

Study on characteristics of EFPI pressure sensors for HT/HP oilwell

QI WANG*, YONG ZHAO, YA'NAN ZHANG, YUYAN ZHANG, BO HAN, LU BAI, WEI HOU
College of Information Science and Engineering, Northeastern University, Shenyang, China, 110819

In this work, the hysteresis phenomenon of the fiber optic Fabry-Perot interferometric (FPI) pressure sensors is investigated. The method of fabricate EFPI pressure sensors with a high-energy carbon dioxide (CO₂) laser as the heating source to thermally fuse tube and fiber is analyzed systematically. Through theoretical analysis and experiments, we find out there are three reasons that cause hysteresis of the EFPI pressure sensors. Firstly, the shape of the two bonding points is not symmetrical around the tube for the nonuniformity of energy around the bonding points. That result in the friction between the fiber and the tube will lead to the hysteresis in the EFPI pressure sensors. Secondly, the residual stress in the bonding points produced in the procedure of sensor fabrication will release at HT/HP environments and will also cause hysteresis. Finally, the friction between the fiber and the tube at the bonding points also will result in hysteresis. For solve those problems, a method of insert a spindle-shaped diaphragm in the optical route to improve the energy distribution around the tube is proposed. And a method of putting the EFPI pressure sensor into a high pressure and high temperature environment to level off the residual stress in the bonding points to eliminate hysteresis were demonstrated. Finally, the hysteresis characteristic of an EFPI pressure sensor is experimentally measured after it was improved by the above method, and we can see from the results that the hysteresis of the pressure sensor is eliminated.

(Received June 26, 2011; accepted September 15, 2011)

Keywords: Fiber optic sensor, Extrinsic fiber Fabry-Perot interferometer, Hysteresis, High pressure, High temperature

1. Introduction

Fiber optic sensors are widely used in many fields because they have many advantages over conventional electrical sensors, such as immunity to electromagnetic interference, ability to respond to a wide variety of measurands, high resolution, large bandwidth, small size, light weight and potential for multiplexing [1-5]. A variety of fiber optic sensors have been successfully commercialized in the past two decades, such as fiber optic Fabry-Perot (F-P) sensors, Fiber Bragg Gratings, Fiber Optic Gyroscopes, and Fiber Optic Hydrophones and etc. Compared with other types of fiber optic sensors, FFPI sensors have the advantages of being simple and compact, insensitive to environmental fluctuations and polarization-induced signal fading, being capable of point measurements with minimal cross sensitivity, and offering high resolution and sensitivity. A lot of single-mode fiber optic sensors based on a Fabry-Perot interferometer (FPI) have been developed in the past several decades for the detection and measurement of various physical, chemical, and biomedical parameters. Such fiber F-P interferometers (FFPIs) include the intrinsic fiber F-P interferometer (IFPI) [6], the extrinsic F-P interferometer (EFPI) [7,8], the in-line fiber etalon (ILFE) [9], the diaphragm-based [10] or the microelectromechanical system (MEMS)-based

[11] FPI, the thin-film interferometer [12], and all other etalon-type devices. Especially extrinsic F-P interferometer (EFPI) sensors are widely used in the downhole monitoring systems for monitoring oil well parameters such as pressure, temperature flow rates and phase fraction [13]. To date there are two main methods to fabricate EFPI fiber sensors, one is that the tube and fibers are glued with epoxies [14]. The performance of a sensor fabricated by this method is mainly dependent on the characteristics of the epoxy. The maximum operating temperature of these EFPI sensors is limited by the epoxy which is relatively low. The other method is to use high-energy carbon dioxide (CO₂) laser as the heating source to thermally fuse the silica fibers and tube for EFPI sensor fabrication [15]. The EFPI sensors fabricated with this method have a number of advantages, such as good mechanical strength and a high thermal stability and low temperature cross sensitivity. However, The EFPI sensors fabricated with this method have one disadvantage; i.e., there are usually exist hysteresis in these sensors. This will greatly influence the accuracy of the sensors.

In this article we will discuss the phenomenon that the hysteresis of EFPI sensors, and find out the reason that cause the hysteresis of the sensor by analysis and experiments. Finally, we will give the methods that resolve the problem, and the experimental results of pressure

measurement experiments.

2. EFPI pressure sensors and fabrication

As shown in Fig. 1, the basic pressure sensing element is an EFPI formed by aligning a signal lead in/out fiber and a reflecting fiber with their end facets cleaved inside a glass capillary tube. The fibers and the glass capillary tube are bonded with a CO₂ laser beam. The air gap between two fiber end facets forms the Fabry-Perot (F-P) cavity. As illustrated in Fig. 1, L_p is the length between two thermal bonding points, L_f is the length from the lead in fiber thermal bonding point to the lead-in fiber end, L_{fr} is the length between the end facet of the reflecting fiber and the thermal bonding point of the reflecting fiber, and d is the F-P cavity length. From the principles of mechanics, the cavity length change Δd_p has relationship with applied pressure P as following:

$$\Delta d_p = \frac{PL_g r_o^2}{E(r_o^2 - r_i^2)}(1 - 2\mu) \quad (1)$$

Where Δd_p represents the pressure induced cavity length change, r_o and r_i are the outside and inside radius of the capillary tube respectively, μ is Poisson's ratio and E is Young's modulus of the capillary material.

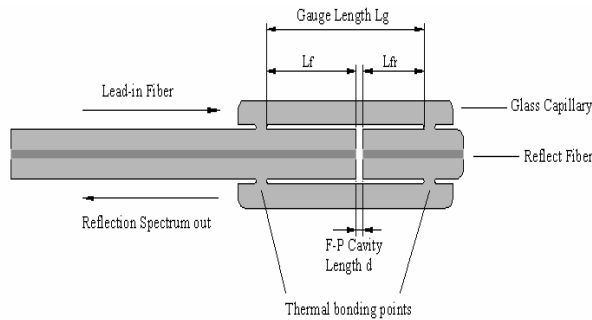


Fig. 1. The structure of EFPI fiber sensor.

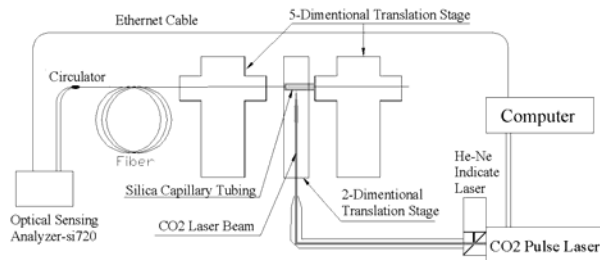


Fig. 2. Scheme of the fabrication system of EFPI sensors.

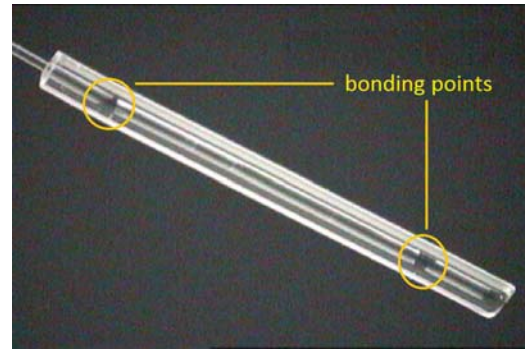


Fig. 3. Picture of a sensor head fabricated with this system.

Fig. 2 shows the Scheme of our EFPI sensors head fabrication system. The heating source used in the fabrication system is a SYNRAD Inc CO₂ laser. The frequency of CO₂ laser pulse can be set as 5 kHz, 10 kHz, 20 kHz. And the maximum output optical power under continuous mode operation is 25 W. The demodulation system used in the experiment is a Micron Optics, Inc optical sensing analyzer si720, the accuracy of the gap length can be demodulated is up to ~10nm. The tube and fiber are each fixed to a 5-dimensional translation stage respectively to keep them be precisely aligned. Between the two translation stages, a 2-dimensional translation stage with two mirrors with 120° angle on top is used to achieve energy uniform distribution.

The EFPI sensors used in the experiments are fabricated with this system. Fig. 3 is the picture of the sensor head fabricated with this system.

3. Pressure measurement experiments

Usually, an optical fiber sensing system includes a fiber sensor probe and an optical fiber sensor interrogation unit. The sensor probe is used to detect the environment physical measured change. The interrogation unit is used to demodulate the reflected optical signals, and give out the measured that we need. Thus, the sensor probe firstly determines the accuracy and sensitivity of the sensing system. So, it is important for us to optimize and improve the sensor probe and its fabrication system to make the sensor achieve high accuracy and sensitivity.

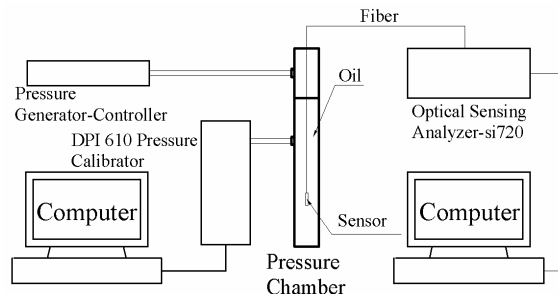


Fig. 4. A diagram of a sensor testing setup.

We use the calibration system - GE. Druck Inc Model DPI 610 Pressure Calibrator to calibrate the EFPI sensors heads fabricated with the system in Fig. 2. The accuracy of the calibrator is 0.05% F.S. Fig. 4 shows a diagram of a sensor testing setup. The sensor was sealed in a pressure chamber whose pressure was supplied and controlled by a pressure generator-controller. The sensor's output was detected by the Optical Sensing Analyzer-si720.

The pressure was first increased and then decreased to calibrate the sensors that fabricated with the system, many calibration curve of them indicate that hysteresis cannot be negligible. Fig. 5 is the calibration curve of an EFPI pressure sensor. It indicates that the hysteresis of the sensor is 2.13%, and it cannot be negligible. To remove the hysteresis of the sensor, we put the sensor in the high pressure (about 30 MPa) environment about 24 hours. Then we found that the hysteresis of the sensors is decreased very much. The hysteresis left of the sensor is 0.48%. Fig. 6 is the calibration curve of the sensor that has been deal with high pressure annealing. After the sensor is put in the high pressure (about 30 MPa) environment about 24 hours, we put the sensor into the stove (about 1000°C) for 24 hours. Fig. 7 is the calibration curve of the sensor. The hysteresis of the sensor is 0.33%. The hysteresis of the sensor is improved moreover.

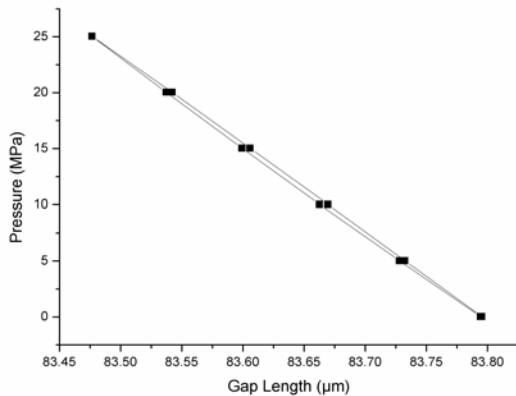


Fig. 5. The calibration curve of an EFPI pressure sensor before deal with high pressure.

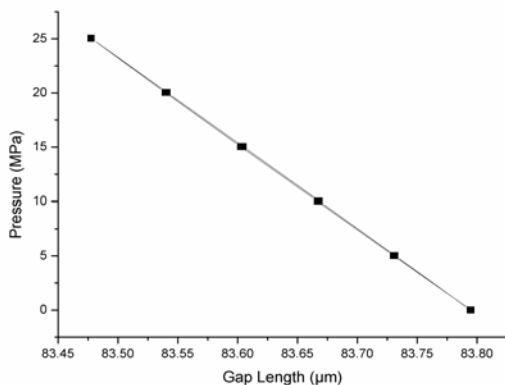


Fig. 6. The calibration curve of the EFPI pressure sensor that has been deal with high pressure.

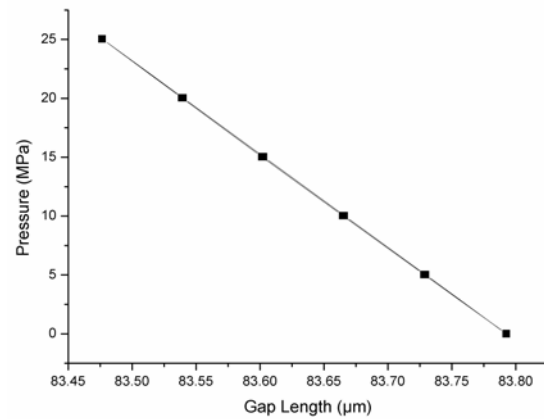


Fig. 7. The calibration curve of the EFPI pressure sensor that has been deal with high pressure and high temperature annealing.

We can see from Fig. 6 and Fig. 7 that the EFPI sensor gap length is changed after annealing. This is a result of the high temperature annealing.

4. Results and discussion

Hysteresis is a key factor that influences the accuracy and sensitivity of the sensor. So it is important for us to eliminate the hysteresis of the sensor. Experiments indicate that the hysteresis can be removed by put the sensor either into the high pressure environment or into the high temperature environment or both for a length of time. For by this method the residual stress introduced during the fabrication of the sensor can be released. When the EFPI sensor is fabricating, i.e. during the temperature of the tube and the fiber raising and falling, the residual stress is produced in the bonding points. Expose the sensor head to the high pressure and high temperature for a period of time will help release the residual stress in the bonding points.

The reason that cause the residual stress in the bonding points are two. One reason is that, after the tube and fiber are fused and bonded, the falling of the temperature of the bonding points is too fast. Another reason is that the energy around the bonding points cannot achieve uniform distribution, so the shape of bonding points is not symmetrical around the tube. Although theoretical analysis [16, 17] can draw the conclusion that the light intensity on the surface of tube exposed under three focused laser beams is uniform, actually it is not. For theoretical analysis is based on the reflectivity of the two reflect mirrors 100%, but actually it cannot achieve 100%. So the light intensity on the surface of tube is not uniform. Thus we need to add a diaphragm to improve the intensity distribution on the tube surface of the CO₂ pulse Gaussian Beam.

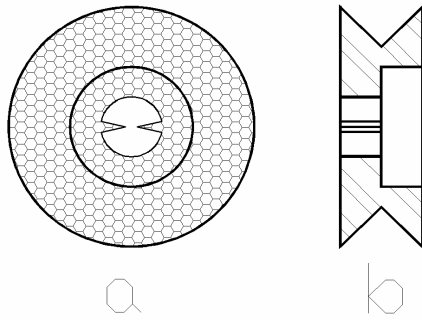


Fig. 8. The spindle-shaped diaphragm spatial filter.

The reflectivity of the two mirrors used in the experiment set-up is about 95%. We have designed a spindle-shaped diaphragm for spatial filtering. Fig. 8 is the scheme of the spindle-shaped diaphragm spatial filter. The spindle-shaped diaphragm consists of a disk with a small hole in the center. In the small hole there are two metal isosceles triangles symmetrical distribution in it.

The aim of insert a spindle-shaped diaphragm is to improve the stability of the laser power on the tube surface, and also to improve the laser intensity uniformity on the tube surface. Hence, for reduce the influence of the edge of the CO₂ laser Gaussian beam; we should firstly determine the radius of the inner circularity. We consider the intensity distribution of the CO₂ laser as a Gaussian distribution. The beam waist diameter of the CO₂ Laser used in the experiment set-up is 3.5 mm. The diameter of the tube we used in the experiment is 500 μm. The radius of the spatial filtering inner circularity is set to 1.5 mm. The inner triangles are isosceles triangles. The bases of the two inner triangles are both 1mm. For the reflectivity of the mirrors is 95%, we expect that the center power of the Gaussian Beam is 95% of the power of 500 μm far from the center. Fig. 9 is the calculated result of the intensity distribution of the CO₂ laser focused by a cylindrical lens. Fig. 10 is the calculated result of the intensity distribution of the CO₂ laser after insert a spindle-shaped diaphragm into the optical path.

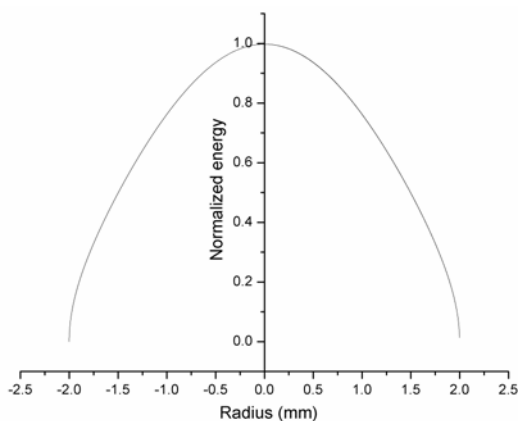


Fig. 9. Calculated results of intensity distribution of the CO₂ laser focused by a cylindrical lens.

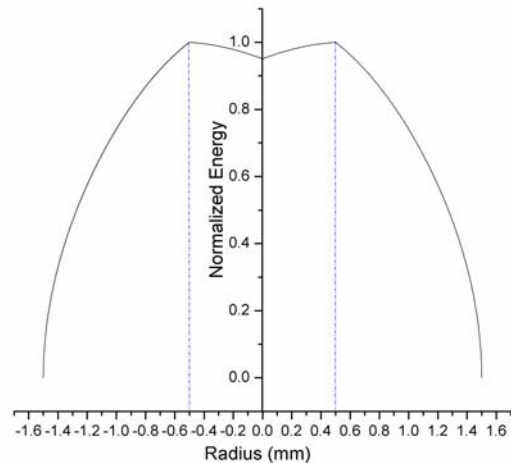


Fig. 10. The calculated result of the intensity distribution of the CO₂ laser after insert a spindle-shaped diaphragm into the optical path.

We can see from the Fig. 12 that the center power of the Gaussian Beam is 95% of the power of 500 μm far from the center. And then we fabricate several EFPI sensors for hysteresis test. We got a very good result. The hysteresis of the sensors fabricated with the system is improved obviously.

3. Conclusions

In this paper the hysteresis phenomena of the fiber optic pressure sensors based on Fabry-Perot interferometric (FPI) has been discussed. The method of fabricate EFPI pressure sensors with a high-energy carbon dioxide (CO₂) laser as the heating source to thermally fuse tube and fiber is analyzed systematically. We find out the reasons that cause the hysteresis of the EFPI sensors are three. One reason is that the shape of the two bonding points is not symmetrical around the tube; this is because the energy around the bonding points is not uniform. And another reason is the residual stress in the bonding points. The residual stress is caused in the course of fabricating the sensor; the temperature decreased too fast. The third reason is that the friction between the fiber and the capillary tube cause the hysteresis too. We have designed a spindle-shaped diaphragm and insert it into the optical path to improve the energy distribution around the tube; experiments indicate that the hysteresis of sensors fabricated with the improved system is much smaller than before. And also we put the EFPI pressure sensors with large hysteresis into a high pressure and high temperature environment to level off the residual stress in the bonding points. Finally through the above two method, the friction between the fiber and the tube are eliminate, and we found that the hysteresis of the EFPI pressure sensors is removed.

Acknowledgments

This work was partly supported by the Fundamental Research Funds for the Central Universities (N090504002, N100404006), the National Natural Science Foundation of China (61074170), and the Specialized Research Fund for the Doctoral Program of Higher Education of China (20100042110029), and the China Postdoctoral Science Foundation funded project (20110491511).

References

- [1] Qi Wang, Yong Zhao, Yuyan Zhang, Ya'Nan Zhang, Bo Han, *J. Optoelectron. Adv. Mater.* **13**(5), 471 (2011).
- [2] Zhao Yong, Wu Hongke, Wang Qi, *J. Optoelectron. Adv. Mater.* **13**(5), 457(2011).
- [3] Zhao Yong, Wang Qi, Huang He. *J. Optoelectron. Adv. Mater.* **12**(12), 2343 (2010)
- [4] Zhao Yong, Huang He, Wang Qi, *J. Optoelectron. Adv. Materi.* **12**(7), 1457(2010)
- [5] E. Udd, *Fiber optic sensors*, Wiley, New York (1991).
- [6] Zhengyu Huang, Yizheng Zhu, Xiaopei Chen, Anbo Wang, *IEEE Photon. Technol. Lett.*, **17**, 2403 (2005).
- [7] K. A. Murphy, M. F. Gunther, A. Wang, R. O. Claus, A. M. Vengsarkar, *Proc. 8th Opt. Fiber Sens. Conf.*, Jan., 193 (1992).
- [8] Guiju Zhang, Qingxu Yu and Shide Song, *Sens. Actuators A*, **116**, 33 (2004).
- [9] Jesus M. Corres, Javier Bravo, Francisco J. Arregui, gnacio R. Matias, *Sens. Actuators A*, **132**, 506(2006).
- [10] B. Yu, D. W. Kim, J. Deng, H. Xiao, A. Wang, *Appl. Opt.*, **42**, 3241 (2003).
- [11] M. A. Chan, S. D. Collins, R. L. Smith, *Sens. Actuators A*, **43**, 196 (1994).
- [12] P. C. Beard, T. N. Mills, *Appl. Opt.*, **35**, 663 (1996).
- [13] S. H. Aref, H. Latifi, M. I. Zibaii, M. Afshari, *Optics Communications*, **269**, 322 (2007).
- [14] R. O. Claus, M. F. Gunther, A. Wang, K. A. Murphy, *Smar Materials and Structures*, **1**, 237 (1992).
- [15] Yinbing Zhang, (Ph. D dissertation) Virginia Polytechnic Institute and State University, 2000.
- [16] Yu Qingxu, Song Shide, Zhang Guiju, Cui Ning, *Journal of Optoelectronics • Laser*, **15**, 1372 (2004).
- [17] Qi Wang, Lei Zhang, Qingxu Yu, *IEEE Sensors Journal*, **8**, 1879 (2008).

*Corresponding author: wangqi@ise.neu.edu.cn