

Low-noise and highly stable optical fiber temperature sensor using modified pulse-reference-based compensation technique

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We modify the pulse-reference-based compensation technique and propose a low-noise and highly stable optical fiber temperature sensor based on a zinc telluride film-coated fiber tip. The system noise is measured to be 0.0005 dB, which makes it possible for the detection of the minor reflectivity change of the film at different temperatures. The temperature sensitivity is 0.0034 dB/°C, so the resolution can achieve 0.2°C. The maximum difference of the temperature output values of the sensor at 20°C at different points in time is 0.39°C. The low cost, ultra-small size, high stability, and good repeatability of the sensor make it a promising temperature sensing device for practical application.

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In the past decades, optical fiber temperature sensors have been widely investigated^[1-7] because of their durability, easy multiplexing, immunity to electromagnetic interference, and capacity to work in hazardous environments. Among them, various types of reflective optical fiber temperature sensors based on fiber tips are attracting more and more attention, including multimode interference^[8,9], optical thin film interference^[10,11], photonic crystal fiber^[12,13], micrometric optical fiber coupler^[14], and other special structures^[15,16]. They show several advantages, including ultra-small size, compactness, high responsivity, and fast response.

However, these sensors are mainly based on wavelength modulation, and the temperature-induced wavelength variations are detected via an optical spectrum analyzer (OSA). Considering the equipment costs and complex interrogation units to extract the temperature information, they do not show a great potential in mass production and practical application fields.

Temperature-induced intensity variation of a fiber tip temperature sensor has gained little attention. The main reasons is, compared with the system noise of conventional intensity-modulated optical fiber sensing systems, the temperature-induced intensity variation is not obvious to satisfy a reasonable resolution requirement^[17]. The detected intensity might be affected by the fluctuation of the light source and other factors with time and external perturbations, which will reduce the accuracy of output temperature information and cause stability problems.

Although some kinds of semiconductors have been applied in this field based on the detection of the optical absorption edge shift as a result of temperature-induced

semiconductor band gap change under temperature variation^[17-19], their structures are complex, and special short-wavelength light sources are needed to achieve intrinsic absorption.

The recently proposed pulse-reference (PR) compensation technique can largely reduce the system noise by compensating the power fluctuation of the light source, the change of optic components transmission loss, and the coupler splitting ratio^[20]. Its system noise is much lower than that of conventional intensity-modulated optical fiber sensing systems. Therefore, by using the PR compensation technique, some structures and principles that could not be previously utilized, owing to unnoticeable intensity variation, can be developed. On the other hand, this compensation technique still suffers the time drift problem in long work hours as in the previous sensor^[20], which affects its stability and repeatability.

In this Letter, we pay attention to the temperature-induced reflectivity variation of the fiber tip coated by a zinc telluride (ZnTe) thin film and modify the PR compensation technique with a low-frequency square wave modulation to achieve good stability and repeatability. A low-noise and highly stable optical fiber temperature sensor based on a ZnTe film-coated fiber tip has been demonstrated. The low system noise level provided by the PR compensation technique makes it possible for the detection of the minor temperature-dependent reflectivity variation at different temperatures.

The reflectivity and sensibility of the fiber tip can be largely improved by involving multibeam interference of a semiconductor thin film, compared with a fiber tip

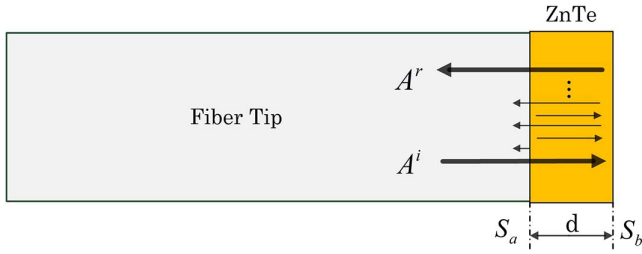


Fig. 1. Schematic diagram of the ZnTe thin film-coated fiber tip.

coated by a bulk semiconductor. The schematic diagram of the ZnTe thin film-coated fiber tip is illustrated in Fig. 1.

According to the multibeam interference theory^[10,11,17], the reflectivity of the thin film can be written as

$$R = \frac{A^r \cdot A^{r*}}{A^i \cdot A^{i*}} = \frac{r_a^2 + r_b^2 e^{-4\alpha d} + 2r_a r_b e^{-2\alpha d} \cos \delta}{1 + r_a^2 r_b^2 e^{-4\alpha d} + 2r_a r_b e^{-2\alpha d} \cos \delta}, \quad (1)$$

where A^i and A^r are the amplitudes of the incident light beam and reflective light beam. r_a and r_b are the reflective ratios of surfaces S_a and S_b . d and α represent the thickness of the film and the absorption coefficient of ZnTe, respectively. δ represents the phase delay between the two consecutive beams.

Owing to the thermo-optic effect, the refractive index changes as the temperature varies, and the reflectivity R of the thin film will change accordingly. According to various references, the thermo-optic coefficient dn/dT of ZnTe is estimated to be 7.5×10^{-5} ^[21–23]. Considering its thermal expansion coefficient is at least one order smaller than the thermo-optic coefficient, we will neglect it in the following discussion. The common wavelengths for ordinary light source are 1310 and 1550 nm. Their photon energy (0.949 and 0.802 eV, respectively) is much lower than the band gap of ZnTe (2.2 eV^[24,25]), so the intrinsic absorption can be neglected, and absorption coefficient α is very small and can be ignored. The refractive index of ZnTe is 2.73 at room temperature^[21–23]. In the field of optical coating processing, 500 nm is a common thickness.

Therefore, at the wavelength $\lambda = 1310$ nm, the reflectivity variations under different temperatures for ZnTe film with certain thicknesses (495, 500, and 505 nm) can be calculated, as shown in Fig. 2.

It can be seen from the above theoretical calculations that the reflectivity varies under different temperatures, but the variation is not obvious. It is difficult to detect this minor variation if conventional intensity sensing systems are still used. The PR compensation technique can provide a low system noise level by compensating the power fluctuation of the light source, the change of optic components transmission loss, and the coupler splitting ratio^[20]. Based on this compensation technique, the minor temperature-dependent reflectivity variation at different temperatures can be detected, and the whole temperature

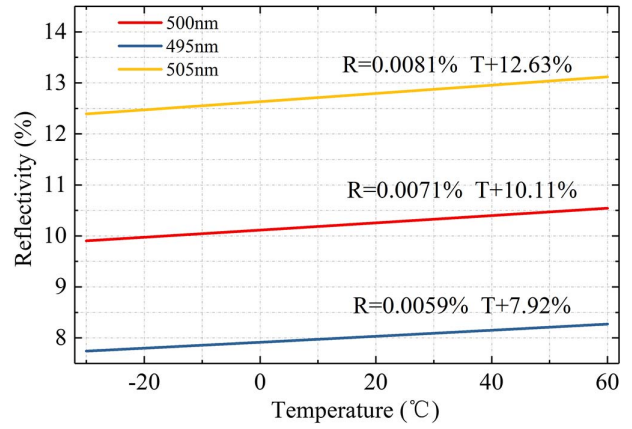


Fig. 2. Reflectivity variations under different temperatures for the ZnTe film with certain thicknesses (495, 500, and 505 nm).

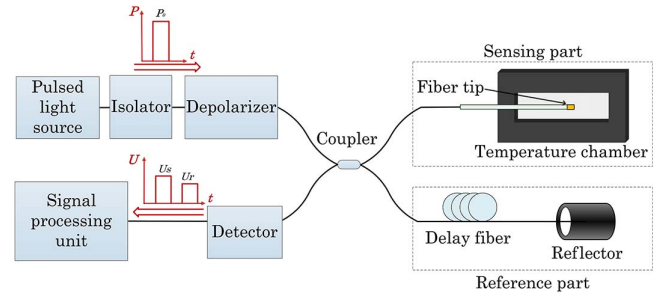


Fig. 3. Schematic diagram of the optical fiber temperature sensor based on the ZnTe film-coated fiber tip.

sensor can be set up. Figure 3 shows the schematic diagram of the optical fiber temperature sensor based on a ZnTe film-coated fiber tip using the PR-based compensation technique. The 2×2 fiber optic coupler divides the light pulse into two pulses, which enter the sensing part and reference part, respectively. The delay fiber in the reference part provides a time delay for the reference pulse. After being reflected by their respective reflective interfaces, the two pulses will be received and analyzed by the detector and the signal processing unit.

However, the PR-based compensation technique suffers a time drift problem in long work hours in the previous sensor^[19], which severely affects stability and repeatability of the sensor. Based on analysis, the theoretical explanation is as follows: the actual output voltage of the photodetector for the signal and reference pulses can be written as

$$U_s = DP_0\alpha_0(1 - C)\alpha_s r_s \alpha_s C + N_{ad}, \quad (2)$$

$$U_r = DP_0\alpha_0 C\alpha_r r_r \alpha_r (1 - C) + N_{ad}, \quad (3)$$

where D is the responsivity of the detector. P_0 is the incident light power. α_0 , α_s , α_r are the transmittance of the common optical path, sensing part, and reference part. C is the coupling ratio of the 2×2 fiber optic coupler. r_s and r_r are the reflectance of the first and second reflector,

respectively. N_{ad} represents the additive noise, including the dark current of photodetector.

It can be seen from the equations above that there is a bias caused by additive noise, resulting in deviation. The additive noise including the dark current drifts over time, owing to the changing external environment, such as temperature variation. Even though its drift rate is slow, it might cause the output drift if the former output computing method of $S = \frac{U_s}{U_r}$ is still used^[20]. In order to solve this problem, the PR compensation technique should be modified, and a low-frequency square wave modulation is used. After modulation, the power of the incident light varies from one state P_1 to another state P_2 periodically. As is shown, Fig. 4(a) is the output power of the light source after modulation, and Fig. 4(b) is the output voltage of photodetector.

The new output computing method can be written as

$$S^* = \frac{U_{s1} - U_{s2}}{U_{r1} - U_{r2}} = \frac{\alpha_s^2 r_s}{\alpha_r^2 r_r}, \quad (4)$$

and it is obvious that S^* is unrelated to the initial light pulse intensity P , the coupling ratio C , the transmittance of the common optical path α_0 , the photodetector responsivity R , and the additive noise I_{ad} , which means it will not be influenced by these factors.

If the output ratio at 20°C (S_{20}^*) is chosen to be a benchmark and is regarded to correspond to the theoretical reflectivity at 20°C (R_{20}), the reflectivity R at other temperatures can be calculated as $R = R_{20} \frac{S^*}{S_{20}^*}$, where S^* is the output ratio at the corresponding temperature.

A 1.31 μm wavelength (line width 40 nm) pulsed light source with a 250 ns pulse width and 10 kHz repetition rate was used. The relative length between the sensing fiber and the delay fiber was set to be 60 m, providing a 600 ns time delay. The pulses were detected by the photodetector (New Focus, Model 2053). The amplitudes of the signal pulses and reference pulses were converted into digital data by data acquisition card NI PXIe-5122. An Al-coated fiber tip was used as the reflector in the reference part, and all the components in the reference part were protected to keep them away from any fluctuation. In order to avoid the polarization and interference problem, a Loyt depolarizer fabricated by two 45° cross-polarization maintaining fibers^[26] was used, and the degree of polarization after depolarization was measured to be

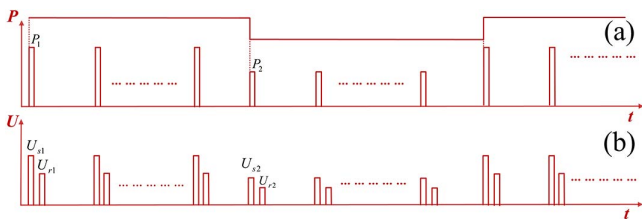


Fig. 4. (a) Output power of the light source after modulation. (b) Output voltage of the photodetector.

lower than 5%. In addition, all the other optical fibers used in the system were bend-insensitive fibers (YOFC TZ01141CE01), so that the influence of bending and vibration on the light intensity can be eliminated. A ~ 500 nm ZnTe-coated optical fiber tip was fabricated under the magnetron sputter coating process and was fixed in a temperature control chamber. Through LabVIEW programming, periodic instruments could be input into the pulsed light source, so the periodic modulation was achieved. Considering the drift rate of the dark current is a very slow variable, the low-frequency square wave modulation frequency was set to be 1 Hz.

The temperature is controlled by the temperature chamber. When the temperature decreased from 60°C to -30°C , we recorded the reflectivity with an interval of 5°C. To test its repeatability, the temperature returned to 60°C after reaching -30°C . In order to demonstrate the modification effect, we recorded the testing results of reflectivity with conventional PR compensation technique ($S = \frac{U_s}{U_r}$) and modified PR compensation technique ($S^* = \frac{U_{s1} - U_{s2}}{U_{r1} - U_{r2}}$), respectively, as is shown in Fig. 5.

It can be seen from Fig. 5 that the hysteresis could be largely improved with low-frequency square wave modulation. For the testing results of reflectivity with the modified PR compensation technique, the slope is measured to be

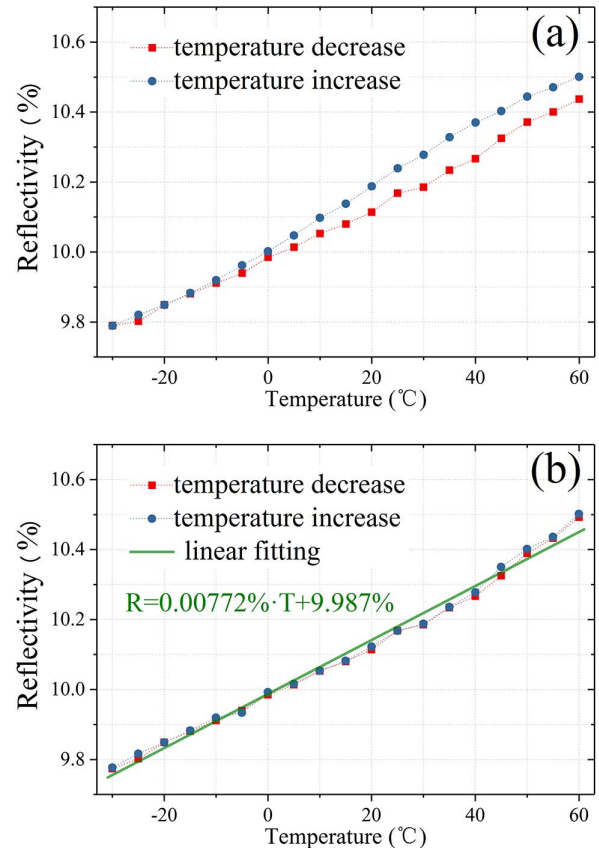


Fig. 5. Testing results of reflectivity under different temperatures (a) with the conventional PR compensation technique and (b) with the modified PR compensation technique.

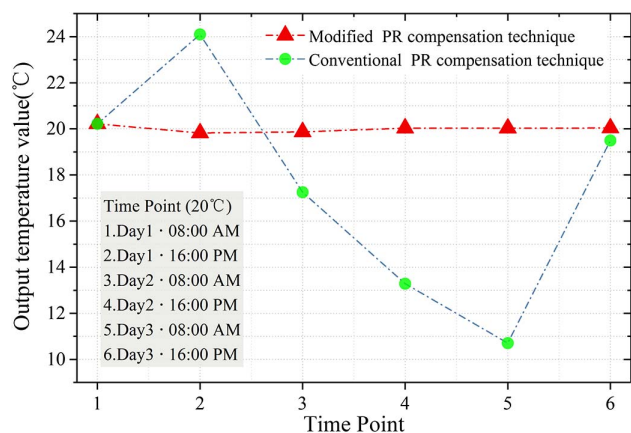


Fig. 6. Output temperature values at different time points at 20°C with the conventional PR compensation technique and the modified PR compensation technique.

0.0077%/°C ($R = 0.00772\% \cdot T + 9.987\%$), according to linear fitting, with its R-square value better than 0.99. If we choose the reflectivity at -30°C as a benchmark, the temperature sensitivity of this temperature sensor can achieve 0.0034 dB/°C. The system noise is measured to be 0.0005 dB at any constant temperature, which is much lower than that of conventional intensity-modulated optical fiber sensing systems, so the resolution can achieve 0.2°C. The experimental result of the temperature sensitivity basically agrees with the theoretical sensitivity above when the thickness is set to be 500 nm.

As a temperature sensor, the stability and repeatability of the response to the same temperature at different points in time are very important, especially in the practical temperature sensing field. The temperature in the temperature chamber was set at a constant 20°C, and we recorded the actual output values of the sensor at different time points with the conventional PR compensation technique and the modified PR compensation technique, respectively. The corresponding output temperature values were calculated according to the previously obtained relation $R = 0.00772\% \cdot T + 9.987\%$, as is shown in Fig. 6.

The maximum difference of the output temperature values with the modified PR compensation technique is 0.39°C, which is much smaller than that with the conventional PR compensation technique (13.39°C).

The results of this study suggest that the modified PR compensation technique can detect the minor changes of the sensor head because of the low system noise level it provides, and the sensor based on a ZnTe film-coated fiber tip using this modified compensation technique shows advantages of ultra-miniature size, low cost, and high stability, as well as good repeatability. In the meantime, this kind of fiber tip coated with thin film shows its batch fabrication capability because a large number of sensor heads with the same thin film thickness can be obtained through the one time coating process. Therefore, this sensor can be used as a promising temperature sensing device in practical application fields. Further work can be carried out to

explore more appropriate coating materials or apply this compensation technique in wider intensity-modulated sensing fields.

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