Pulse reference-based compensation technique for intensity-modulated optical fiber sensors

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We propose a compensation technique based on pulse reference for intensity-modulated optical fiber sensors that can compensate the power fluctuation of the light source, the change of optical components transmission loss, and the coupler splitting ratio. The theoretical principle of this compensation technique is analyzed and a temperature sensor based on fiber coating-covered optical microfiber is carried out to demonstrate the compensation effect. The system noise is measured to be 0.0005 dB with the temperature sensitivity reaching -0.063 dB/°C, and the output drift is 0.006 dB in 2 h at room temperature. The output shows a slight variation (0.0061 dB) when the light source and the common light path suffer a 3 dB attenuation fluctuation.

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Intensity-modulated optical fiber sensors (IM-OFSs) are one of the most important and earliest developed OFSs for their simplicity, using inexpensive light sources, and potential low cost. In past decades, IM-OFS have been well studied to detect several types of physical quantities such as displacement[1], temperature[2,3], bending[4], strain[5], magnetic field intensity[6], and others[7,8]. However, owing to directly using optical intensity as the information carrier, IM-OFSs have the problem that the output might be affected by the fluctuation of the light source, the change of optical components transmission loss, and the coupler splitting ratio, as well as other factors with time and external perturbations. Many compensation techniques were proposed to solve this problem: the light source negative-feedback compensation technique[9], the light split compensation technique[3,10], the twin-receiving-fiber compensation technique[11], the dual-wavelength compensate technique[12], the network-based compensation technique[13], and the neural-network compensation technique[14]. The performances of the IM-OFSs were improved[15–19] but there still exist some unavoidable problems for the compensation techniques mentioned above. For example, though the light split compensation technique can compensate the fluctuation of the light source, it cannot solve the splitting ratio fluctuation caused by the optical splitter itself. The network-based compensation technique can avoid the splitting ratio fluctuation problem, but it introduces more optical components transmission loss fluctuation problems.

In this Letter, we propose a compensation technique based on pulse reference. This compensation technique can compensate the power fluctuation of the light source, the change of optical components transmission loss, and the coupler splitting ratio, while at the same time keeping the structure simple and the design flexible for a wide application range. Another advantage of this compensation technique is that it is completely compatible with optical time division multiplexing system, which can integrate a large number of sensors and decrease the cost of per sensor. After the explanation of this technique, an optical microfiber temperature sensor was carried out to demonstrate the good compensation effect of this technique.

The schematic diagram of the pulse reference-based compensation technique is shown in Fig. 1. A light pulse emitted by the light source is divided into two light pulses (signal pulse and reference pulse) by the 2×2 fiber optic coupler. These two pulses will both come back again to the coupler after being transmitted and reflected by their respective fiber and reflector. Then the detector will receive two pulses and transform them into electrical signals. The signal processing unit is responsible for converting them into digital signals and analyzing these signals.

The time delay Δt between the signal pulse and reference pulse depends on the relative length of the sensing fiber and delay fiber. For the purpose of distinguishing these two pulses in the time domain, Δt is supposed to
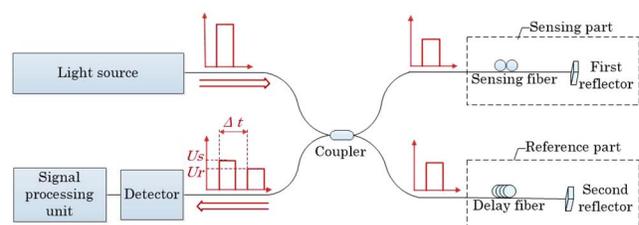

Fig. 1. Schematic diagram of the pulse reference-based compensation technique.

be much longer than the laser pulse width. The output voltage of the signal pulse U_s and the reference pulse U_r can be expressed as

$$U_s = RI_0\alpha_0(1 - C)\alpha_s r_s \alpha_s C, \tag{1}$$

$$U_r = RI_0\alpha_0 C\alpha_r r_r \alpha_r(1 - C). \tag{2}$$

Here, R is the responsibility of the detector; I_0 is the initial light intensity; α_0, α_s, α_r are the transmittance of the common optical path, sensing fiber, and reference fiber; 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.

We define a measurement parameter, relative loss (RL) of the sensing part, from Eqs. (1) and (2) as follows:

$$\mathrm{RL} = -10 \cdot \log\left(\frac{U_s}{U_r}\right) = -10 \cdot \log\left(\frac{r_s\alpha_s^2}{r_r\alpha_r^2}\right). \tag{3}$$

It is obvious that RL is unrelated to the initial light pulse intensity I_0, the coupling ratio C, the transmittance of the common optical path α_0, and the photodetector responsibility R. That means, theoretically, RL will not be influenced by those parameters' fluctuation.

So, if we keep α_r and r_r stable and design α_s or r_s sensitive to a certain physical quantity (temperature, displacement, refractive index, salinity, etc.), we can use this system to detect it.

To demonstrate the effect of the pulse reference-based compensation technique, a temperature-sensing experiment based on a fiber coating-covered optical microfiber was carriedout with this techniqueout, as shown in Fig. 2.

A 1.55 μm wavelength semiconductor pulsed laser (Connet, Pulsed Fiber Laser Source, VSLC-1559-M-P) with 250 ns pulse width and 10 kHz repeat frequency was used as the light source. The laser line width is about 40 nm. The relative length between the sensing fiber and the delay fiber was set to be 60 m, providing a 600 ns time delay. Two Faraday rotating mirrors (FRMs) were used as reflectors. The sensing head, which was fabricated

utilizing an optical microfiber covered by a fiber coating, was placed in a temperature chamber. The pulses were detected by the photodetector (New Focus, Model 2053) with an 80 MHz bandwidth. The amplitudes of the signal pulses and reference pulses were converted into digital data by data acquisition card NI PXIe-5122 with a 100M sample rate. All data was dealt by LabVIEW software in a computer to get the average voltage value of each pulse for further calculation.

The sensing optical microfiber used in this experiment was drawn from a conventional single-mode fiber (SMF) with the modified flame-brush method[20]. The diameter of the drawn optical microfiber is ∼2 μm, as its microscope photograph shows in Fig. 3(a). The fiber coating fabricated by The Chinese North Coating Research Center is a good material for the encapsulation of optical microfiber, with its refractive index reaching 1.42. Ultraviolet light was used to cure the fiber coating after the optical microfiber was embedded into it. A photograph of the optical microfiber covered by a fiber coating is shown in Fig. 3(b).

Because of the optical microfiber's excellent optical properties, such as large evanescent field, compact size, and low loss, it can be utilized as a good alternative material for sensing. When light passes through the optical microfiber, there is a large fraction of power propagating outside the optical microfiber as an evanescent field that makes it very sensitive to the change of external physical quantities[21]. The absorption coefficient of the fiber coating changes accordingly when the external temperature changes, altering the transmittance of the fiber coating-covered optical microfiber in the meantime[3]. In this experiment, α_r, r_s, and r_r remain relatively stable due to the usage of temperature insensitive optical fiber and FRM.

For convenience we choose a specific RL_0 as a benchmark and just observe the variation of RL of sensing part as

$$\delta_{\mathrm{RL}} = \mathrm{RL} - \mathrm{RL}_0. \tag{4}$$

The external temperature of the sensing head was controlled by the temperature chamber. The RL decreases from −0.54 dB at 10°C to −3.69 dB at 60°C throughout the experiment. The RL value at 10°C is chosen to be the benchmark RL_0. So, according to Eq. (4), we obtain δ_{RL} in different temperatures, as shown in Fig. 4. δ_{RL} and temperature show an approximate linear
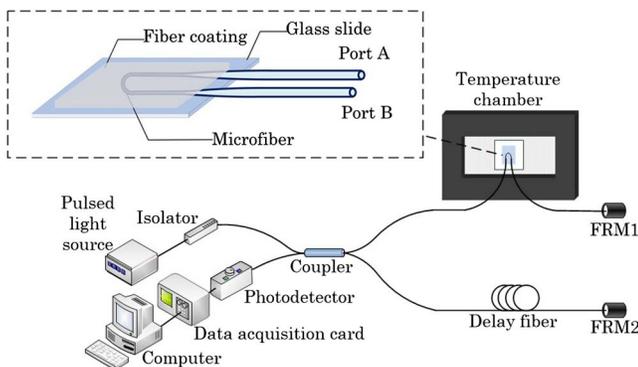

Fig. 2. Schematic diagram of the temperature OFS based on the fiber coating-covered optical microfiber with the pulse reference-based compensation technique.

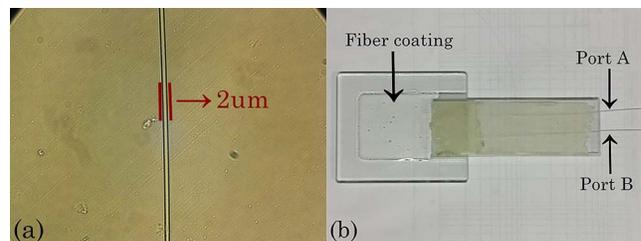Fig. 3 (a) The microscope photograph of the drawn optical microfiber. (b) The photograph of the optical microfiber covered by fiber coating

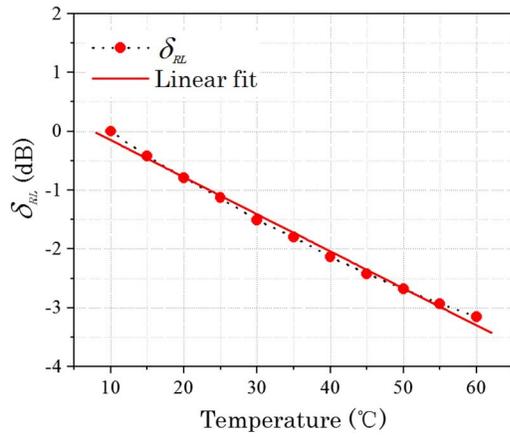Fig. 4. δ_{RL} versus temperature.

Fig. 6. Output drift of δ_{RL} in 2 h at room temperature, about 25℃.

relationship and the temperature sensitivity is −0.063 dB/°C, with its R-squared value better than 0.99, according to linear fitting. The system noise is measured to be 0.0005 dB in a short time at any constant temperature, as an example in 25°C is shown in Fig. 5.

The system noise is much lower than that of conventional IM-OFSs[3,21–24], and also allows the minimum detectable temperature variation to reach 0.008°C for this temperature sensor.

Long-term stability is also a key index for a temperature sensor. The δ_{RL} variation was monitored for 2 h at room temperature, about 25°C. As shown in Fig. 6, the output drift of δ_{RL} is measured to be only 0.006 dB.

To evaluate the influence of the fluctuation of the light source and the change of optical components transmission loss and coupler loss, an attenuator was inserted between the isolator and the fiber optic coupler to simulate those influences at room temperature. By setting the attenuator, the light intensity of the incident pulse decreased by 1 dB per minute until the loss reached 3 dB and then gradually returned to its original value in the next few minutes. We detected δ_{RL} and output voltages of signal pulse and reference pulse in real time. As is shown in Fig. 7, δ_{RL} keeps constant with about a 0.0061 dB change when
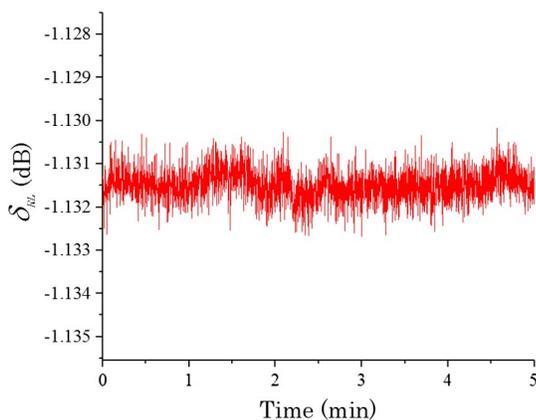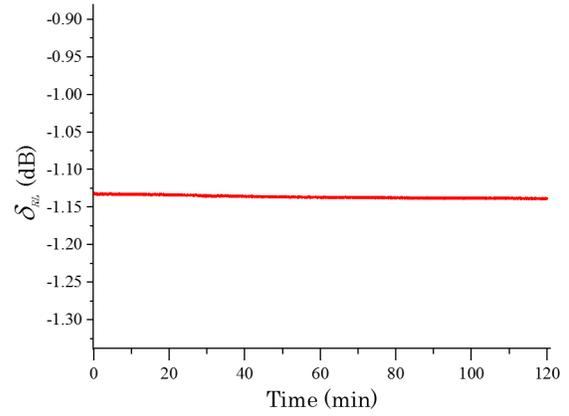
3 dB attenuation is set by the attenuator, which is quite small. The variation might result from the existence of bias, which leads to the difference between the measured values and theoretical values of U_s and U_r. But this result can still demonstrate the good effect of our compensation technique.

In conclusion, a compensation technique for IM-OFSs based on pulse reference is proposed in this Letter. A temperature sensing experiment using fiber coating-covered optical microfiber was designed and carried out to demonstrate the compensation effect. With this compensation technique, the system noise is only 0.0005 dB, much lower than that of conventional IM-OFSs. The sensitivity of the temperature sensor is −0.063 dB/°C with its resolution reaching 0.008°C. The output changes slightly by 0.0061 dB when the attenuation of the light source and common light pulse reach 3 dB and the output drift is only 0.006 dB in two hours at room temperature, demonstrating the good compensation effect and long-term stability of this system.

The further improvement on this compensation effect can be done in terms of the polarization state, the laser line width, and the bias problem. The compensation technique also shows its potential in time division multiplexing and quasi-distributed sensing in the case of a
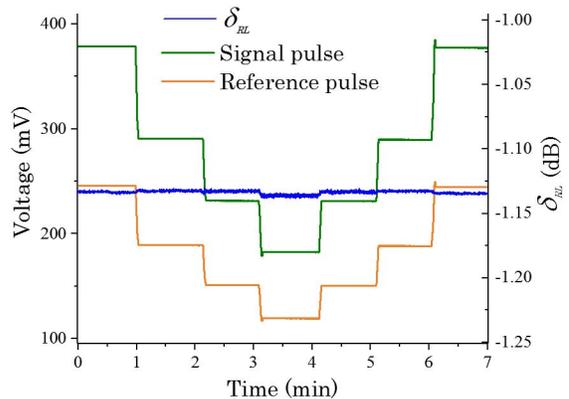

Fig. 5. Fluctuation of δ_{RL} in 5 min at 25℃.

Fig. 7. (Color online) Fluctuation of δ_{RL} output in different attenuations.

suitable lightpath design. Our follow-up work will be carried out in these aspects.

References

1. B. Dong and E. J. Hao, J. Opt. Soc. Am. B **28**, 2332 (2011).
2. R. M. Silva, J. M. Baptista, J. L. Santos, A. B. Lobo Ribeiro, F. M. Araújo, A. L. Ferreira, and O. Frazão, Opt. Commun. **291**, 215 (2013).
3. Z. Wei, Z. Song, X. Zhang, Y. Yu, and Z. Meng, Chin. Opt. Lett. **11**, 110602 (2013).
4. M. A. Zawawi, S. O'Keeffe, and E. Lewis, Sensors **13**, 14466 (2013).
5. M. Moscato, E. Schena, P. Saccomandi, M. Francomano, D. Accoto, E. Guglielmelli, and S. Silvestri, in *IEEE Engineering in Medicine and Biology Society* (2012), p. 5790.
6. J. Zheng, X. Dong, P. Zu, and J. Ji, Appl. Phys. Lett. **103**, 090601 (2013).
7. W. Dong, J. Wei, X. Wang, Z. Kang, and X. Xu, Chin. Opt. Lett. **12**, 6 (2014).
8. H. Zhang, L. Feng, Y. Hou, S. Su, J. Liu, W. Liu, J. Liu, and J. Xiong, Chin. Opt. Lett. **13**, 080601 (2015).
9. H. Yang, L. Haibao, T. Xu, and W. Luo, Laser Technol. **26**, 453 (2002).
10. H. Yang, L. Haibao, T. Xu, and W. Luo, in *Instrument Technique and Sensor* (2001).
11. L. Yuan, J. Pan, T. Yang, and G. Han, Sens. Actuators A **36**, 177 (1993).
12. G. Murtaza and J. M. Senior, Opt. Commun. **120**, 348 (1995).
13. X. Jin and Y. Liao, Acta Opt. Sin. **16**, 1002 (1996).
14. X. Wang, Acta Opt. Sin. **22**, 215 (2002).
15. Y. Guo and Y. Wang, J. Phys. Conf. Ser. **48**, 892 (2006).
16. C. Li, X. Zhang, and P. Zhang, in *International Conference on Mechatronics and Automation (ICMA)* (2011), p. 1861.
17. A. Vallan, M. L. Casalicchio, M. Olivero, and G. Perrone, IEEE Trans. Instrum. Meas. **61**, 1377 (2012).
18. Y. Guo, Y. Wang, and M. Jin, Optik **125**, 126 (2014).
19. G. Brambilla, J. Opt. **12**, 043001 (2010).
20. J. Lou, Y. Wang, and L. Tong, Sensors **14**, 5823 (2014).
21. B. Dong and E. Ha, J. Opt. Soc. Am. B **28**, 2332 (2011).
22. X. Dong, L. Shao, H. Fu, H. Tam, and C. Lu, Opt. Lett. **33**, 482 (2008).
23. S. Abad, F. M. Araújo, L. A. Ferreira, J. L. Santos, and M. Lópezamo, Appl. Opt. **42**, 5040 (2003).
24. J. Zhou, Y. Wang, C. Liao, G. Yin, H. Jun, and S. Bing, in *Asia Communications and Photonics Conference* (2014).