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Dynamic Temperature Characteristics of Liquid Filled Photonic Crystal Fiber

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Abstract: The dynamic characteristics of high sensitivity temperature sensor are studied by using siphon method to fill the air hole near the core of the hollow photonic crystal fiber with Cargille matching liquid, and the two ends are fused with single-mode fiber in this work. We analyzed the working principle of filled photonic crystal fiber sensor by using the standard coupling mode theory of directional coupler. The coupling process was simulated by COMSOL software. When the photonic crystal fiber filled with 10 mm liquid was scanned by tunable laser, the temperature sensitivity was 7.50 nm /℃, the average temperature response time was 0.317 s, the average release time was 3.732 s, and the temperature variation linearity was 100%. The experimental results show that the liquid filled photonic crystal fiber has the advantages of high temperature sensitivity, fast response time and good linearity.

Key words: optical fiber; photonic crystal fiber; filling; temperature; dynamic testing

1 Introduction

Photonic crystal fiber (PCF) is usually made of pure quartz or polymer materials. There are complex refractive index distributions on the mode cross section of PCF, and there are different arrangements of pores. The size of these pores is about the same order of magnitude as the wavelength of light wave and runs through the whole length of the device. Light wave can be limited in the core of low refractive index fiber. According to the different transmission principle of light wave in fiber structure, photonic crystal fiber can be divided into total internal reflection type[1] and photonic band gap type[2]. PCF temperature sensor takes advantage of this unique waveguide structure, which has the advantages of anti- electromagnetic interference, integration of sensing and transmission, remote measurement and monitoring in high-risk environment. It has been widely concerned and highly valued by scholars at home and abroad [3-6]. For example, Yu *et al*[7] filled the total reflection PCF with liquid ethanol, and the temperature detection sensitivity reached 0.315 db/℃; Ayyanar *et al*[8] designed a liquid filled asymmetric double elliptical core PCF, which realized higher temperature sensing sensitivity with shorter filling length. Peng *et al*[9] designed a liquid selectively filled PCF temperature sensor by controlling the air hole collapse in the post-processing process of PCF, and the temperature sensitivity reached −5.5 nm /℃; Hsu *et al*[10] proposed a liquid filled PCF Michel interferometer with ultra-compact and high sensitivity based on material dispersion engineering. In addition, some researchers have plated gold nano film or titanium nitride film on the surface of PCF to realize temperature sensing characteristics by using surface plasmon resonance effect[11-13].

Based on the above analysis, we think that the liquid medium filled with high temperature sensitivity characteristics is the key factor to improve its temperature sensing sensitivity for liquid filled PCF temperature sensor. Therefore, we investigated the characteristics of static and dynamic temperature of PCF by using siphon method to fill the air hole near the core of the hollow photonic crystal fiber with Cargille matching liquid with high refractive index and welding the two ends with single-mode fiber. In addition, the coupling principle of PCF is analyzed by using the standard cou-

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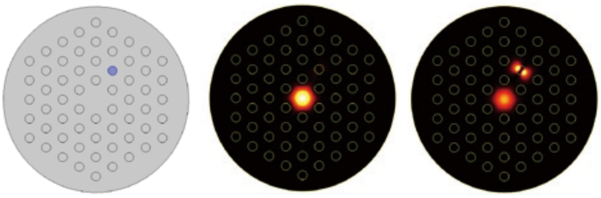
pled mode theory of directional coupler.

2 Mode coupling method of photonic crystal fiber

Photonic crystal fiber air hole can be regarded as a series of air and fluid reactors, which provides a good space and degree of freedom for filling functional materials in the fiber. When functional materials are filled into the micropores, the interaction between materials and light can lead to the change of optical fiber transmission characteristics. Through the analysis of transmission characteristics, a large number of interactive information can be obtained. By filling the air hole with electro-optic, thermo-optical, acousto-optic and magneto-optical functional materials, the micro nano optical band gap structure, mode coupling and transmission characteristics can be controlled. The working principle of the filled photonic crystal fiber sensor can be explained by the standard coupling mode theory of directional coupler.



(a) (b) (c)

Fig.1 Schematic of mode coupling : (a)Cross view of the PCF device; (b) Fundamental mode in the core; (c) Hybrid mode

When the distance between core mode and cladding mode is large enough, there is no mode coupling in selectively filled photonic crystal fiber. When the filling hole is close to the core (as shown in Fig.1), there is no independent guided mode in the core and the filling hole, and the perturbation can be considered to have been introduced into the fiber. Each guided mode can be distributed in the air hole and in the core. When the two modes reach the same phase velocity at a certain frequency, the perturbation reaches the maximum value, and the energy will be coupled from the core to the cladding. In this case, the plane wave expansion method can be used to obtain the mode coupling equation of dual core fiber considering two coupling modes at the same time[14].

$$\frac{dP_a}{dz}=-i\kappa_{ab}P_b e^{-i[(\beta_b+M_b)-(\beta_a+M_a)]z} \quad (1)$$

$$\frac{dP_b}{dz}=-i\kappa_{ba}P_a e^{i[(\beta_b+M_b)-(\beta_a+M_a)]z} \quad (2)$$

In Eqs.(1) and (2), $\kappa_{ab\,(ba)}$ is the cross-coupling coefficient, $M_{a(b)}$ is the coupling coefficient, $\beta_{a(b)}$ is the transmission parameter, P_a and P_b is the transmitted energy in the filling hole and the core respectively. z is the propagation distance. When the filling hole is close to the core, the transmission energy at the core is equal to that at the filling hole. At the same time, $\beta_b+M_b\approx\beta_a+M_a$. The equation holds and the energy propagation distance from the core to the filled hole is equal to $z_m=\pi/(2\kappa_{ab})$. When the two modes are far away from the coupling point, the cross-coupling coefficient will be reduced, and the energy of one mode is high and the energy of the other mode is low. In this paper, COMSOL software is used to simulate the above coupling method, and the results are shown in Fig.1(b) and 1(c).

3 Static temperature characteristics of photonic crystal fiber

In order to observe the relationship between the wavelength of absorption peak and temperature, the experimental device as shown in Fig.2 was adopted in this paper, which was composed of PCF, heating furnace, broadband light source, temperature controller and spectrum analyzer. Among them, the PCF was the commercial LMA-10 PCF from NKT. The spectral range of broadband light source was set at 1 500-1 580 nm (YSLP, China). The average diameter of air hole in optical fiber is 3.04 μm, and the hole spacing is 6.26 μm. During the experiment, siphon method was used to fill the air hole with Cargille matching solution with a length of 10 mm and a refractive index of 1.508 in order to make it have a higher refractive index (1.445) than the silicon glass used in LMA-10. Each end of the filled photonic crystal fiber was welded with single-mode fiber, and the reflection spectrum was scanned by high-precision spectrometer OSA (AQ6370c, Yokogawa, Japan).

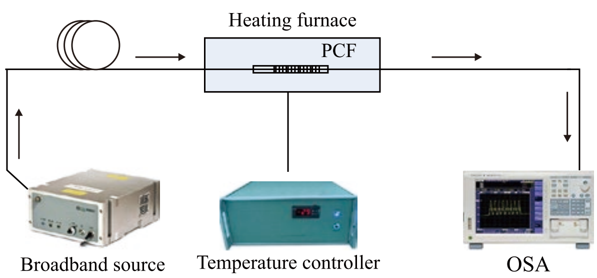


Fig.2 Experimental setup of Static temperature measurement

The photonic crystal fiber was placed in the semiconductor temperature control device. In the initial condition, the photonic crystal fiber was at room tem-

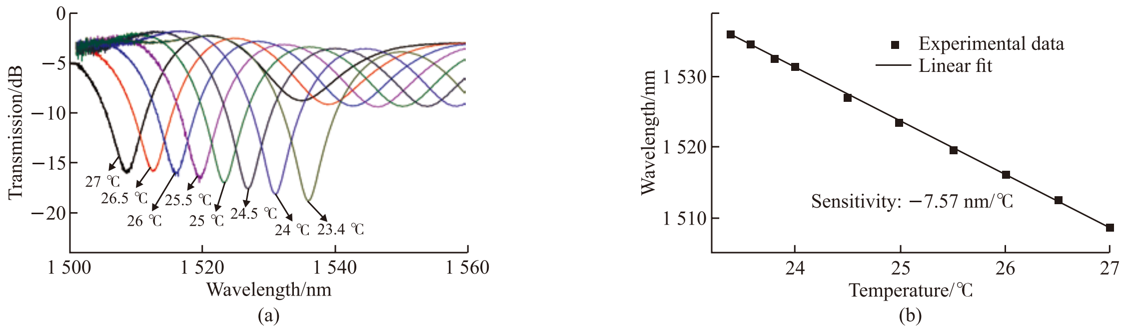


Fig.3 (a) The transmission spectra of the device at different temperature; (b)The wavelength shift of the resonance dip with temperature variation

perature (23.4 ℃). The main absorption peak of the reflection spectrum is 1 535.88 nm. Then the temperature was gradually adjusted to 27.0 ℃, and the absorption peak was shifted to 1 508.64 nm. The corresponding absorption spectrum is shown in Fig.3(a). When the temperature range is 3.6 ℃, the spectral shift reaches 27.24 nm and the sensitivity reaches 7.50 nm /℃. The absorption peak wavelength is approximately linear with temperature, as shown in Fig.3(b).

4 Analysis of dynamic temperature characteristics of photonic crystal fiber

According to the experimental results of static temperature characteristics, when the temperature is 24.5 ℃, the reflection spectrum of liquid filled photonic crystal fiber has two absorption peaks, 1 526.84 and 1 556.20 nm, as shown in Fig.5 (E). In order to study the response time of filled photonic crystal fiber to temperature, four points (a), (b), (c) and (d) are selected as working points. For each point, there is a 50% drop in the relative power. The corresponding wavelengths are 1 524, 1 534, 1 544 and 1 557 nm respectively.

In the experiment, the tunable laser is adjusted to the four wavelength positions, and the CO_2 laser is used as the heating device to scan the photonic crystal fiber at a speed of 4 m/s. The output waveform of the circulator is observed with an oscilloscope. The device for heating the photonic crystal fiber is shown in Fig.4, and the waveforms are shown in Fig.5 (a), (b), (c) and (d). The temperature response time and release time of

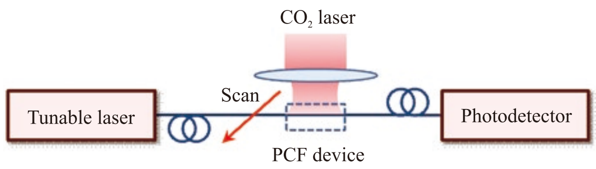


Fig.4 The CO_2 laser heated device

Table 1 PCF thermal response schedule

Probe point	(a)	(b)	(c)	(d)	average
Response time τ/s	0.267	0.328	0.310	0.312	0.317
Release time Δt/s	5.420	3.854	3.692	3.691	3.732

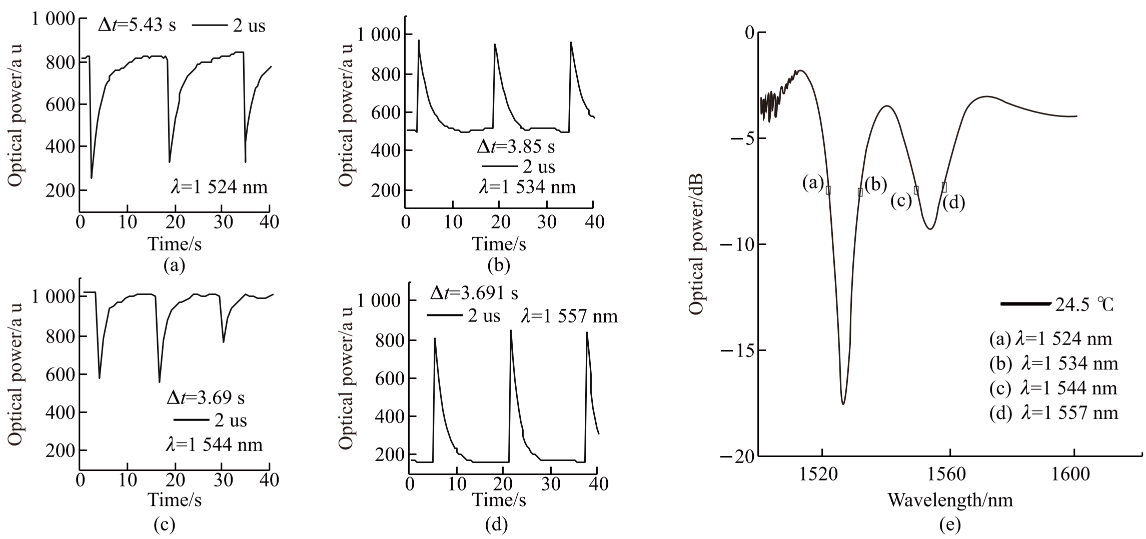


Fig.5 Reflected waveforms at the wavelength of (a) 1 524 nm; (b) 1 534 nm; (c) 1 544 nm; (d) 1 557 nm; (e) temperature response curve at 24.5 ℃

the four operating points are shown in Table 1.

5 Conclusions

The temperature switching characteristics and dynamic response time of photonic crystal fiber filled with tunable laser scanning were investigated. The bandwidth of the light source was set at 80 nm, and the temperature setting range was 3.6 ℃. In this range, the temperature sensitivity of filled matched liquid photonic crystal fiber with liquid refractive index of 1.508 reached 7.50 nm / ℃. The dynamic temperature characteristics of PCF show that the linearity of temperature change is about 100% and the temperature response time is about 0.317 s. It can be used as a temperature sensitive element and has great application in highly sensitive temperature detection.

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