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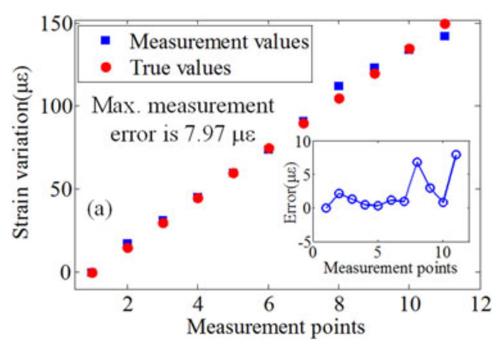

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Distributed Strain and Temperature Discrimination Using Two Types of Fiber in OFDR

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Abstract: We present a simple and effective method to achieve a distributed strain and temperature discrimination using two types of fiber by a Rayleigh backscattering spectra (RBS) shifts in optical frequency domain reflectometry. We paired two types of single mode fiber (SMF) side by side as the sensing fibers. One is the reduced-cladding (RC) SMF, and the other is the standard SMF. Since the RC SMF and the standard SMF have different sensitivity responses to strain and temperature variation, we can measure strain and temperature variation simultaneously by monitoring RBS shifts. We demonstrate that the measure errors are 0.31 °C in temperature and 7.97 $\mu\varepsilon$ in strain with a measurement range of 50 m and a spatial resolution of 18 cm.

Index Terms: Fiber optics systems, sensor, scattering, tunable lasers.

1. Introduction

Distributed fiber optical sensors (DOFS) have an ability to measure temperature and strain at thousands of points along a fiber, which is extremely useful for health monitoring in industrial infrastructure, aerospace, architectural structure, and so on. Several DFOS techniques have been developed based on the measurement of intrinsic backscattering of fibers, which include techniques based on Raman [1], [2], Brillouin [3]–[5], and Rayleigh backscattering [6], [7].

Among them, Froggatt *et al.* [6], [8] present a method using the Rayleigh backscattering spectra (RBS) shifts in optical frequency domain reflectometry (OFDR) to achieve distributed strain and temperature measurements with a high sensitivity and a high spatial resolution. Rayleigh backscattering is caused by random refractive index fluctuations along a single mode fiber (SMF), and it can be modeled as a long, weak FBG with random periods. The strain or temperature variation causes a local RBS shifts, which can be calculated from the cross-correlation between the measurement RBS and the reference RBS.

However, one of the most significant limitations of this RBS shifts based method is that it has the sensitivity to both temperature and strain. Undesirable temperature sensitivity of RBS shifts may complicate its application as strain gauges. On a single measurement of RBS shifts, it is impossible to differentiate between the effects of changes in strain and temperature. The ability to distinguish between strain and temperature measurements is a critical issue to the RBS shifts based method. To achieve strain and temperature discrimination using the RBS shifts in OFDR, some attempts have been made for this purpose. Froggatt *et al.* [9], [10] use a polarization maintaining fiber (PMF) to sense strain and temperature variation simultaneously by autocorrelation and cross-correlation of RBS shifts. However, the strain sensitivity response of using the autocorrelation RBS shifts is 111 times less than that of using the cross-correlation. The temperature sensitivity response of using the autocorrelation RBS shifts is 40 times less than that of using the cross-correlation [11], which will have a serious impact on the performance of this method comparing with only using the cross-correlation RBS shifts. In addition, Zhou *et al.* [12] combine Brillouin optical time-domain analysis (B-OTDA) and OFDR to distinguish between strain and temperature. However, this method is so expensive and complex that two complicated systems need to be implemented.

In this paper, we present a simple and effective method to achieve distributed strain and temperature discrimination using two types of fiber by RBS shifts in OFDR. We paired two types of SMF side by side as the sensing fibers. One is the reduced-cladding (RC) SMF that is a normal fiber with a smaller outer diameter, and the other is the standard SMF. The OFDR system measures RBS shifts in two types of SMF simultaneously. Since the RC SMF and the standard SMF have different sensitivity responses to strain and temperature variation, we can measure strain and temperature variation simultaneously by monitoring the RBS shifts. More importantly, the sensitivity responses to strain and temperature of using the RC SMF are higher than those of using the standard SMF, and therefore, the maximum errors of strain and temperature in theory using our presented method are not deteriorated obviously comparing with the single parameter (strain or temperature) measurement by only using a standard SMF as the sensing fiber. In the experiment, a measurement range of 50 m and a spatial resolution of 18 cm are demonstrated with errors of 0.31 °C in temperature and 7.97 $\mu\varepsilon$ in strain.

2. Principle

OFDR allows the measurement of a reflectivity pattern, such as Rayleigh backscattering along a segment of fiber. The Rayleigh backscattering is caused by defects that induce a local variation in the index, and it can be modeled as a long, weak FBG with random periods. The temperature or strain variation causes shifts in the local RBS. The processes to obtain the local RBS shifts have been described in [6]. We provide just a brief introduction here. The optical frequency information detected by an OFDR is converted to the spatial information by FFT. The sliding window is used to separate the total fiber to the local segments. The width of the sliding window ΔX is the sensing spatial resolution (SSR). Each segment ΔX is converted to the optical frequency domain by an inverse FFT, namely, the local RBS. By the cross-correlation between the measurement RBS (loading strain and temperature) and the reference RBS (no extra strain and temperature), the local RBS shifts $\Delta\upsilon$ can be obtained. Then, $\Delta\upsilon$ caused by the strain variation $\Delta\varepsilon$ and temperature variation ΔT are given by

$$\Delta\upsilon = K_S\Delta\varepsilon + K_T\Delta T \tag{1}$$

where K_S and K_T are the sensitivity responses to strain and temperature variation, respectively. From (1), $\Delta\upsilon$ is caused by a combination of strain and temperature, which assumes that the strain and thermal responses are essentially independent. When the strain and temperature vary at the same time, we cannot obtain $\Delta\varepsilon$ and ΔT by only a single measurement of $\Delta\upsilon$.

A method for the simultaneous, independent measurement of temperature and strain by using FBG is proposed and demonstrated [13], [14]. FBGs of different diameter show similar temperature sensitivities but different strain responses to an applied stress. As Rayleigh backscattering can be modeled as a long weak FBG with random periods, the RBS shifts based method will have this property in theory. We will experimentally verify that this property above.

Assuming that K_{S1} and K_{T1} are the sensitivity responses to strain and temperature variations of using a standard SMF and that K_{S2} and K_{T2} are that of using a RC SMF and that $\Delta\upsilon_1$ and $\Delta\upsilon_2$ are the RBS shifts of a standard SMF and a RC SMF, the following relation holds:

$$\begin{bmatrix}\Delta\upsilon_1\\ \Delta\upsilon_2\end{bmatrix} = \begin{bmatrix}K_{S1} & K_{T1}\\ K_{S2} & K_{T2}\end{bmatrix}\begin{bmatrix}\Delta\varepsilon\\ \Delta T\end{bmatrix}. \quad (2)$$

Thus the variation of temperature and strain can be calculated by using (2) and taking a reverse matrix operation:

$$\begin{bmatrix}\Delta\varepsilon\\ \Delta T\end{bmatrix} = \frac{1}{K_{S1}K_{T2}-K_{T1}K_{S2}}\begin{bmatrix}K_{T2} & -K_{T1}\\ -K_{S2} & K_{S1}\end{bmatrix}\begin{bmatrix}\Delta\upsilon_1\\ \Delta\upsilon_2\end{bmatrix} \quad (3)$$

and thus

$$\Delta\varepsilon = \frac{K_{T2}\Delta\upsilon_1 - K_{T1}\Delta\upsilon_2}{K_{S1}K_{T2}-K_{T1}K_{S2}} \quad (4)$$

$$\Delta T = \frac{K_{S1}\Delta\upsilon_2 - K_{S2}\Delta\upsilon_1}{K_{S1}K_{T2}-K_{T1}K_{S2}}. \quad (5)$$

The strain and temperature measurement errors of this method are determined by the condition of the mapping matrix in (3) and the maximum errors $\delta\varepsilon$ and δT could be estimated conveniently by [15], [16]

$$|\delta\varepsilon| = \frac{|K_{T2}|\,|\delta\upsilon_1| + |K_{T1}|\,|\delta\upsilon_2|}{|K_{S1}K_{T2}-K_{T1}K_{S2}|} \quad (6)$$

$$|\delta T| = \frac{|K_{S1}|\,|\delta\upsilon_2| + |K_{S2}|\,|\delta\upsilon_1|}{|K_{S1}K_{T2}-K_{T1}K_{S2}|} \quad (7)$$

where $\delta\upsilon_1$ and $\delta\upsilon_1$ are the RBS shifts measurement errors of using the standard SMF and RC SMF, respectively.

From (6) and (7), the maximum measurement errors $\delta\upsilon_1$ and $\delta\upsilon_2$ will be transferred to $\delta\varepsilon$ and δT. In this method, OFDR system measure the RBS shift directly not strain or temperature. The RBS shifts of standard SMF and RC SMF are measured by the same OFDR system and method. The maximum measurement errors of RBS shift come from the measurement system and method, so $\delta\upsilon_1$ and $\delta\upsilon_1$ will be the same as $\delta\upsilon(\delta\upsilon_1 = \delta\upsilon_2 = \delta\upsilon)$. Equations (6) and (7) can be simplified as:

$$|\delta\varepsilon| = \frac{|K_{T2}| + |K_{T1}|}{|K_{S1}K_{T2}-K_{T1}K_{S2}|}\,|\delta\upsilon| \quad (8)$$

$$|\delta T| = \frac{|K_{S1}| + |K_{S2}|}{|K_{S1}K_{T2}-K_{T1}K_{S2}|}\,|\delta\upsilon|. \quad (9)$$

3. Experimental Results and Discussion

3.1. Setup

Our OFDR experimental setup for distributed strain sensing is shown in Fig. 1(a). A TLS (Agilent 81600B) is used as the light source for OFDR system. The tuning speed, tuning range, and starting wavelength of the TLS are 5×10^3 GHz/s (40 nm/s), 2.5×10^3 GHz (20 nm), and 1520 nm, respectively. The light from the laser is split into two paths by a 1: 99 coupler. The 1% light is sent to an auxiliary interferometer (a Michelson interferometer) with two Faraday rotating mirrors and a delay fiber of 300 m. The auxiliary interferometer provides an external clock (f-clock) to trigger the data acquisition card, which samples the interference signal at equidistant instantaneous optical frequency points to reduce the nonlinearity of the frequency tuning of the TLS [17]. The 99%

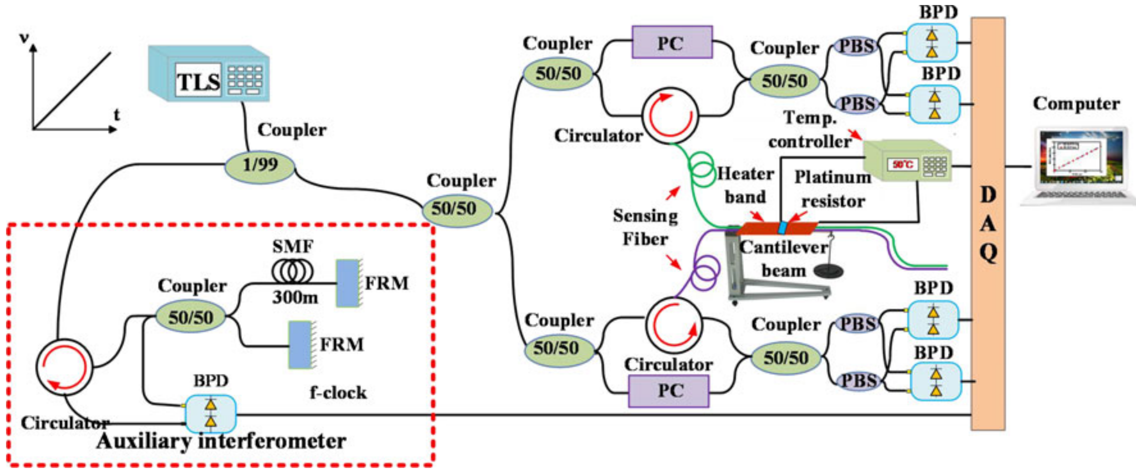

Fig. 1. Experimental setup for distributed strain and temperature sensing based on RBS shifts in OFDR. TLS: tunable laser source, FRM: Faraday rotating mirror; PC: polarization controller; BPD: balanced photo detector; DAQ: data acquisition card. The two types of sensing fiber standard SMF and RC SMF are adhered to the cantilever beam side by side closely. A heat band lays over the sensing fibers and heats them. The strain caused by the cantilever beam can be obtained from the applied weights. The temperature of the heat band can be obtained from the temperature controller and the platinum resistor.

light is sent to a 50/50 coupler that connects the two same Mach-Zehnder interferometers. The measurement arm of these two interferometers is composed of the two types of the sensing fiber: one is a standard SMF (YANGTZE inc., FullBand Plus Low Loss Single-mode Fiber, G.652.D), where the cladding diameter is 125 μm, and the coating diameter is 250 μm. The other is a RC SMF (YANGTZE inc., RC1017-F), which cladding diameter is 80 μm and the coating diameter is 165 μm. The length of the sensing fiber is about 50 m. The OFDR system can measure the RBS shifts of the standard SMF and RC SMF simultaneously. In the experiments, the two types of the sensing fibers are adhered to the cantilever beam side by side closely. A heater band is used to heat the sensing fibers and lays over them. As the strain caused by the cantilever beam can be obtained from the applied weight, we can calibrate the RBS shifts in the different strain values. A temperature controller and a platinum resistor could control the temperature of the heater band. We also can calibrate the RBS shifts in the different temperature values based on the measurement values of a platinum resistor. The location of the cantilever beam and heater band is about 34.4 m of the sensing fiber. In our OFDR system, the spatial resolution for one data point ΔZ is 0.004 cm based on$\Delta Z = c/2n\Delta F$, where n is the refractive index of fiber, c is the light speed in vacuum, and ΔF is the entire optical frequency tuning range of a tunable laser source (TLS) ($\Delta F = 2.5 \times 10^3$ GHz).

3.2. Calibration of Sensitivity Responses to Strain and Temperature Variation

To obtain the sensitivity responses to the strain and temperature variations of using a standard SMF and RC SMF, we calibrate the RBS shifts in two types of SMF in the different strain and temperature variations. In the comparison experiments of using the standard SMF and RC SMF, the sensing spatial resolution ΔX is 18 cm based on $\Delta X = N \times \Delta Z$ and $N = 4500$.

The calibration curves of RBS shifts by using the standard SMF vs. $\Delta\varepsilon$ and $\Delta T$are shown in Fig. 2(a) and (b). The range of $\Delta\varepsilon$ implemented by the cantilever beam is form 0 to 150 $\mu\varepsilon$ and the increasing interval of $\Delta\varepsilon$ is 15 $\mu\varepsilon$. The range of ΔT implemented by the heater band is from 0 to 12 °C and the increasing interval is about 1 °C. The temperature ranges from 52 °C to 64 °C. We fit linearly with the raw RBS shifts data induced by the evenly interval strain or temperature variation and obtain the slope of the linear fitting, namely, the sensitivity responses to strain or temperature variation. The sensitivity response to strain variation of using the standard SMF K_{S1} is

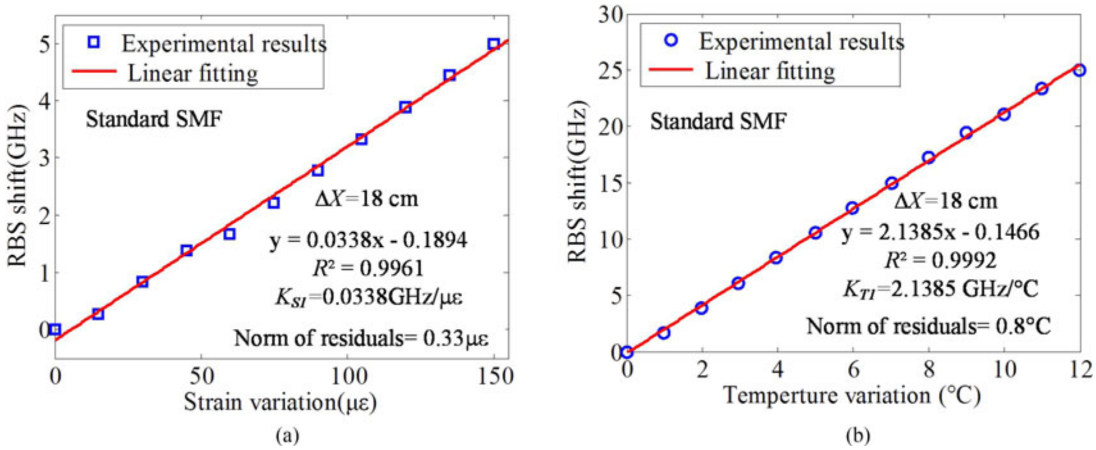

Fig. 2. Measured RBS shifts of the standard SMF at different strain variations (a) and temperature variations (b). The measurable strain range is form 0 to 150 $\mu\varepsilon$ and the interval is 15 $\mu\varepsilon$. The range of temperature variation is from 0 to 12 °C. The temperature ranges from 52 °C to 64 °C. The increasing interval is about 1 °C. The solid line is a linear fitting of the standard SMF data. The slope of the solid line is the sensitivity responses to the strain or temperature variation. $K_{S1} = 0.0338$ GHz/$\mu\varepsilon$, and $K_{T1} = 2.1385$ GHz/°C. The sensing spatial resolution is 18 cm.

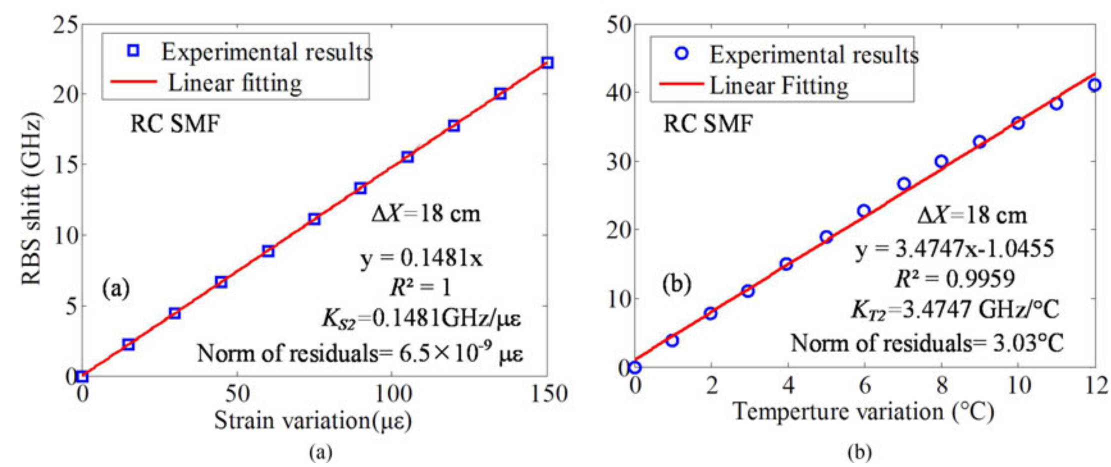

Fig. 3. Measured RBS shifts of the RC SMF at different strain variations (a) and temperature variations (b). The measurable strain range is form 0 to 150 $\mu\varepsilon$, and the interval is 15 $\mu\varepsilon$. The range of temperature variation is from 0 to 12 °C. The temperature is from 52 °C to 64 °C. The increasing interval is about 1 °C. The solid line is a linear fitting of the RC SMF data. The slope of the solid line is the sensitivity responses to strain or temperature variation. $K_{S2} = 0.1481$ GHz/$\mu\varepsilon$, and $K_{T2} = 3.4747$ GHz/°C. The sensing spatial resolution is 18 cm.

0.0338 GHz/$\mu\varepsilon$. The sensitivity response to temperature variation of using the standard SMF K_{T1} is 2.1385 GHz/°C.

The calibration curves of the RBS shifts by using the RC SMF vs. $\Delta\varepsilon$ and ΔT are shown in Fig. 3(a) and (b). The ranges of $\Delta\varepsilon$ and ΔT are the same as those of using the standard SMF. The sensitivity response to strain variation of using the RC SMF K_{S2} is 0.1481 GHz/$\mu\varepsilon$. The sensitivity response to the temperature variation of using the RC SMF K_{T2} is 3.4747 GHz/°C. From Figs. 2 and 3, the responses to strain and temperature variations of using the RC SMF are higher than those of using the standard SMF. In addition, as K_{S1}, K_{T1}, K_{S2} and K_{T2} satisfy with the relation of $K_{S1}K_{T2} - K_{T1}K_{S2} \neq 0$, we can use (4) and (5) to measure the strain and temperature variation simultaneously.

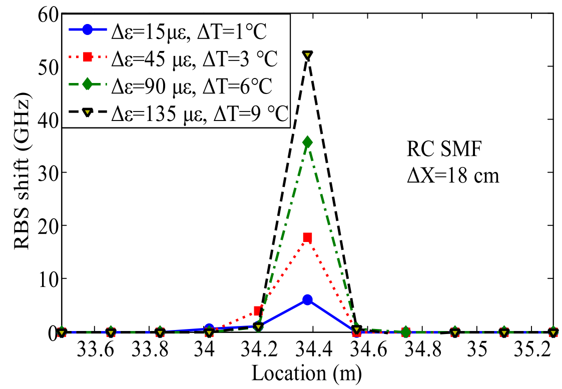

Fig. 4. Distributed RBS shifts from 34 m to 35 m using the RC SMF applied different strain and temperature variation simultaneously. The sensing spatial resolution is 18 cm.

3.3. Strain and Temperature Discrimination Using Two Types of Fibers

We apply strain and temperature variation to the standard SMF and RC SMF at the same time by using a cantilever beam and heater band. As the standard SMF and RC SMF are placed side by side closely, the strain and temperature applied to the two types of the sensing fibers are similar. Fig. 4 shows a graph of distributed RBS shifts locating from 34 m to 35 m using the RC SMF applied different strain and temperature simultaneously. This RBS shift is caused by both strain and temperature. We cannot distinguish that the contribution proportion of the strain and temperature to the RBS shifts by a single measurement in one type fiber. If we add the measurement of RBS shifts in the standard SMF, we can discriminate the strain and temperature simultaneously based on (4) and (5).

To demonstrate the ability to distinguish between the strain and temperature responses by using two types sensing fibers of a RC SMF and a standard SMF in our OFDR system, we will compare the measurement values of our proposed method with the true values from the weighs applied on the cantilever beam and the data of the platinum resistor on the heater band. We set 11 measurement points with the $\Delta\varepsilon$ ranging from 0 to 150 $\mu\varepsilon$ and ΔT ranging from 0 to 12 °C and measure the RBS shifts of the RC SMF and the standard SMF simultaneously, and then, the measurement values of $\Delta\varepsilon$ and ΔT are calculated by (4) and (5). The contrast results between the measurement values and true values are shown in Fig. 5. We define that the measurement error is the absolute value of the difference between the measurement value and the true value. From Fig. 5, the measurement values and the true values are closed. The maximal measurement error of the strain variation is 7.97 $\mu\varepsilon$, and that of the temperature variation is 0.316 °C.

3.4. Discussion

We will theoretically analyze the maximum measurement errors of our presented method and the previous PMF based method [9]–[11] based on the relative errors not the absolute errors, because the strain and temperature sensitivity response of the cross-correlation RBS shifts using a PMF [9]–[11] and of using a standard SMF in our method are different due to difference in the calibration methods and systems of these two methods. If we also use the same calibration methods, the strain and temperature sensitivity responses of using a PMF is similar to those of using a standard SMF [6], [11]. Here we use the errors of the single parameter (strain or temperature) measurement by only using a standard SMF as a criterion. The different methods of two parameters measurement will compare with this criterion. Using this idea, the measurement errors using different methods can be compared, even though the calibration methods are different. Assuming that $\delta\varepsilon_s$ and δT_s are the maximum errors of the single parameter (strain or temperature) measurement by only using a standard SMF as the sensing fiber, $\delta\varepsilon_s$ and δT_s can be considered as an criterion to evaluate

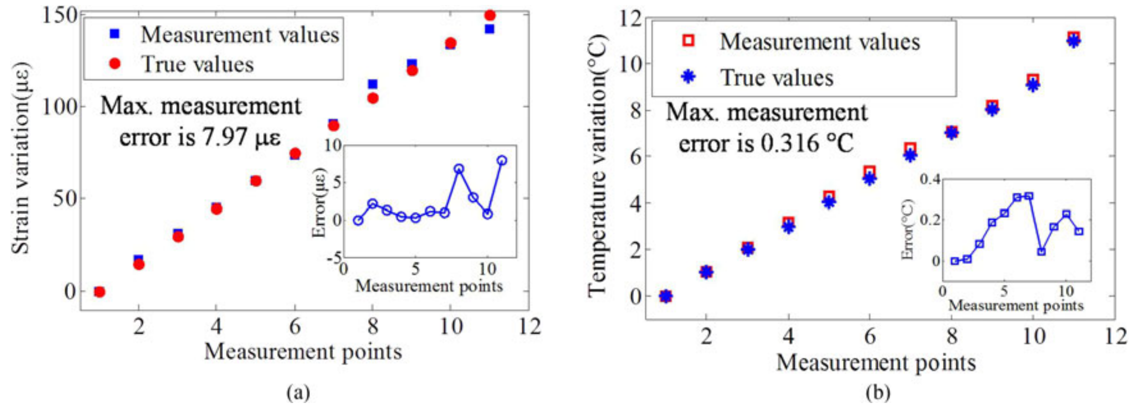

Fig. 5. Measurement values of our proposed method with respect to the true values at the different strain variations (a) and temperature variations (b). The strain and temperature variation are applied on the standard SMF and RC SMF simultaneously. The strain variation ranges from 0 to 150 $\mu\varepsilon$, and the temperature variation ranges from 0 to 12 °C. The auxiliary figures are the measurement errors for each measurement points. The maximal measurement error of the strain variation is 7.97 $\mu\varepsilon$, and that of the temperature variation is 0.316 °C.

different methods of discrimination between temperature and strain. $\delta\varepsilon_s$ and δT_s can be expressed as

$$|\delta\varepsilon_s| = \frac{|\delta\upsilon|}{|K_{S1}|} \tag{10}$$

$$|\delta T_s| = \frac{|\delta\upsilon|}{|K_{T1}|}. \tag{11}$$

In the PMF based method [9]–[11], the strain sensitivity response of the autocorrelation RBS shifts is 111 times less than that of the cross-correlation [11], which can be expressed as

$$|K_{S1}| = 111\,|K_{S2}|\,. \tag{12}$$

In PMF based method [9]–[11], the temperature sensitivity response of the autocorrelation RBS shifts is 40 times less than that of the cross-correlation [11], which can be expressed as

$$|K_{T1}| = 40\,|K_{T2}|\,. \tag{13}$$

Submit (10)–(13) to (8) and (9), the maximum errors of the PMF based method [8]–[10], $\delta\varepsilon_p$ and δT_p can be expressed as

$$\left|\delta\varepsilon_p\right| = 64.1\frac{|\delta\upsilon|}{|K_{S1}|} = 64.1\,|\delta\varepsilon_s| \tag{14}$$

$$\left|\delta T_p\right| = 63.1\frac{|\delta\upsilon|}{|K_{T1}|} = 63.1\,|\delta T_s|\,. \tag{15}$$

From (14) and (15), the maximum errors of the PMF based method are much higher than those of the single parameter (strain or temperature) measurement by only using a standard SMF.

In our method, the sensitivity responses to strain and temperature of using the RC SMF are higher than those of using the standard SMF. From the slopes of the fitting lines in Fig. 2 and Fig. 3, we have the relations as

$$|K_{S2}| = 4.38\,|K_{S1}| \tag{16}$$

$$|K_{T2}| = 1.62\,|K_{T1}|\,. \tag{17}$$

Submiting (10), (11), (16), and (17) to (8) and (9), the maximum errors of our presented method $\delta\varepsilon_r$ and δT_r can be expressed as

$$|\delta\varepsilon_r| = 0.94\frac{|\delta\upsilon|}{|K_{S1}|} = 0.94\,|\delta\varepsilon_s| \quad (18)$$

$$|\delta T_r| = 1.94\frac{|\delta\upsilon|}{|K_{T1}|} = 1.94\,|\delta T_s|\,. \quad (19)$$

From (18) and (19), the maximum errors of our presented method are not be deteriorated obviously comparing with those of the single parameter (strain or temperature) measurement by only using a standard SMF.

4. Conclusion

We present a simple and effective method to achieve distributed strain and temperature discrimination using two types of fiber by RBS shifts in OFDR. In the future, we will use a single main Mach-Zehnder interferometer with a wavelength-division multiplexing scheme to replace the system with two main Mach-Zehnder interferometers. In addition, PMF based method [9]–[11] uses a single fiber, which is a non-negligible advantage that makes the cable simpler and probably the measurements more reliable. In our presented method, we will try to fabricate the sensing optical fiber cable that interrogates the two core including the standard SMF and RC SMF appended side by side, which will make our system more practical.

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