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An optical fiber-folded distributed temperature sensor based on Raman backscattering

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ABSTRACT

A temperature sensor is presented, which is based on optical fiber-folded distributed feedback and Raman backscattering. In the proposed configuration, different locations of optical fiber are put in the same environment to sense the same temperature. The proposed method and traditional method are used to demodulate different temperature fields. By comparing the demodulating results, two main problems have been solved. First, differential attenuation in the traditional method is eliminated between anti-Stokes and Stokes signal when they propagate along the fiber. Second, localized changes in the Stokes are removed, which is caused by other external factors except for the temperature. Furthermore, the detected signal consists of anti-Stokes only, which greatly simplifies the experimental device system. The proposed method has been verified by theoretical simulation to be simple and auto-correct.

1. Introduction

Fiber-optic sensors has caught the attention for decades because of peculiar advantages, one of important parameters is temperature in many applications. In recent years, society attaches great importance to the fire safety of large ships and warehouse. Therefore, more and more scientific research institutions and researchers pay attention to the study of the fiber distributed temperature sensor (DTS) based on Raman backscattering. The basic theory is that incident light generates Raman backscattering which contains anti-Stokes and Stokes components in the localization of optical fiber where temperature situation has the change, then utilizing Stokes to demodulate anti-Stokes [1–4]. However, there are some limitations to this method. One is the attenuation difference between Stokes wave and anti-Stokes wave caused by the wavelength difference, which ranges from 100 nm to 200 nm based on the optical fiber type. The attenuation difference results in an error which causes a temperature profile downward sloping with the fiber length. Finally, we get a wrong temperature. Another issue is that bending or other factors results in noise or error of temperature obtained.

In recent years, researchers solve these two problems in many methods [5]. In the early years, the dual-ended (DE) configuration was proposed for the automatic correction of differential attenuation [6,7]. In this configuration, two parallel optical fibers were adopted, but a light switch was added to control the light into two ends of the fiber which increases the complexity of the system. In the next study, a dual-light source scheme was proposed to avoid this problem [8]. In the schematic configuration, two light sources with different wavelength were used and the incident wavelength of the primary source coincides with the Stokes wavelength of the secondary source. In this method, Stokes and anti-Stokes produced the same attenuation in their returned signals and automatic correction, but this method has lower practical operation. Stokes and anti-Stokes wavelengths are uncertainty and particularity because frequency shift of Raman Phonon is different for different types of fiber. The wavelength of laser is quite difficult to match them on the market. Moreover, two light sources increase cost. Recently, a simple structure scheme with reflecting mirror was proposed [9]. This scheme has realized auto-correction with one source only, however the detector receives signals with lots of components owing to reflecting mirror. The useless components increase complexity of the signal and difficulty of post-processing.

In this paper, a DTS system is presented with fiber-folded configuration. The proposed system and traditional method are used to demodulate the same temperature field. By comparing the demodulating results for different types of temperature fields, the superiority of the proposed method is proved. For the proposed

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method, the error of the demodulated temperature does not increase with the increase of the fiber distance and not affected by the external effect such as bending and pressure. In addition, the temperature can be demodulated only by detecting anti-Stokes intensity, which greatly simplifies the experimental device and the measuring process.

2. Temperature demodulating principle in the traditional method

The inelastic nature of spontaneous Raman scattering causes anti-Stokes and Stokes components when the pump light propagates along the optical fiber. The scattered light intensity of Raman Stokes and anti-Stokes can be affected by temperature, it can be expressed by [2,8]

$$I_{as} = K_{as} S \upsilon_{as}^4 I_0 R_{as}(T) e^{-(\alpha_0+\alpha_{as})L} \quad (1)$$

$$I_s = K_s S \upsilon_s^4 I_0 R_s(T) e^{-(\alpha_0+\alpha_s)L} \quad (2)$$

where

$$R_{as}(T) = (e^{h\Delta\upsilon/kT} - 1)^{-1}$$

$$R_s(T) = (1 - e^{-h\Delta\upsilon/kT})^{-1}$$

In the traditional method, ignoring the difference of scattering K and loss α between Stokes and anti-Stokes, the ratio of Eqs. (1) and (2) at a certain location L and approximate temperature demodulation equation is expressed as

$$I(T) = \frac{I_{as}}{I_s} = \left(\frac{v_{as}}{v_s}\right)^4 e^{-h\Delta\upsilon/kT} \quad (3)$$

$$\frac{1}{T} = \frac{1}{T_0} - \frac{k}{h\Delta\upsilon} \ln \frac{I_{as}(T)/I_s(T)}{I_{as}(T_0)/I_s(T_0)} \quad (4)$$

Because of no consideration of the difference between Stokes and anti-Stokes there are two problems occurred in the traditional method. One is that the measurement error is increased with the increase of the distance. The other is that the temperature error can vary with the location of the selected reference points. Fig. 1 reveals the existence of these problems. Fig. 1a shows the temperature vs. the distance when the reference point is selected as 20 m, 30 m, 40 m and 50 m. With the increase of the distance, the deviation relative to the measured temperature 40° becomes larger and larger. The temperature vs. the distance is shown in Fig. 1b, when the environment temperature is 40°, 60° and 80°, respectively, and the reference point is at 50 m. Fig. 1(a) and (b) can be expressed by Eq. (4), and the parameters as shown in Table 1.

3. Working principle in the fiber-folded DTS system

The proposed fiber-folded DTS system is shown in Fig. 2. The 1550 nm laser is coupled into the sensing fiber through the optical circulator. The length of the sensing fiber is $2L$ and the fiber is folded at the half length. The backscattering anti-Stokes light is detected by APD through the optical circulator and Raman filter. The fiber at the location l and $2L$-l is put in the same temperature field. The detected anti-Stokes intensity at these two locations is expressed as

$$I(l) = K_{as} S \upsilon_{as}^4 I_0 R(T) \exp[-(\alpha_0 + \alpha_{as})l] \quad (5)$$

$$I(2L - l) = K_{as} S \upsilon_{as}^4 I_0 R(T) \exp[-(\alpha_0 + \alpha_{as})(2L - l)] \quad (6)$$

Table 1
Simulation parameters.

Symbol	Parameter	Value	Unit
α	Fiber attenuation	0.2	dB/km
k	Boltzmann's constant	$1.38 * 10^{-23}$	J/K
h	Planck's constant	$6.626 * 10^{-34}$	J s
Δv	Frequency shift of Raman	$1.3 * 10^{13}$	Hz

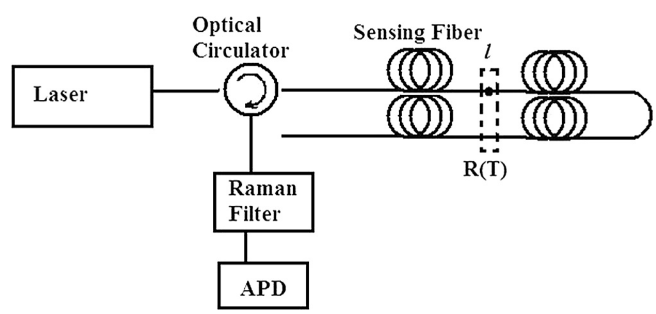

Fig. 2. The schematic configuration of fiber-folded DTS system.

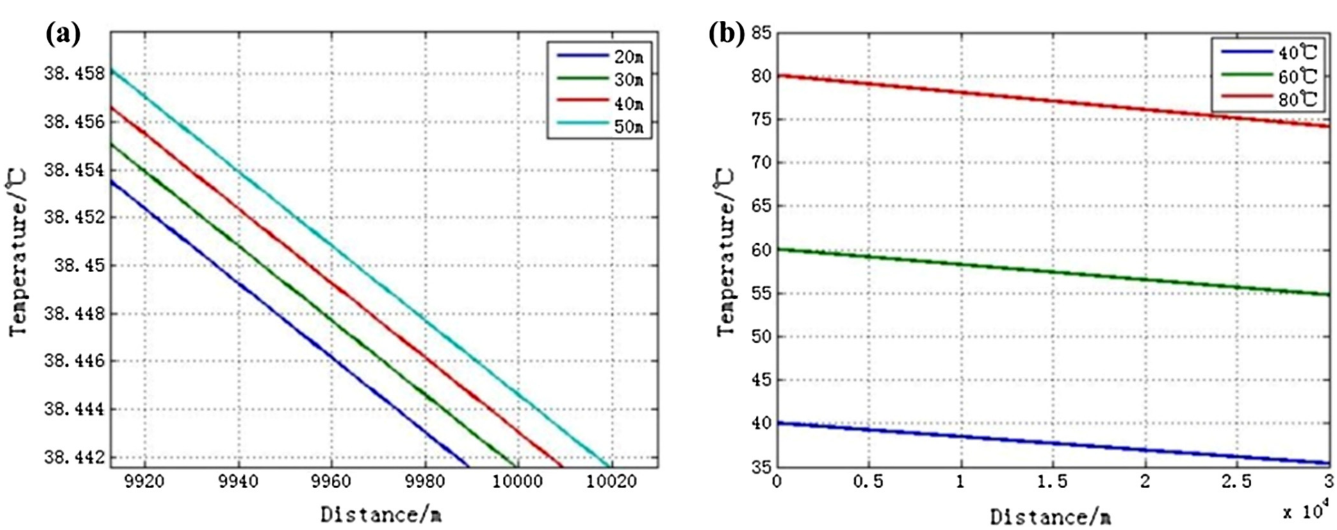

Fig. 1. (a) Temperature changed with the distance when the reference point is selected as 20 m, 30 m, 40 m and 50 m. (b) The temperature changed with the distance when the environment temperature is 40°, 60° and 80°, respectively and the reference point at 50 m.