Optical fiber temperature sensor using a thin film band pass filter and dual wavelength push-pull reflectometry

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ABSTRACT

This experimental temperature sensing system uses dual wavelength push-pull reflectometry and a thin-film band pass filter deposited on an optical fiber end face. The system presents advantages over fiber Bragg grating sensors: it can use the mature optical time domain reflectometry (OTDR) technology instead of expensive wavelength-selective technology; it can probe the temperature in a small spot area; and it can be free from influences of disturbances along the optical fiber or within the measuring system. Moreover, it preserves merits of optical fibers such as low transmission loss and immunity to electromagnetic noise. The presented system has measurement accuracy of better than ±0.5°C.

Keywords: Optical fiber measurement, Optical filters, Pseudo noise coding, Correlators, Reflectometry, Temperature measurement

1. INTRODUCTION

For remote sensing of temperature, the fiber Bragg grating (FBG) sensor based on wavelength-selective technique is widely used to take advantage of optical fibers, which have very low transmission loss, immunity to electromagnetic noise, and which require no electric wiring. However, the wavelength-selective technique used in devices such as optical spectrum analyzers is expensive. Furthermore, because the FBG is incorporated in an optical fiber and has a length of 4–20 mm, it has difficulty in probing a temperature in a small volume, which is very often necessary in practical applications. We have proposed a new temperature sensing system which uses an optical band-pass filter (BPF) on an optical fiber end (BOF: BPF on the fiber end)\(^2\). The temperature is obtained by measuring the temperature dependence of the BPF’s center wavelength. This new sensor has a small sensing area that is limited to the end of an optical fiber. For that reason, it can probe temperatures in small localized areas, and is suitable for numerous practical applications. This sensing system can measure a center wavelength with good accuracy and with low cost. We apply a well-known correlation OTDR method\(^3\) to dual wavelength ratiometry\(^2\). This enables simultaneous measurement at many points along the optical fiber. The center wavelength can be determined by taking the ratio of reflectance from the BOF with respect to the dual wavelengths on both sides of the center wavelength, where the gradient of the reflectance for each wavelength is opposite. This ratiometric measurement eliminates the influence of disturbances such as an inadequate connection or fiber bending.

We present experimental results related to the new sensing system. The principle of the measurements is described briefly in section 2. Fabrication and characterization of the BOF sensor probe is explained in section 3. The sensing system structure and measurement results are presented in section 4. Finally, we summarize them in section 5.

2. PRINCIPLE

Figure 1(a) shows a reflectance spectrum of the BOF schematically. The horizontal axis shows the wavelength. The reflectance is measured at dual wavelengths \(\lambda_1\) and \(\lambda_2\), each of which is located on a side of the center wavelength \(\lambda_0\). When the reflectance spectrum of the BOF changes to longer wavelength according to the ambient temperature, as portrayed in Fig. 1(a), the reflectance at \(\lambda_1\) and \(\lambda_2\) varies in a complementary push-pull manner. Consequently, we can calculate the spectrum shift by taking the reflectance ratio of \(\lambda_1\) to \(\lambda_2\); we can then derive the temperature change from the reflectance ratio.

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Our objective is to measure temperatures at several points distributed along an optical fiber using BOFs under identical specifications. Figure 1(b) depicts the measurement system configuration. We use dual-wavelength pseudorandom noise-code reflectometry (DW-PNCR), in which a similar method to correlation OTDR is applied to two different wavelengths for measuring the temperature separately at each BOF. The system consists of a platform and a sensor network. The platform comprises a PN generator, two distributed feedback laser diodes (DFB-LDs) and their drivers with temperature stabilizers, a fiber coupler, a photodiode (PD) connecting to an amplifier, and a correlator. A generated pseudorandom noise (PN) signal flows into the LD drivers. The non-inverted signal drives the LD of wavelength $\lambda_1$; the inverted signal drives the other LD of wavelength $\lambda_2$. The optical signal combined within the fiber coupler consists of dual wavelengths $\lambda_1$ and $\lambda_2$, which mutually alternate according to the PN code. This signal is launched into the sensor network; it travels through the trunk fiber and separates into sensor branches at a number of couplers. Each branch has a BOF sensor at its end. When a combined signal reaches a BOF sensor, $\lambda_1$ and $\lambda_2$ are reflected subject to their reflectance. The reflected signal of each wavelength has different intensity if the respective reflectances of the two wavelengths differ. The converted electrical signal retrieves the original PN signal according to the difference in intensity when the reflected signal, after traveling back through the trunk fiber and couplers, reaches the PD. The reflectance difference and the distance to the BOF from the platform can be determined simultaneously using the correlation between the received signal and the original signal. Consequently, we can compute the variation of the temperature separately at the end of each sensor branch.

3. FABRICATION AND CHARACTERIZATION OF THE BOF SENSOR PROBE

The BOF was produced on the end face of the optical fiber that is maintained in a quartz ferrule. The optical band pass filter was a dual-cavity Fabry-Perot type with two TiO$_2$ cavities and four pairs of TiO$_2$/SiO$_2$ reflective layers on both sides of the cavities. Each layer was deposited using ion-assisted evaporation to render it sufficiently dense and to prevent the influence of moisture. Figure 2(a) shows a sample of the optical fiber supported in the ferrule, which has a band-pass filter on its end face. Figure 2(b) shows the BPF layer structure. The sample was polished at a 45° angle and observed using an optical microscope. We inserted the ferrule and the tailing fiber into a metal tube, and the remaining fiber into a plastic tube to fabricate a sensor probe, as shown in Fig. 2(c).
We measured the temperature dependence of the center wavelength $\lambda_0$ of BOF. The measurement system consisted of an ASE light source, a return loss module, an optical spectrum analyzer, and a thermostatic chamber. The temperature was varied from -20–50°C. Figure 3(a) depicts the temperature dependence of the reflectance spectrum of the BOF. The temperature dependence of $\lambda_0$, which is obtained as the center of the 3 dB points above the minimum reflectance, is about 14 pm/°C, as shown in Fig. 3(b). Reportedly, the temperature coefficient of the center wavelength of the TiO$_2$/SiO$_2$ BPF with TiO$_2$ cavity deposited on a quartz substrate is about 16 pm/°C, which is a slightly larger value than our 14 pm/°C. The temperature coefficient of the center wavelength is strongly affected by the difference in the linear expansion between the film and the substrate. The difference in the number of layers between our sample and the number used in that previous study might explain the difference in the temperature coefficient.

![Graph](image)

Fig. 3: Measured data of BOF sensor probe. (a) Temperature variation of the reflectance spectrum, (b) Temperature dependence of the center frequency of the BPF.

### 4. EXPERIMENTAL SYSTEM AND ITS PERFORMANCE

Our experimental system had the platform of the same configuration as portrayed in Fig. 1 (b). The sensor network consisted of a 1000-m single-mode trunk fiber having a single sensor branch, which connects to the sensor probe as shown in Fig. 2(c). The trunk fiber was terminated at the end. The respective wavelengths $\lambda_1$ and $\lambda_2$ of the DFB-LDs were 1529 nm and 1541 nm. The optical output power of each LD was -6 dBm. The chip rate and the code length of the PN code were, respectively, 6.25 Mcps (megachips per second) and $2^{21}-1$.

We dipped the probe head in temperature-stabilized water and obtained the reflectance ratio from the correlator output while changing the temperature of the water. Figure 4(a) shows an example of a correlator output. A peak at the distance of 1000 m corresponds to the reflection from the BOF in the probe. Figure 4(b) presents the temperature dependence of the reflectance ratio, which is equal to the difference of the peak levels corresponding to $\lambda_1$ and $\lambda_2$. The reflectance ratio changes linearly with temperature, as understood from the solid regression line. For that reason, the temperature is obtainable from the reflectance ratio using this relation.

![Graph](image)

Fig. 4: Temperature measurement using our experimental system. (a) Correlator output example, (b) Temperature dependence of the reflection ratio.
Figure 5 presents a comparison between the temperature variation measured using our system and that measured using a thermocouple. We dipped both the BOF sensor probe and the thermocouple in hot water simultaneously and then left them to cool for 2.5 h. The result shows very good agreement between them: the temperature difference is within ±0.5°C.

![Figure 5](image_url)

**Fig. 5: Temperature measurement result compared to that measured using a thermocouple**

5. SUMMARY

A new system using BOF and two-wavelength ratiometry was presented. Results of this study reveal the feasibility of temperature sensing with accuracy better than ±0.5°C. A new sensor using BOF can probe the temperature in a small spot and is suitable for many practical applications. The DW-PNCR method, which is a modification of the mature correlation OTDR technology, enables simultaneous measurements using multiplexed BOFs. Ratiometric measurement of DW-PNCR eliminates the influence of disturbances such as insufficient connection or fiber bending. Furthermore, DW-PNCR method has several advantages over systems using FBGs: it has a high dynamic range because of its correlation method; when the system supports numerous sensor branches, these branches can be connected and disconnected easily because of the bus topology.

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