Study of a high-temperature and high-pressure FBG sensor with Al_2O_3 thin-wall tube substrate*

ZHOU Hong**, **QIAO Xue-guang, WANG Hong-liang, FENG De-quan, and WANG Wei**

Optical Fiber Sensing Laboratory, Xi'an Petroleum University, Xi'an 710065, China

(Received 2 January 2008)

A fiber Bragg grating (FBG) high-temperature and high pressure sensor has been designed and fabricated by using the Al_2O_3 thin-wall tube as a substrate. The test results show that the sensor can withstand a pressure range of 0-45 MPa and a temperature range of –10-300 °C, and has a pressure sensitivity of 0.0426 nm/MPa and a temperature sensitivity of 0.0112 nm /°C

CLC numbers: TN253 **Document code:** A **Article ID:** 1673-1905(2008)04-0260-4

DOI 10.1007/s11801-008-7151-2

FBGs used for sensing detection have become a research hot point [1-5]. However, FBGs commonly can't endure high-temperature of 160 °*C*, and the stress sensitivity of a bare FBG is low, which is about 0.003 nm/MPa. And a bare FBG is very fragile. Experiments show that the FBG may be broken when increasing the external tensile force to 700 g, the rupture limit is about 7860 $\mu\varepsilon$.

This paper has selected Al_2O_3 thin-wall tube as substrate , which can withstand high-temperature (softening point being about 2730°C), and has low elastic modulus of 7.4×10^4 MPa. A temperature and pressure dual-parameter sensor with measuring ranges of –10-300°C and 0-45 MPa has been fabricated, and its performance is tested.

The structure of the sensor is shown in Fig.1. Two ends of the Al_2O_3 thin-wall tube with certain length are sealed with top covers, and a small port is drilled at the center of top cover. Outside the thin-wall tube, a stainless steel sleeve for protection is additionally installed, and four oil-inlet orifices are uniformly opened along the circular direction in the middle of the sleeve. Two high-temperature FBGs are written in by using ultra-violet mould-masking method. The FBG 1is used as a pressure FBG, and the FBG 2 is used as a temperature FBG. The FBG 2 is loosely fixed in the thin-wall tube, while the FBG 1 is axially stuck on the inner wall surface of the Al_2O_3 thin-wall tube. A suitable pressure is applied by a special clamping device before sticking, and the magnitude of the pressure is monitored by the AQ 6319 spectrometer. The slide-fit shaft design and oil-resistant adhesive agent based on double-constituent epoxy are adopted to close the seal between the top cover and the tube mowth. The nano-metric particles of a certain ratio are mingled into the adhesive agent to increase the stiffness and sturdiness of the adhesive agent and its long-term high-temperature resisting performance.

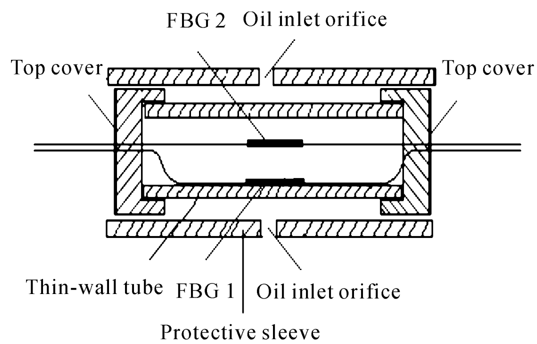

Fig.1 Structural schematic diagram of the sensor

Based on the coupling mode theory of FBGs, in a homogeneous non-flickering FBG, the coupling between guide mode of forward propagation and that of backward propagation forms a reflected wave of narrow band, and the Bragg wavelength of the reflected wave may be expressed as follows [6,7],

$$\lambda_B = 2n_{\text{eff}}\Lambda, \tag{1}$$

where n_{eff} is the effective refractivity of the optical fiber core, and Λ is the period of FBG. In the event of varying the stress and temperature around the FBG, the n_{eff} or Λ may be changed

* This work has been supported by the National "863" Project of China (No.2002AA313150).

** E-mail: hongzhouteacher@yahoo.com.cn

due to elasto-optic effect and thermo-optic etc., thereby the central reflected wavelength may be shifted and the shift of central wavelength resulted from the variation of stress and temperature may be expressed in the following,

$$\Delta\lambda_B = 2n_{eff}\Lambda\left(\left[1-\left(\frac{n_{eff}^2}{2}\right)[P_{12}-\gamma(P_{11}+P_{12})]\right]\Delta\varepsilon+[\alpha+\xi]\Delta T\right) , \quad (2)$$

where $\Delta\varepsilon$ is the strain increment, ΔT is the temperature increment, P_{ij} is the elasto-optic tensor component of the optical fiber material, γ is the poisson ratio of the optical fiber material, ξ is the thermo-optic ratio of the optical fiber material, and α is the thermal expansion of the optical fiber material.

Because the FBG 1 is securely stuck on the inner-wall surface of Al_2O_3 thin-wall tube, it is sensitive to both of fhe external pressure (stress) and the temperature; whereas the FBG 2 is in a state of relaxation, hence, it is only sensitive to the temperature. The wavelength shift of two FBGs, as well as the variation of the pressure and the temperature may be expressed as follows,

$$\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}=\begin{bmatrix}K_{P1} & K_{T1}\\ 0 & K_{T2}\end{bmatrix}\begin{bmatrix}\Delta P\\ \Delta T\end{bmatrix} , \quad (3)$$

where K_{p1}, K_{T1} and K_{T2} are the sensitivity coefficients of ΔP and ΔT, respectively. Because the sensitive coefficients of matrix K are determined by the sensor structure and the material parameters, after optimization of the sensor structure and determination of materials, various values in matrix K can be obtained through theoretical calculation or experimental measurement. In case the two-stage matrix in formula (3) satisfy the nonsingular condition, ΔP and ΔT can be found by using the matrix inverse method. In facts, so long as the shift of wavelength $\Delta\lambda_1$ and $\Delta\lambda_2$ at two reflected peak values concerning FBG 1 and FBG 2 can be measured respectively, the variation of ambient pressure and temperature can then be inferred.

The sensor made from Al_2O_3 thin-wall tube is working under compressive stress, based on the generalized Hooke's law, and the stress is in proportion to the strain in the elastic range, i.e.$\sigma=E\varepsilon$. In a normal case of the stress, for a uniform and ideal elastomer, the relationship between strain and stress can be determined[8].

From the working principle of the sensors, it is clear that the Al_2O_3 thin-wall tube will produce strain when it is subjected to an external pressure. This strain transmitted to the pressure-measuring FBG 1 causes the shift of its wavelength. The contact state of FBG 1 with the tube-wall is different, thus the corresponding contact condition is different, which also makes the strain sensitivity of the sensor different. Because the FBG 1 is securely stuck on the inner wall surface of thin-wall tube, all points on the contact surface haven't clearance along the normal direction and haven't sliding movement along the tangential direction. Therefore, the strain sensitivity of the sensor is only determined by stress and strain of the tube-wall.

In the design, based on the resolution of the demodulation system, the band-width of the light source and the reuse width of the wave components, it is required that the strain sensitivity of the sensor will be in a range of $40 \leqslant K_\varepsilon \leqslant 50$ pm/MPa. If 1000 με is produced on the FBG, the shift of wavelength at peak value is about 1 nm, hence, the strain range on inner wall surface of the thin-wall tube can be estimated as the range of $1.80 \times 10^{-3} \leqslant \varepsilon \leqslant 2.25 \times 10^{-3}$. The result of calculation using ANSYS shows that the maximum strain is situated at the middle of thin-wall tube with value of 2.13×10^{-3}, and the minimum strain is situated at two ends of the thin-wall tube with the value of 1.87×10^{-3}. In the event of tube length varying between 50 mm and 70 mm, the strain at various nodal points is slightly different. However, the strain at all points without exception can satisfy the design requirements of strain sensitivity of the sensor.

Based on above finite element analysis, considering the requirements in engineering, the parameters of the Al_2O_3 thin-wall tube are selected as Φ_D= 12.10 mm, t_m= 1.20 mm and L = 60.00 mm. The sensor is shown in the Fig.1 in a capsule form. The sensor has been positioned in an oil vessel with pressure endurance of 60 MPa. The silicone oil with flashing point of 330 °C is charged into the entire vessel as high-temperature medium. The oil vessel is put into a DHG-9248A type thermostat of 0-400 °C .

The test principle is shown in Fig.2.

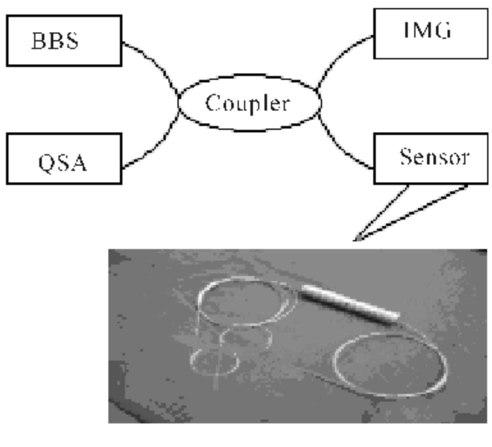

Fig.2 Schematic diagram of the experimental setup

The pressure in vessel is controlled by a YS-60 type piston pressure meter, and measured by a pressure meter of 2.5 grade with minimal scale division of 0.1 MPa. The temper ature is controlled by using PID parameter selfsetting, and measured by a digital temperature meter with minimal scale division of 0.1 °C. For the detecting section, an erbium-doped FBG is adopted. The light generated from a wide-band light source with threshold value of 7.0 dB and band-width of 40 nm passes through a light coupler of 3 dB for incidenting to the FBG. The reflected light satisfying the Bragg condition, after passing through the light coupler, is detected by a spectrum analyzer with resolution of 0.01 nm.

The spectrogram of FBG 1 (for pressure-measuring) and of FBG 2 (for temperature-measuring) under the conditions of temperature 19.2 °C and pressure 0 MPa is shown in Fig.3. The measured wavelength at peak values are 1546.6463 nm and 1551.2411 nm, respectively.

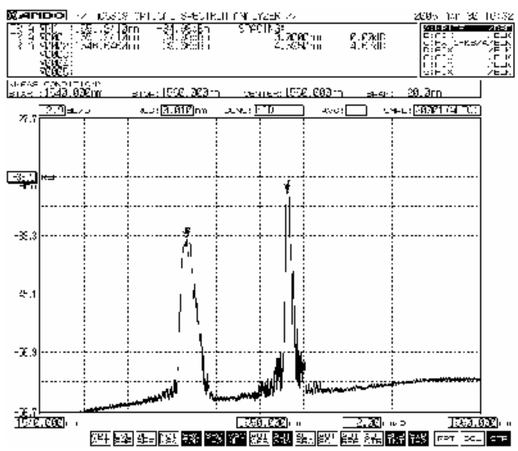

Fig.3 Spectrogram of the dual FBGs

With the increase of the temperature and pressure, the peak value of FBG 1 shifts toward the short-wave direction, and the peak value of FBG 2 shifts toward the long-wave direction. The relation between measured wavelength at the peak value and temperature is shown in Fig.4. Three curves are basically in parallel, and the temperature sensitivities of them are 0.0113 nm / °C, 0.0112 nm / °C, and 0.0110 nm / °C, respectively. The linear fitness of temperature is all above 0. 9999.

Based on the verification from the experiments preciously, the temperature sensitivity coefficients in the range of 0-18 °C of the FBGs are very close to above mentioned ones, and have a good linearity and repeatability. Therefore, temperature measurement in the range of –10-300 °C can be preformed by using the FBG 1.

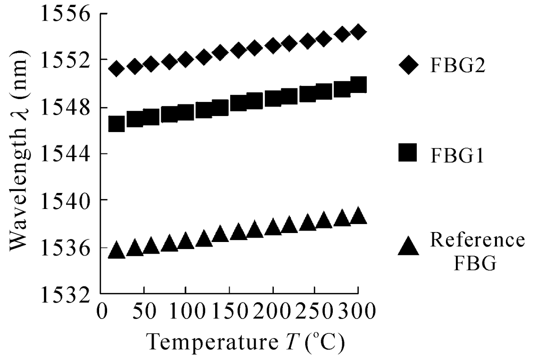

Fig.4 The wavelength at peak value vs temperature for FBG1, FBG2, and the reference FBG

Fig.5 shows the relation between the wavelength at peak value and pressure for the FBG 1 under temperatures of 19. 2 °C, 60 °C, 100 °C, 140 °C, 180 °C, 220 °C, 260 °C and 300 °C respectively. The linear fitness is all above 0.9998. The pressure sensitivities are 0.0427 nm/MPa, 0.0427 nm/MPa, 0. 0426 nm/MPa, 0.0426 nm/MPa, 0.0425 nm/MPa, 0.0432 nm/ MPa, 0.0419 nm/MPa, and 0.0425 nm/MPa, respectively, which are very closing to the designed value $40 \leqslant K_\varepsilon \leqslant 50$ pm/MPa.

The results show that the design scheme is successful and advanced.

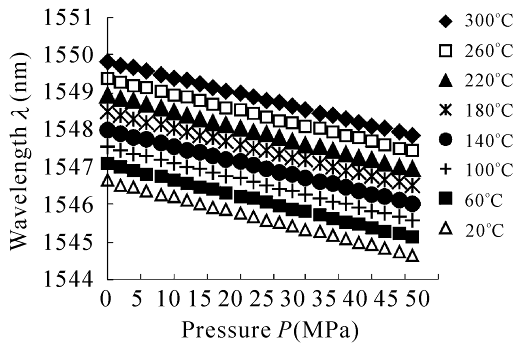

Fig.5 The wavelength at peak value vs pressure of FBG 1 under different temperatures

In summary, the FBG sensor made from Al_2O_3 thin-wall tube can meet the requirements of high-temperature, high-pressure, and corrosion resistance, and has higher stress sensitivity and repeatability, which is suited to the application in oil-gas well and in high-temperature and high-pressure circumstances. The design method for a FBG sensor with finite element analysis can avoid many blind experiments, and save material and financial resources. By readjusting parameters of the model, the sensors with different temperature measuring ranges and stress sensitivities can be obtained.

References

[1] WANG Hong-liang ,QIAO Xue-guang and ZHOU Hong, Journal of Optoelectronics • Laser. **16** (2005), 395. (in Chinese)

[2] WANG Hong-liang, QIAO Xue-guangbn and ZHOU Hong, Acta Optica Sinica. **25** (2005), 875.

[3] WANG. Hong-liang, QIAO Xue-guang and FU Hai-wei, Journal of Optoelectronics • Laser. **16** (2005), 259. (in Chinese)

[4] WANG Hong-liang, QIAO Xue-guang and FU Hai-wei, Chinese Journal of scientific Instrument. **25** (2006), 536.

[5] SHAO Jun, LIU Jun-hua and QIAO Xue-guang , Journal of Optoelectronics・Laser.**17** (2006):807.

[6] LI Chuan, ZHANG yi-mu and ZHAO Yong-gui . Principle and technology of fibre grating sensors , Beijing Scientific Publishing House, 2006, 106.

[7] Fan Shang-chun. Sensor technology and application, Publishing House of Beijing Aerospace university, 2004, 107.

[8] JIANG Yu-chuan, ZHANG Jian-hui, LI Zhang-zheng. Elastic mechanics and finite element method , Beijing Scientific Publishing House, 2006 42.