

Wavelength Dispersion Analysis on Fiber-Optic Raman Distributed Temperature Sensor System

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Abstract: The influence of the wavelength dispersion on the temperature accuracy of the Raman distributed temperature sensor system (RDTS) is analyzed in detail, and a simple correction algorithm is proposed to compensate the fiber position error caused by the wavelength dispersion. The principle of the proposed algorithm is described theoretically, and the correction on each point along the entire fiber is realized. Temperature simulation results validate that the temperature distortion is corrected and the temperature accuracy is effectively improved from $\pm 5^\circ\text{C}$ to $\pm 1^\circ\text{C}$.

Keywords: Distributed temperature sensor, wavelength dispersion, correction algorithm

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1. Introduction

The Raman distributed temperature sensor (RDTS) system has attracted much attention for decades [1–3]. Owing to its immunity to the electromagnetic interference, the capability of handling much higher bandwidth, safety in hazardous conditions, the distributed temperature sensor (DTS) system has found successful implementation in various application fields, such as power cable monitoring, leakage-detection of oil pipelines and health monitoring of dams [4, 5].

The vast majority of the Raman distributed temperature systems described in literature employ the optical time-domain reflectometry (OTDR) technique to realize the accurate space orientation. With a short pulsed laser launched into one end of a

sensing fiber through a fiber coupler, two kinds of spontaneous Raman backscattering light are generated [6]. The higher frequency light is anti-Stokes (AS) component which is extremely sensitive to the temperature than the lower frequency signal named Stokes (S). The scattered light collected in different time is corresponding to different fiber positions. The temperature information could be obtained by calculating the ratio of AS and S signals in order to cancel out the effect of the laser source fluctuation and environmental influence. However, the usable signal is always submerged in the system noise inevitably due to the fact that the intensity of the scattering light is typically being one-millionth of the incident light. Therefore, the high-performance InGaAs avalanche photodiodes (APDs) integrated with the

multi-amplifying circuit are chosen for detection. Then, a high-speed data acquisition (DAQ) card converts analog signals to digital signals and accomplishes 10^5 or 10^6 times sample averaging simultaneously [7, 8].

In 1985, Darkin *et al.* reported the first experimental temperature measurements along silica-based fibers using a semiconductor laser source and an avalanche photodiode (APD) detector [9]. For thirty years, many groups have researched into improving the performance of the RDTS. L. Zhang *et al.* adopted the deconvolution algorithm to improve the spatial resolution without reducing the pulse width of the light source [10]. F. Baronti *et al.* presented a novel method based on cyclic codes for enhancing the signal-to-noise ratio (SNR) of the DTS [11]. However, the effect of dispersion existing in the RDTS was rarely discussed to the best of our knowledge. In the silica fiber, the Raman frequency shift is 13.2 THz, and the wavelength difference of AS and S is about 200 nm. Thus, they propagate along the sensing fiber with different velocities due to their unique wavelengths. At the same sampling rate of the DAQ card, it will lead to a time delay of the detected signals of the two channels corresponding to the same fiber position. The ratio of AS and S obtained from the collected data of two channels has some dislocation, and the temperature accuracy is deteriorated. Traditionally, the matched fiber is added in one channel for correcting the time delay and position error caused by different velocities. By this method, not every point along the fiber is corrected because the matched fiber length is fixed, and only a certain distance of dispersion is compensated.

In this paper, an auto-correction algorithm is proposed to compensate the effect of the wavelength dispersion on the DTS system, which realizes the correction on every point along the entire fiber. The theoretical analysis of this algorithm is described in detail. The simulation results validate that the temperature accuracy is improved five times

effectively, and the corresponding experimental verification will be carried out in our future work.

2. Theoretical analysis

2.1 Wavelength dispersion

In the range of $0.2\mu\text{m}$ to $4.0\mu\text{m}$, the refractive index of the fiber core which is made of silicon could be expressed approximatively as (1):

$$n^2 - 1 = \frac{0.6961663\lambda^2}{\lambda^2 - (0.068403)^2} + \frac{0.4079426\lambda^2}{\lambda^2 - (0.1162414)^2} + \frac{0.8974794\lambda^2}{\lambda^2 - (9.896161)^2} \quad (1)$$

where λ is the wavelength in μm , and n is the refractive index, respectively.

It is well known that the wavelength of Raman scattering light can be given by

$$\frac{1}{\lambda_{\text{as,s}}} = \frac{1}{\lambda_0} \pm \Delta\gamma \quad (2)$$

where λ_0 is the pump wavelength, and $\Delta\gamma$ is the wavenumber separation from the pump wavelength [12, 13]. Therefore, the backscattered AS and S components generated by a source laser wavelength of 1550 nm and a silica fiber with a wavenumber shift of 440cm^{-1} can be calculated as 1451 nm and 1663 nm, respectively. From (1), it is seen that the refractive index is dependent on the wavelength, and thereby signals with different wavelengths have different propagating velocities. By using $v=c/n$, the propagating velocities of AS, S signals and 1550 nm incident signal are obtained as follows:

$$\begin{aligned} v_{\text{as}} &= 2.0759 \times 10^8 \text{ m/s} \\ v_{\text{s}} &= 2.0795 \times 10^8 \text{ m/s} \\ v_{\text{in}} &= 2.0775 \times 10^8 \text{ m/s} . \end{aligned} \quad (3)$$

Traditionally, the OTDR technology is incorporated in the DTS system to realize the space orientation [14]. The detected signal in a different time is corresponding to the temperature information of the different distance of the fiber, which is always

expressed as

$$l = \frac{ct}{2n}. \quad (4)$$

Since the velocities of the AS and S components are different, there will be a time error detected by the APDs at the same point along the fiber. For example, assuming $l = 1$ m, the time error is calculated as

$$t_{\text{error}} = \frac{l}{v_{\text{as}}} - \frac{l}{v_{\text{s}}} = 8.5015 \times 10^{-3} \text{ ns}. \quad (5)$$

It is obvious that when the fiber length is short for example in the order of meter, the time error can be neglected. However, for the long distance fiber, the time error is large, i.e., the time error of a 10-km-length fiber is 85.4 ns. Thus, the time error should be under consideration due to its effect on the deterioration of the temperature accuracy.

In order to reduce the background effects, the ratio of AS and S signal intensities is calculated to obtain the temperature information along the whole fiber. Therefore, if the scattered light we detected is not corresponding to the same point at a certain time, it will inevitably lead to a decrease in the temperature accuracy. Assuming the sampling frequency of the DAQ is 100 MHz, for the same sampling time interval of the two channels, the relationship of the actual positions of AS and S is given by

$$\frac{l_{\text{s}}}{v_{\text{in}}} + \frac{l_{\text{s}}}{v_{\text{s}}} = \frac{l_{\text{as}}}{v_{\text{in}}} + \frac{l_{\text{as}}}{v_{\text{as}}}. \quad (6)$$

At a certain time, the scattered AS signal of the position l_{as} and the S signal of the position l_{s} are acquired. If the fiber position of AS is chosen as the reference length, the position error $l_{\text{s}} - l_{\text{as}}$ is shown as Fig. 1(a). It is observed that the synchronism error of the AS and S increases linearly with an increase in the fiber length. While the fiber length is 10 km, the position error reaches approximately 9 m.

If the temperature information is acquired from the ratio of corresponding AS and S points without correction, there will be a large error owing to the dispersion effects. On the other hand, the extension

of the sending distance is limited to a certain extent. Therefore, some special correction algorithm or improvement of the system setup should be introduced to compensate the degradation of the temperature accuracy.

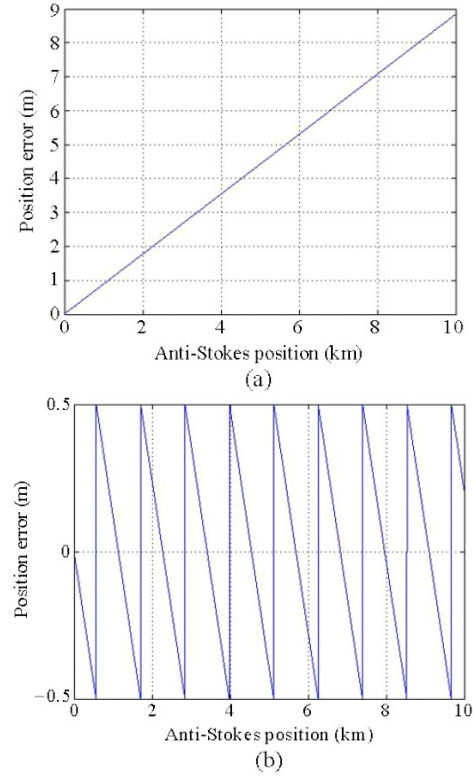


Fig. 1 Position error of the AS and S signals (a) without the wavelength dispersion correction and (b) corrected by the proposed correction algorithm.

2.2 Principle of the correction algorithm

A simple and effective correction algorithm is presented in this section through searching for the points of AS data which is closest to the S signal in an adjacent region. The principle of this correction algorithm and the detailed calculating procedure is described as follows:

Firstly, the fiber length corresponding to each data point of AS and S is calculated according to (7) and stored in the array L_{as} and L_{s} , respectively.

$$L_{\text{as}} = \frac{ct}{2n_{\text{as}}}, L_{\text{s}} = \frac{ct}{2n_{\text{s}}}. \quad (7)$$

where t is the sampling time, and the length of the

array L_{as} and L_s is N . The data points in L_{as} and L_s are not one-to-one correspondence. Assume the n -th value of L_s is $L_s(n)$, $n=1, 2, 3, \dots, N$. Then, we consider $L_s(n)$ as the referenced value and compare $L_s(n)$ with all the data in the array L_{as} . The closest data point is searched from L_{as} and stored in a new array L'_{as} as the n -th value. Finally, the temperature profile is figured by use of the ratio of L'_{as} and L_s .

As depicted in Fig. 1(b), the position error of AS and S light corrected by the proposed algorithm is decreased to within ± 0.5 m, which can be ignored. Moreover, compared with Fig. 1(a), the corrected position error exhibits a periodic variation trend within the range of ± 0.5 m instead of a linear increasing with the fiber length. Therefore, the limitation of extending the sensing distance is eliminated, and the position error is reduced to an acceptable error range effectively through the presented correction algorithm.

3. Simulation results

In the case of the DTS system where multi-mode parabolic gradient index fibers are utilized, the power of the backscattered Raman AS and S light, which is measured at the fiber input ($z=0$) at a time t after a pulse is injected into the fiber, could be described by (8) and (9) [15, 16].

$$P_s(t) = P_0 \left(\frac{c\tau}{n_s} \right) \Gamma_s R_s(T) \exp \left[-(\alpha_0 + \alpha_s) \frac{ct}{n_s} \right] \quad (8)$$

$$P_{as}(t) = P_0 \left(\frac{c\tau}{n_{as}} \right) \Gamma_{as} R_{as}(T) \exp \left[-(\alpha_0 + \alpha_{as}) \frac{ct}{n_{as}} \right] \quad (9)$$

where P_0 is the power of the incident pulse light, c is the speed of the velocity of the light in vacuum, τ is the pulse width, n_s and n_{as} are refractive indices of the S and AS light in the fiber core, respectively, Γ_s and Γ_{as} are Raman Stokes and anti-Stokes capture coefficients, respectively, and α_0 , α_s , α_{as} are the attenuation coefficients for the incident pulse light, Stokes wave and anti-Stokes wave, respectively. $R_s(T)$ and $R_{as}(T)$ are the Bose-Einstein factors for the Stokes band and anti-Stokes band which can be

computed using

$$R_s(T) = \frac{1}{1 - \exp(-h\Delta\nu/kT)} \quad (10)$$

and

$$R_{as}(T) = \frac{1}{\exp(h\Delta\nu/kT) - 1}, \quad (11)$$

respectively, where h is the Planck constant, k is the Boltzmann constant, T is the absolute temperature of the fiber, and $\Delta\nu$ is the Raman frequency shift.

Figure 2(a) shows the simulation results about the collected power of S and AS signals without the wavelength dispersion correction. There is a temperature change during the range of 7000 m to 7020 m along the fiber. Obviously, the rising edge of the S signal is in front of that of the AS signal under the same sampling interval of the two channels. This is attributed to the S light transferring faster than the

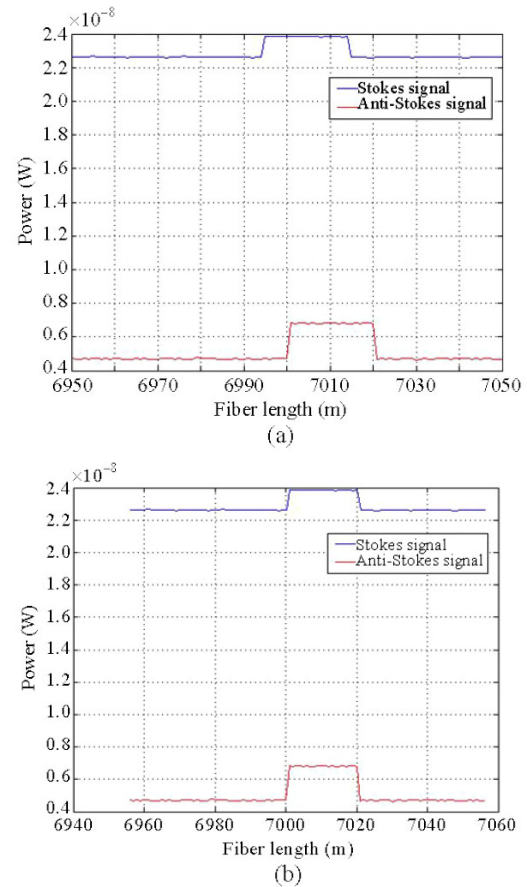


Fig. 2 Collected power curves of the AS and S light (a) without the wavelength dispersion correction and (b) corrected by the proposed correction algorithm.

AS light, and there is a synchronization error as presented in Section 2.1. The corrected power curves of the two channels are plotted in Fig. 2(b), which exhibit perfect synchronization compared with Fig. 2(a), and the influence of wavelength dispersion is compensated at a certain extent.

It is assumed that the fiber spools of 6000 m to 6020 m and 7000 m to 7020 m are kept at 60 °C and 80 °C, respectively. Owing to the position error caused by the wavelength dispersion, the position error exists in every point along the entire fiber length. Based on the description previously, the temperature information acquired by the ratio of AS and S is deteriorated if the position error is not corrected. As illustrated in Fig. 3(a), the simulation temperature curves calculated from the ratio of AS and S point to point without the correction have some distortion at the edge of the temperature

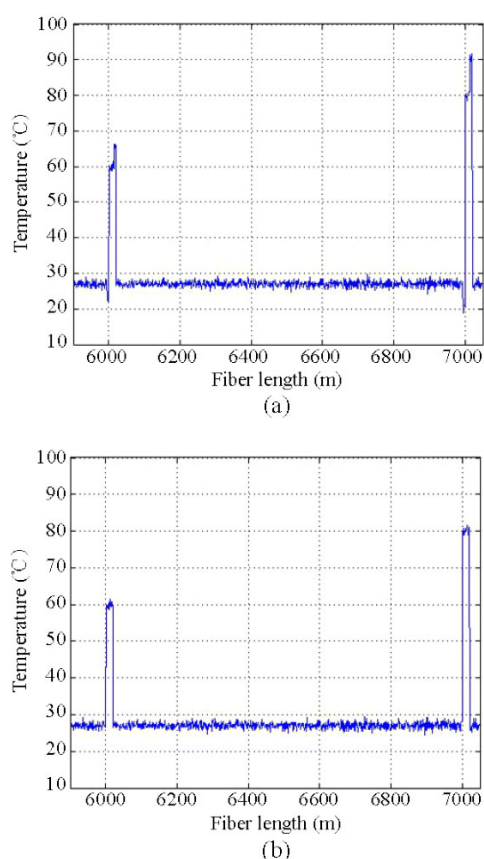


Fig. 3 Temperature profiles (a) without the wavelength dispersion correction and (b) corrected by the proposed correction algorithm.

change, and the temperature error is about ± 5 °C. The corrected temperature results are shown in Fig. 3(b). It is obvious that the temperature distortion is compensated, and the temperature accuracy is improved five times to ± 1 °C effectively. Furthermore, the proposed correction algorithm is able to realize the error correction for each data point. It is much simpler and more precise than employing the matched fiber which is only able to compensate the wavelength dispersion at a certain distance.

4. Conclusions

In this paper, a simple correction algorithm on the position error caused by the wavelength dispersion in the DTS system has been presented, and the simulation results indicate the position error is corrected within the range of ± 0.5 m which can be neglected, instead of a linear increasing relationship with the fiber distance. Unlike the traditional matched fiber method, the proposed algorithm is able to complete the corresponding correction on each data point of the whole fiber. Moreover, the temperature distortion is compensated, and the temperature accuracy is improved five times to ± 1 °C effectively. The relative experimental verification will be carried out in our future work.

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