enough elasticity and weak strength in comparison with tilted grating fiber coating with Young′s modulus 2.45 GPa. Accordingly, the testing sensitivity with the pad is different with only bare TFBG pressure testing. Nevertheless, the increasing and releasing repeated experiments appeared some errors owing to the pad material viscosity.

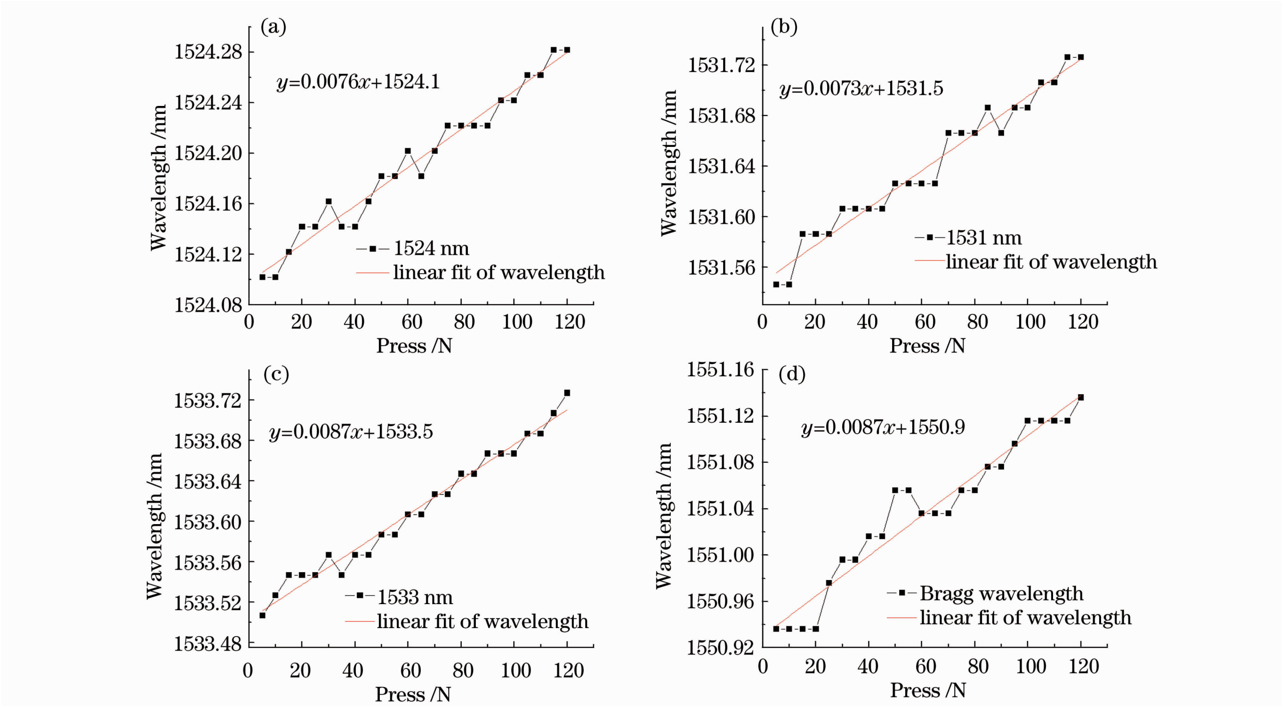

Fig.6. Cladding mode wavelength and Bragg wavelengths of (a) 1524, (b) 1531, (c) 1533, and (d) Bragg wavelength

4 Discussion and Conclusion

In conclusion, a novel small range pressure sensor based on radial compression on TFBG is given and analyzed. In experiment, the bare TFBGs with 0.1-mm-thick elastic textile and 1.5-mm-thick tygon material as top and bottom pad are compressed and released several times by tunable pressure on lateral grating areas of TFBG. The repeated testing procedure keeps nearly consistent at the same load effect. The amplitude, extinction ratio value and central wavelength of some resonance modes are linear with the radial pressure. The amplitude characteristic is good linear and its sensitivity is acceptable. The extinction ratio characteristic is more obvious and sensitive, but its linearity is not so ideal.

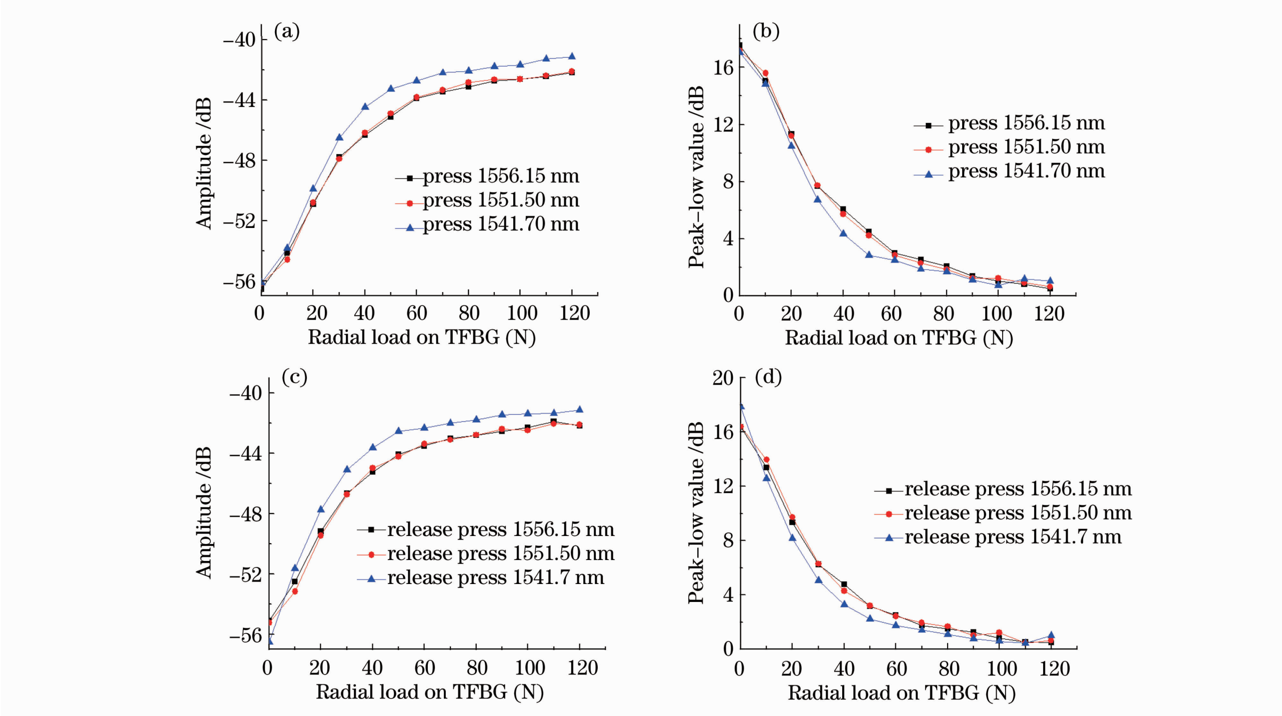

Fig.7. Cladding modes characters versus radial load on TFBG. With different cladding modes, the ralationship between (a) amplitude and press loads, (b) peak-low value and press load, (c) amplitude and release load, and (d) peak-low value and release load

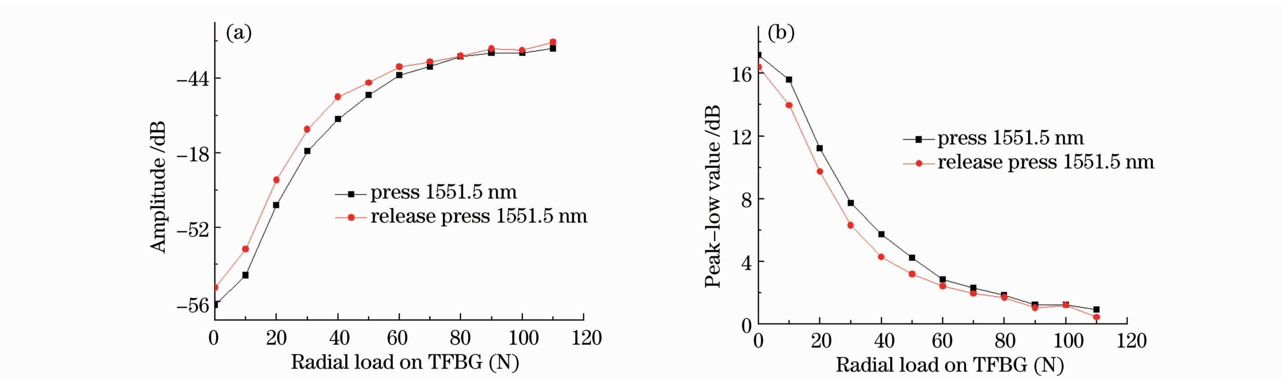

Fig.8. Cladding mode spectrum character (a) increase and (b) release comparison

The central wavelength shift sensitivity with pressure variation is 8 pm/N. The TFBG pressure experiments with elastic and weak strength tygon material pad were finished with sensitivity of 0.25 dB/N. The deviation of this kind of sensor can be lessened further with better elastic pad materials on TFBG.

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References

1 T. Erdogan and J. Sipe, Opt. Soc. Am. A **13**, 296 (1996).

2 T. Erdogan, Opt. Soc. Am. A **14**, 1760 (1997).

3 C. Chen and J. Albert, Electron. Letter, **42**, 1027 (2006).

4 Chen, C. Caucheteur, P. Mégret, and J. Albert, Measurement Sci. and Technol. **18**, 3117 (2007).

5 G. Laffont and P. Ferdinand, Measurement Sci. and Technol. **12**, 765 (2001).

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

7 S. Baek, Y. Jeong, and B. Lee, Appl. Opt. **41**, 631 (2002).

8 Y. Li, X. Xu, and Z. Kang, Acta Photon. Sin. (in Chinese) **37**, 717 (2008).

9 R. T. Schermer, Opt. Express, **15**, 15674 (2007).

10 K. Watanabe, K. Tajima, and Y. Kubota, IEICE Trans. Electron, **E83-C**, 309 (2000).

11 H. J. Sheng, M. Y. Fu, T. C. Chen, W. F. Liu, and S. S. Bor, Photon. Technol. Lett. **16**, 1146 (2004).

12 A. Zhang, B. O. Guan, X. M. Tao, and H. Y. Tam, Opt. Commun. **206**, 81 (2002).