The Nonlinear Changes of Temperature Response Birefringence of Side-Hole Fiber

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Abstracts: For deeply investigate the birefringence responding of side-hole fiber caused by temperature, the response performance are analyzed by finite element method and elastic-optic theory, especially the nonlinear changes. The simulation results showed that the response birefringence is linear with temperature no matter how the geometry changed, but the response sensitivity is nonlinear with geometry parameters. The hole radius and hole-core distance both have their limit value to get obvious temperature sensitivity. Large hole radius and small hole-core distance is good to get high response sensitivity. Furthermore some interesting results are discussed about the response sensitivity changed with the square value of hole-core separation angle. The sensitivity is nonlinear with the square of hole-core separation angle for temperature, which is different to pressure response sensitivity.

1. Introduction

The side-hole optic fiber was proposed as pressure sensor because of its special side-hole structure[1]. Two air tunnels are symmetrically surrounded with fiber core. The internal stress is anisotropic when the pressure is loaded on the fiber. That is favorable to pressure sensing because of large birefringence caused by stress anisotropy. In recent several decades[2-7], the side-hole optical fiber sensor is attractive, such as writing fiber gratings onto side-hole fiber[8-9] or filling some materials into side-hole[10-11]. Simultaneously, this birefringence optical fiber has good thermal stability and pressure-temperature crossing response. Although its pressure response sensitivity is higher than temperature response sensitivity, the temperature sensing performance also gave us great interest [12-13].

The birefringence of side-hole fiber can be attributed to intrinsic birefringence and response birefringence. The intrinsic birefringence is got in optical fiber fabrication. The response birefringence is caused by temperature, pressure or some other parameters. Some analysis [12] has demonstrated that the response birefringence is linear with temperature. By the analysis in this paper, the temperature response performance is not linear with its geometry parameters. Some linear and nonlinear response birefringence performance curves are discussed in this paper, especially its nonlinear performance. The research results give some supplement to the temperature response birefringence theory of side-hole fiber. That is helpful to deeply understand the sensing performance of side-hole fiber.

2. Simulation and Analysis

The structure of side-hole fiber is showed in Figure 1. This kind of anisotropy structure caused the obvious birefringence. The radius of side hole is showed as r. And the hole-core distance is d. The hole-core separation angle, the angle between x axis and the tangent line of fiber core center point to

side-hole outer boundary, is showed as ψ. Because of this structure, the response birefringence is got by stress-optic effect caused some loaded stress. So the anisotropy refractive index distribution of side-hole fiber is got when the outer temperature changed, which caused the temperature response birefringence. According to the photoelastic theory, the birefringence value is got as followed formula showed.

$$B = c \cdot \Delta\sigma \tag{1}$$

$$C = \frac{n^2}{2E}(1+\upsilon)(p_{12}-p_{11}) \cdot \Delta\sigma \tag{2}$$

Where B is response birefringence, c is the piezo-photonic constant, Δσ is the stress difference between x and y direction(as figure1 showed) at fiber core, n is the effective refractive index of fiber, E is Young's modulus of the fiber, υ is Poisson ratio, p11 , p12 are components of strain-optic tensor. For typical side-hole fiber, the Young's modulus E is 7.83×10^{10}，Poisson ratio ν is 0.186，the components of strain-optic tensor P_{11}=0.121,P_{12}=0.27,the effective refractive index of fiber n=1.468. The intrinsic fiber birefringence caused by core ellipticity and fiber residual stresses is ignored in calculation. At the center of optic fiber core, the stress components are approximatively as average stress values in x and y direction of fiber core [14]. By ANSYS software, the finite element method is used in simulation, for calculating the stress distribution at different temperature. Then the birefringence value is got by stress calculation data.
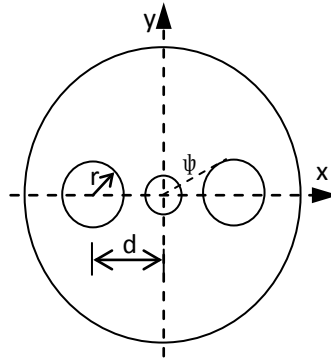

Figure 1. The diagram of side-hole fiber

2.1 Linear Response Curves
The simulations focused on the influence to response birefringence with different geometry parameters. For simulation, the typical hole-core distance and hole radius value are set as 26.6μm, 15.6μm, respectively. In ANSYS software calculations, free meshing method is used to get FEM grid. And the unit size is set as 2μm to get FEM meshing. Then the stress distribution is calculated by ANSYS software after setting the loaded temperature.   Fig.2 shows the relationship between birefringence and temperature with different hole radius, when hole-core distance value is 26.6μm. The hole radius varied from 11.9μm to 19μm. Fig.3 is the curves of response birefringence versus temperature with different hole-core distance, when the hole radius value is 15.6μm. The hole-core distance varied from 20μm to 40μm. For two figures, the temperature varied from 20℃ to 200℃.
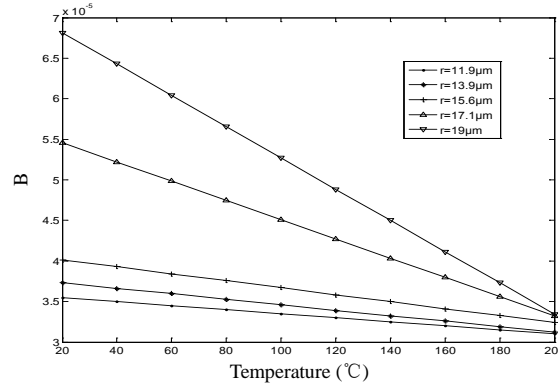
Figure 2. The temperature response curves with different hole-core distance
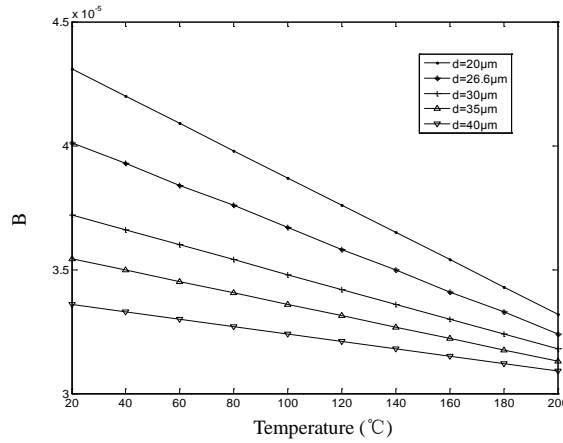
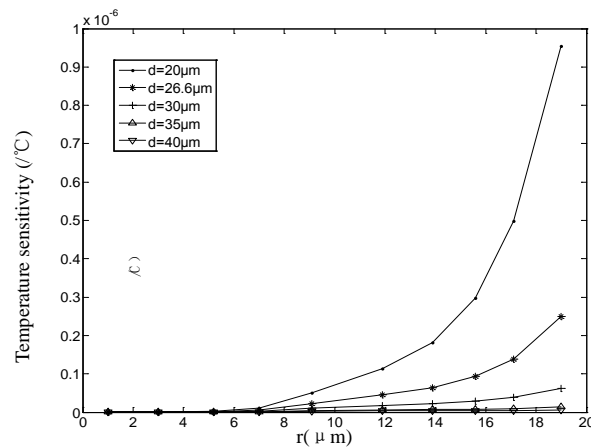**Figure 3.** The temperature response curves with different hole radius

As the above figures showed, the response birefringence is always linear with temperature no matter how the geometry changed. But the interesting thing is that it looks that the slope variation of curves is nonlinear with the changing of hole radius and hole-core distance. That means the changing of response sensitivity value is not linear with the fiber geometry parameters.

2.2 Nonlinear Performance Curves
For deeper investigating the response performance, the response sensitivity is also calculated. The temperature response sensitivity is defined as:

$$K_T = \frac{\Delta B}{\Delta T}$$
(3)

In calculation, the chosen hole-core distance values are 20μm, 26.6μm, 30μm, 35μm, 40μm, respectively. The hole radius value is set as 3μm, 7μm, 11.9μm, 15.6μm, 19μm, respectively. More than ten values are given to simulate response sensitivity curve to each geometry parameters. The temperature response sensitivity curves are showed in Fig.4 and Fig.5. The geometries choosing must be accordant with the actual structure. That means the hole-core distance value must be more than hole radius value. And the radius value cannot be too small to let the software run well.
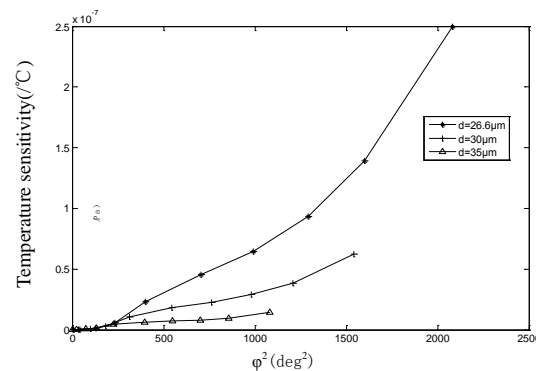
Figure 4. The temperature response sensitivity versus hole radius with different hole-core distance
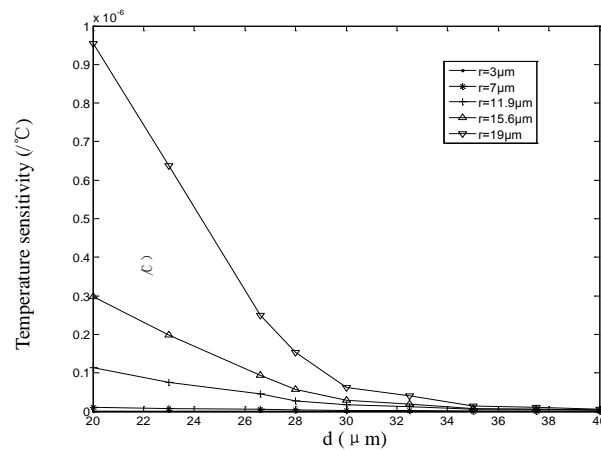
Figure 5. The temperature response sensitivity versus hole-core distance with different hole radius

Obviously the temperature response sensitivity curves are all nonlinear as two figures showed, which is similar to pressure response sensitivity curves at reference [15]. The response sensitivity increased with bigger hole radius or smaller hole-core distance. So large hole radius and small hole-core distance are good to temperature sensing, because of more stronger anisotropy accordingly. Furthermore, the response sensitivity is greatly influenced by hole-core distance when the hole radius value is big. And the sensitivity varied obviously with hole radius value when the hole-core distance value is small. As Fig.4 and Fig.5 showed, the responding is obvious when the hole radius value is more than 7μm, and the hole-core distance value is less than 35μm. That means the hole radius and hole-core distance both have their limit value to get obvious temperature sensitivity.

Some analysis [2, 15] was reported that the pressure response sensitivity is depended lineally on the geometry parameter φ^2, where φ is hole-core separation angle as Fig.1 showed. However, the interesting point is that the temperature response sensitivity changing situation is different by simulations. For deeply investigating this responding performance, the sensitivity curves are simulated with different value of φ^2. For discussing the changing situation, in two simulations, the typical hole-core distance values are uniformly set as 26.6μm, 30μm, 35μm, respectively.

Figure 6. The temperature response sensitivity versus φ^2 with different hole-core distance

As Fig.6 showed, the curves presented the relationship of the temperature sensitivity with φ^2. Obviously the temperature response sensitivity is nonlinear with φ^2. However, according to the results in reference [2], the pressure response sensitivity is linear with φ^2. This interesting difference should be caused by the different influence between the thermal expansion and pressure-induced stress to this special fiber structure.

3. Conclusion

We analyzed the linear and nonlinear temperature response birefringence performance of side-hole fiber in this paper. According to the theoretical analysis, the response birefringence is linearly dependent on external temperature even if with different hole radius and hole-core distance. But the response sensitivity are nonlinear with varied hole radius and hole-core distance. Large hole radius and small hole-core distance are good to improve temperature response sensitivity. And the hole radius and hole-core distance both have their limit value to get obvious temperature sensitivity. Furthermore, different with pressure response sensitivity curves, the temperature response sensitivity is nonlinear with the square of hole-core separation angle. The analysis results are helpful to deeply understand the sensing performance of side-hole fiber, especially the pressure-temperature crossing response performance.

5.References
[1] Xie, H. M., Dabkiewicz, P., Ulrich R. and Okamoto K. Side-hole fiber for fiber-optic pressure sensing. Optics Letters, 1986. 11: 333-335.
[2] Clowes, J. R., Syngellakis, S., Zervas, M. N. Pressure sensitivity of side-hole optical fiber sensors. IEEE Photonics Technology Letters, 1998.10(6): 857–859.
[3] Xin, Y., Dong, X. Y., Meng, Q. Q., Qi, F., Zhao, C. L. Alcohol-filled side-hole fiber Sagnac interferometer for temperature measurement. Sensors & Actuators: A. Physical, 2013. 193: 182–185.
[4] Lee, S. H., Kim, B. H., Han, W. T. Effect of filler metals on the temperature sensitivity of side-hole fiber. Optics Express, 2009.17(12): 9712-9717.
[5] Jin, Y. X., Chan, C. C., Zhang, Y. F., Dong, X. Y. Mechanically induced long-period fiber grating in side-hole single-mode fiber for temperature and refractive sensing. Optics Communications, 2010.283(7):1303-1306.
[6] Frazão O, Silva S. O., Baptista J. M., Santos J. L., Statkiewicz-Barabach G., Urbanczyk W., Wojcik J. Simultaneous measurement of multiparameters using a Sagnac interferometer with

polarization maintaining side-hole fiber. Applied Optics, 2008.47(27):4841-4848.

[7] Bock,W. J., Nawrocka, M. S., Urbanczyk, W. Application of side-hole fibers for dynamic pressure measurements. Proceedings of the Society of Photo-Optical Instrumentation Engineers, SPIE, Quebec City, Canada, June, 2000. pp.1175-1179.

[8] Schroeder, R. J.; Yamate, T.; Udd, E. High Pressure and Temperature Sensing for the Oil Industry Using Fiber Bragg Gratings Written onto Side Hole Single Mode Fiber. 13th International Conference on Optical Fiber Sensors and Workshop on Device and System Technology toward Future Optical Fiber Communication and Sensing, Kyongju, Korea, April, 1999.pp.42-45.

[9] Xin,Y., Dong, X. Y., Yuan,J. W., Li,Y., Jin, S. Z., Zhang, S. L. Sensing characteristics of side-hole fiber long-period grating. Advances in Materials Science and Engineering, 2013(11): 2070-2074.

[10] Lee,S. H., Son, D. H., Kim, B. H. and Han, W. T. 2012. Effect of infiltration pressure on the birefringent properties of a side-hole fiber filled with indium. Optics Letters, 2012.37(12): 2322-2324.

[11] Qi F., Xin Y., Dong X. Y. Meng Q., Zhao C.L., Jin S. Z. Sagnac Interferometer Based Temperature Sensor With Alcohol-Filled Side-Hole Fiber. Laser &Optoelectronics Progress, 2013. 50(1): 99-102.

[12] Moon, D.S., Kim, B. H., Lin A., Sun, G., Han, Y. G., Han, W. T. and Chung Y. G. The temperature sensitivity of Sagnac loop interferometer based on polarization maintaining side-hole fiber. Optics Express, 2007. 15(13):7962-7967.

[13] Dong, X. Y., Jin, Y. X., Zhou, W. J., Shum P. Simultaneous Measurement of Strain and Temperature with Side-hole Fiber Based Bragg Grating. Proceedings of the 7th international conference on Information, communications and signal processing, ICICS 2009, Macau, China, December, 2009. pp.611-613.

[14] Yueai, L., Rahman, B. M. A., Grattan, K. T. V. Thermal-stress-induced birefringence in bow-tie optical fibers. Applied. Optics , 1994. 33 (24): 5611-5616.

[15] Wang N., Fu J., Li D., Zhu H., Tian Y., Wang T. Pressure-Induced Birefringence Analysis of Side-Hole Optic Fiber, Journal of Nanoelectronics and Optoelectronics, 2015.10: 795-798.