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The study of the Raman-based optical fiber-folded distributed temperature sensing system with simplex code

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ABSTRACT

In this article, the simplex code (S code) technique was applied to the distributed fiber Raman temperature sensing system of fiber folded structure. The measured anti-Stokes signal is processed to obtain the temperature information of the whole fiber length. First, the effect of S code length on the system error was investigated and the analysis shows that at a certain level of noise, by increasing the code length, the error of temperature measurement can be largely reduced, but the system space resolution is kept unchanged. Then, the relationship of the noise level, superposition times and temperature error was studied by simulation. The conclusion can provide the basis for the optimization of temperature demodulation time. The research was of great significance to improve the temperature measurement accuracy of distributed optical fiber sensors and to reduce measurement errors.

0. Introduction

Fiber-optic Raman temperature sensing system is a kind of distributed fiber sensing system. In the system, the effect of spontaneous Raman backscattering and optical time domain reflectometry (OTDR) are used to obtain thermometry and the localization respectively. Since the system has the advantages of real-time, reliable, high security, corrosion resistance, distributed and anti-electromagnetic interference, it has been widely applied in many fields, such as electric power, communication, fire detection [1–3].

In the distributed optical fiber sensing system (DOFS) based on Raman scattering, the backward spontaneous Raman scattered light generated by pulsed light is extremely weak and prone to noise interference. In DOFS system, Signal-to-Noise Ratio (SNR) determines measurement accuracy and the measurement distance range of the sensor. Increasing the incident light peak power can enhance the energy of the incident light pulse, then the signal-to-noise ratio of the system can be improved. However, the stimulated Raman scattering has a limit on the incident peak power. Therefore, it is considered that widening the light pulse raise its energy. But at the same time, the spatial resolution s of the system is reduced ($s = \tau c/2$, τ denotes the light pulse width and c is the light velocity in the fiber). Aiming at the contradiction of SNR and spatial resolution, Marcelo A. Soto, et al. [4–6] introduced the coded light impulse signal into DOFS system for improving signal SNR without changing the light impulse width and cumulative times. The coding techniques such as pseudo random signal sequence, Golay code and S code, etc. are introduced into DOFS system. In early, people adopted periodic pseudo random signal for coding. Its irregular sidelobe character had an influence on measurement, which hindering it from applying in practical system. Then Golay code was raised. The Golay code with the code length d improves the system SNR by $\frac{\sqrt{d}}{2}$ times. Then, S code with higher performance, which could improve the system SNR by $\frac{d+1}{2\sqrt{d}}$ times [7–9] is used in the system. Ref. [10] introduces the Golay mutual-complementing code to the system. However, with relative short code length, the improvement of SNR is still lower than that of S encoding. Moreover, the calculation of Golay mutual-complementing code is very complicated. Therefore, S code [11,12] is adopted to improve receiving signal of Raman scattering DOFS.

Wang Zhen [13] proposed a optical fiber folded Raman scattering DOFS system, in which wavelet transform method is used to denoise. The system improved SNR. However, the temperature measuring error of the system remains large. Therefore, this paper applies S code technique into Wang's system for further improving SNR and reducing temperature measuring error. Furthermore, since few researchers pay attention to S code with the code length more than 7, we studied the performance of different encoding lengths larger than 7. In addition, the relationship of the noise level, superposition times and the temperature error is studied by simulation.

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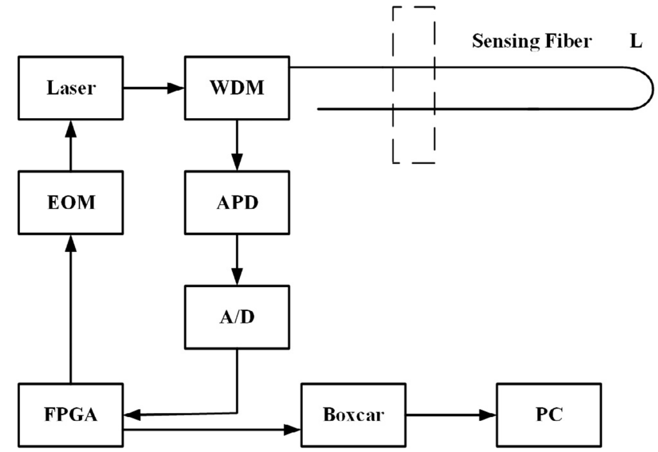

Fig. 1. The schematic diagram of Raman-based distributed fiber temperature sensing system of fiber folded structure with S code.

1. Theory

1.1. An optical fiber-folded DOFS

Fig. 1 shows the schematic diagram of Raman-based distributed fiber temperature sensing system with fiber folded structure using S code. First, a set of S-coded electrical signal pulse sequences is generated by a Field-Programmable Gate Array (FPGA) board and loaded into a pulse modulator. Then the signal is transformed into a S coded light pulse sequence signal by an electro-optical modulator (EOM) and a laser with wavelength 1550 nm. This set of sequence light is divided into two parts one of which is injected into the sensing fiber for the temperature detection. Been scattered, the backward anti-Stokes light, which going through WDM. The scattered signal is converted and amplified by avalanche photoelectric diode (APD) and amplifier circuit respectively, After decoded by FPGA, the scattered signal is output into the acquisition card for collection and stacking. Finally, temperature signal distribution is obtained by calculation in a computer.

The fiber folded structure is achieved by fusing the ends of two identical optical fibers to each other. According to the special structure, locations l and $2L-l$ ($2L$ is the length of the whole sensing fiber) are in the temperature changing area. Since the Raman anti-Stokes scatter at the two positions is arising in the same temperature changing area, the two scattered light intensities at l and $2L-l$ are the same. The backward anti-Stokes Raman scattered light intensity is defined by

$$I(l) = K_{as} S v_{as}^4 I_0 R(T) \exp[-(\alpha_0 + \alpha_{as}) l] \tag{1}$$

$$I(2L-l) = K_{as} S v_{as}^4 I_0 R(T) \exp\left[-\left(\alpha_0 + \alpha_{as}\right)(2L-l)\right] \tag{2}$$

where $R(T)$ is the temperature information field function of fiber point 1 and $2L-1$, which is written as:

$$R(T) = \left[\exp(h\Delta v/kT) - 1\right]^{-1} \tag{3}$$

where, K_{as} is anti-Stokes scattering cross section, S is backscatter factor, V_{as} is anti-Stokes scattering photon frequency, I_0 is incident light intensity, α_0 and α_{as} are the attenuation coefficients of incident light and anti-Stokes scattered light in the fiber respectively, h is Planck constant, Δv is the frequency shift of Raman scattering, k is Boltzmann constant.

We multiply Eq. (1) by (2). The result is written by

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

1.2. S code principle

Suppose that $\omega_1(t)$ is an ideal signal without noise obtained by single pulse light $p_1(t)$ passing through the fiber folded. A series of delayed pulses are defined by $p_2(t) = p_1(t-\tau), p_3(t) = p_1(t-2\tau), \ldots$, where τ is the width of a single pulse of light $p_1(t)$. From those delayed pulses $p_2(t), p_3(t), \ldots$, we can get a series of corresponding ideal signals $\omega_2(t) = \omega_1(t-\tau), \omega_3(t) = \omega_1(t-2\tau), \ldots$. The original signal is encoded with S encoding. Assuming that the actual signal trajectory was detected as the $\eta_1(t), \eta_2(t), \eta_3(t), \ldots$, and the corresponding noise detection each time is $e_1(t), e_2(t), e_3(t), \ldots$, we can get the actual decoded signal at $(n-1)\bullet\tau$ which is written as $\omega'_n(t) = S_n^{-1} \bullet \left[\eta_1(t), \eta_2(t), \eta_3(t)\right]^T$. Where S_n^{-1} is the nth line of the inverse of S matrix.

When an S code with code length d, the detected signal is

$$\begin{bmatrix} \eta_1(t) \\ \eta_2(t) \\ \cdot \\ \cdot \\ \cdot \\ \eta_{d-1}(t) \\ \eta_d(t) \end{bmatrix} = S_d \cdot \begin{bmatrix} \omega_1(t) \\ \omega_2(t) \\ \cdot \\ \cdot \\ \cdot \\ \omega_{d-1}(t) \\ \omega_d(t) \end{bmatrix} + \begin{bmatrix} e_1(t) \\ e_2(t) \\ \cdot \\ \cdot \\ \cdot \\ e_{d-1}(t) \\ e_d(t) \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} \omega'_1(t) \\ \omega'_1(t) \\ \cdot \\ \cdot \\ \cdot \\ \omega'_{d-1}(t) \\ \omega'_d(t) \end{bmatrix} = S_d^{-1} \cdot \begin{bmatrix} \eta_1(t) \\ \eta_1(t) \\ \cdot \\ \cdot \\ \cdot \\ \eta_{d-1}(t) \\ \eta_d(t) \end{bmatrix} \tag{6}$$

After decoding, the signal output is:

$$\begin{aligned} \varpi(t) &= \frac{\omega'_1(t) + \omega'_2(t+\tau) + \cdots + \omega'_{d-1}[t + (d-2\tau)] + \omega'_d[t + (d-1)\tau]}{d} \\ &= \omega_1(t) + \frac{2}{d(d+1)} \sum_{j=1}^{d} \sum_{k=1}^{d} T_{j,k} e_k [t + (d-1)\tau] \end{aligned} \tag{7}$$

$T_{j,k}$ in Eq. (5) is the element in jth row and kth column of the matrix T_d. T_d is written as $T_d = \frac{d+1}{2} S_d^{-1} = \begin{bmatrix} T_{1,1} & T_{1,2} & \cdots & T_{1,d} \\ T_{2,1} & T_{2,2} & \cdots & T_{2,d} \\ \vdots & \vdots & & \vdots \\ T_{d,1} & T_{d,2} & \cdots & T_{d,d} \end{bmatrix}$, where, $T_{j,k} \in \{1, -1\} = 1$ or -1.

1.3. Signal processing

Anti-Stokes scattered light intensity obtained by Eq. (4) is an ideal value. Assuming that the total noise generated by all the detection elements in the system is denoted by a matrix X which contains n rows and m columns white noise. The light intensity detected by APD in Fig. 1 is written as

$$I_1(T) = I * I_p + X \tag{8}$$

After decoding, the light intensity is:

$$I_2(T) = (I_1(T) + I_p^{-1} * I_1(T))/(n * d^2) \tag{9}$$

where, d is the order of the S matrix, I_p is the d-order S matrix, I_p^{-1} is the inverse of the d-order S-matrix, and n is the rows of white noise X.

Assuming that the reference temperature is T_0, the formula of demodulated temperature is:

$$T = \left[\frac{K}{h\Delta v} \ln\left(\frac{I(T_0)}{I_2(T)}\right) \exp\left(\frac{h\Delta v}{KT_0} - 1\right) + 1\right]^{-1} \tag{10}$$

Since only the anti-Stokes scattered light is utilized for demodulation, the loss caused by the wavelength difference between the Stokes scattered and the anti-Stokes scattered light has non influence on the measurement. The SNR of the system is increased after the signal denoising using S code, and the temperature measuring accuracy is improved significantly.