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A large range temperature sensor based on an angled fiber end

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ABSTRACT

We proposed a simple structure optical fiber temperature sensor, which is easy to be fabricated and used. The fiber sensor is made by polishing the optical fiber end to be 30° angle and its operating principle is based on Michelson interferometer. In order to demonstrate the performance of the fabricated temperature sensor, we carried out low temperature experiment (−40 °C–140 °C) and high temperature experiment (250 °C–900 °C) with two different kinds of thermostats. The results show us that the temperature sensitivity of the sensor increases with increasing temperature both in the low temperature range (−40 °C–140 °C) and in the high temperature range (250 °C–900 °C). The measured temperature sensitivity is 9.5 pm/°C at −40 °C and the measured temperature sensitivity is 17.86 pm/°C at 900 °C.

1. Introduction

Nowadays, temperature is one of the most fundamental physical quantities in science and technology [1], because every precision process must have either a monitored or controlled temperature. There are mainly two kinds of sensors to measure the temperature, they are electrical sensors and optical sensors. Temperature sensors based on optical fiber have been designed and investigated widely in recent years with the advantages of easy remote sensing capability [2], high sensitivity [3,4], and immunity to electromagnetic interference [5] and so on. Several kinds of optical fiber temperature sensors have been reported. Phase mask engraved fiber Bragg gratings (FBGs) are a typical and practical kind of temperature sensors, but the sensitivity is relatively low, which are around 10 pm/°C, meanwhile the temperature measuring range is usually small, which is from −200 °C to 150 °C [6–8]. The sensitivity of the Fabry-Perot interferometer-based fiber tip temperature sensor is 9.17 pm/°C [9]. Another kind of fiber temperature sensor based on whispering gallery modes was presented with a sensitivity of 0.377 nm/°C in the temperature range 25 °C–45 °C [10]. Fiber optic surface plasmon resonance (SPR) based temperature sensor can get the sensitivity of 629 pm/°C in the temperature range 0 °C–99 °C [11,12]. Hollow-core fiber (HCF) structures are often used to measure the temperature, these sensors [13–15] are the commonly used SMF-HCF-SMF sensing structures. The work of Hao Sun et al. reports the sensitivity of 18.7 pm/°C and its high temperature measurement range can reach up to 460 °C [16]. By contrast, fiber-tip assembly free temperature sensors have a good application prospect, whose structure is simple and temperature measurement range is particularly wide [17–19].

In our paper, we proposed and fabricated a high temperature sensor based on the fiber end which was polished to be 30° angle by fiber polishing machine. Compared to the previous sensors, the structure of our proposed sensor was simple and it was easy to be fabricated and used. Furthermore, the experiment was performed at temperatures under 0 °C, which is an improvement to what has been done already [17–19].

2. Theory

Fig. 1 shows the diagram of the proposed optical fiber sensing head. The sensing head was made by the normal SMF 28 fiber, whose end was polished to be 30° by the fiber lens polishing machine. Based on the Snell's law, when the light is incident on fiber-core/air interface, the critical angle of total internal reflection can be calculated to be 43°. Thus, when the light propagating in the fiber core arrives at the tilt face of the fiber end, the total internal reflection will happen. And then the light will be split into two beams at the interface of the fiber core and the fiber clad, one is the reflected light I_1 and the other is the refracted light I_2. From Fig. 1 we can see that the reflected light I_1 will bounce back at the tilt fiber end, thus the light I_1 will return along the original way. The refracted light I_2 will reflect at the interface of the fiber clad and air and then it will bounce back at the interface of the fiber clad and the air with the incoming angle of 0°. Thus, both the reflected light I_1 and the refracted light I_2 will return along the original way and they will be combined into one beam again with a phase difference

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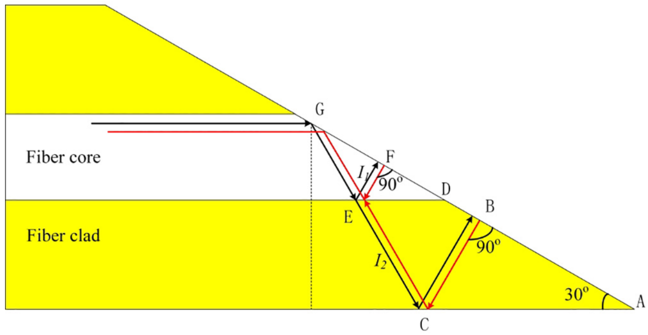

Fig. 1. Schematic diagram of temperature sensor based on angled fiber end.

$\Delta\phi = \frac{2\pi OPD}{\lambda}$ and propagate back along the fiber core. Here OPD is optical path difference of the two light beams. OPD can be obtained from Fig. 1.

$$\begin{aligned} OPD &= 2(EC + BC)\cdot n_{cl} - 2FE\cdot n_{co} \\ &= 2\left[\frac{2\sqrt{3}}{3}r_{cl} + \frac{\sqrt{3}}{3}(2r_{co} + r_{cl})\right]\cdot n_{cl} - 2\cdot\frac{2\sqrt{3}}{3}r_{co}\cdot n_{co} \\ &= 2\sqrt{3}\,r_{cl}\cdot n_{cl} - \frac{4\sqrt{3}}{3}r_{co}(n_{cl} - n_{co}) \end{aligned} \tag{1}$$

where $n_{cl} = 1.4628$ and $n_{co} = 1.4682$, $r_{cl} = 62.5$ μm, $r_{co} = 4.1$ μm.

Because the two beams come from the same light and then they are combined to be one beam again, so the Michelson interferometer will be stablished at the fiber end. The intensity of the interferential spectrum can be defined by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cdot\cos\frac{2\pi OPD}{\lambda} \tag{2}$$

When $\Delta\phi = (2m + 1)\pi$, where m is an integer, an interference dip can emerge. The corresponding dip wavelength λ_m is

$$\lambda_m = \frac{2OPD}{2m + 1} \tag{3}$$

The fringe spacing between two adjacent interference dips can be expressed as:

$$\Delta\lambda = \frac{\lambda^2}{OPD} \tag{4}$$

For a standard single-mode fiber (Corning SMF-28), we can obtain the fringe spacing is 7.5847 nm at 1550 nm.

When the ambient temperature fluctuation is imposed on the sensing head, both refractive index and radius of the fiber will change because of the thermo-optic effect and the thermal expansion of the fiber. Thus, the temperature sensitivity of Michelson interferometer can be derived as:

$$\begin{aligned} \frac{d\lambda_m}{dT} &= \left(\frac{1}{n_{cl}}\cdot\frac{dn_{cl}}{dT} + \frac{1}{r_{cl}}\cdot\frac{dr_{cl}}{dT}\right)\lambda_m \\ &= \left(\frac{1}{n_{cl}}\cdot\frac{dn_{cl}}{dT} + \frac{1}{r_{cl}}\cdot\frac{dr_{cl}}{dT}\right)\frac{2OPD}{2m+1} \\ &= (\xi + \alpha)\frac{2OPD}{2m+1} \end{aligned} \tag{5}$$

where ξ is the thermo-optic coefficient and α is the thermal expansion coefficient of the optical fiber, and for the silica glass fiber ξ is $1.0 \times 10^{-5}\,K^{-1}$ and α is $1.1 \times 10^{-6}\,K^{-1}$ [20]. Since both the thermo-optic coefficient and the thermal expansion coefficient are positive, so they both have a positive contribution to the temperature sensitivity. As a result, the ambient temperature can be monitored by observing the wavelength.

3. Fabrication

The proposed fiber sensing head is shown in Fig. 1. The sensor is made by polishing a 30° angled reflector at the end of the SMF. The key concept is to split the incoming light beam into two beams at the 30° fiber end.

To demonstrate the concept, the 30° fiber end was fabricated at the end of a SMF with core/cladding diameter of 8.2/125 μm using a fiber-lensing machine (Ultra Tec Manufacturing. Inc.). The sensor fabrication process can be completed in two steps. Firstly, we polished a 30° angled ceramic ferrule with a 126 μm through-hole, as shown in Fig. 2(a). A 9 μm diamond lapping film was stuck onto the platen. After the platen ran for several minutes with a speed of 60 rpm, we gradually lowered the ceramic ferrule until it came to contact with the diamond lapping film with a slight pressure. As the material of the ceramic ferrule was removed, the pressure between the ceramic ferrule becomes small. When the pressure disappeared, we lowered the ceramic ferrule with 10 μm again. This process is repeated until the middle hole of the ceramic ferrule is polished. Next, we will polish the fiber end to be 30°, as shown in Fig. 2(b) and (c). Raising the position of ceramic ferrule so that it is 100 μm away from the diamond lapping film. The optical fiber with polymer coating layer removed in the tail was inserted into the ceramic ferrule and the fiber end was in contact with the diamond lapping film. When grinding the fiber, we replaced the lapping film with 1 μm diamond lapping film. After grinding the fiber end face with a slight pressure for about 1 min, a coarse 30° angled fiber end face is completed. To keep high optical properties, the polish obtained from the 1 μm diamond lapping film is insufficient. We changed the lapping film to a finer 0.3 μm diamond lapping film. Polishing for about 20 s again, a smooth 30° angled fiber end face is finally obtained. The fabrication process of the proposed sensor is much easier than the sensor in paper [19]. Fig. 3 shows us the front view and the side view of the 30° angled fiber end under the microscope. When the light is incident on the sensor, there are three reflection point on the 30° angled fiber face and one reflection point on the back of the 30° angled fiber face, as shown in Fig. 1. When the red light is incident on the fabricated sensor, we can observe the four reflection points in Fig. 3(b).

4. Experiment and analysis

In order to study the temperature sensing performance of the fabricated 30° angled fiber end sensor, we carried out temperature experiment with the experimental setup shown in Fig. 4(a). An ASE source with the wavelength range of 1525 nm to 1605 nm was used as the light source. An optical spectrum analyzer (OSA, YOKOGAWA, AQ6370) was used to measure the interference spectrum. The resolution of the OSA was chosen as 0.05 nm. The light from the source was launched into the fiber sensor via a circulator. The light is split into two beams due to the

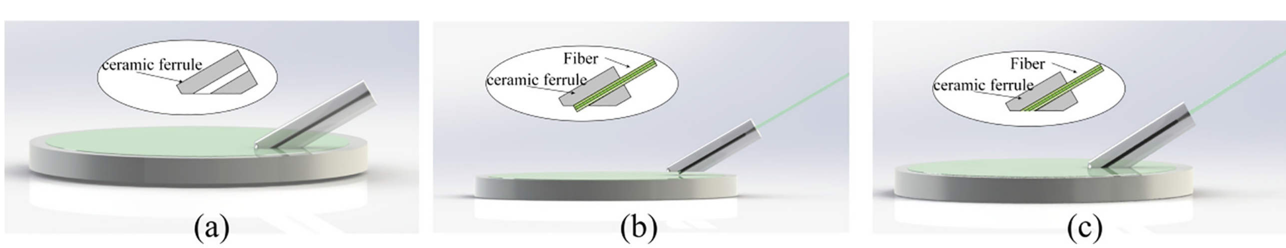

Fig. 2. (a) The schematic of grinding ceramic ferrule (b) The schematic when starting to grind the fiber (c) The schematic when optical fiber was grinded to 30° angle.