Fiber-optic distributed disturbance sensor based on merged Sagnac interferometers

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Abstract: The fiber-optic distributed disturbance sensor (FDDS) based on merged Sagnac interferometers is proposed and investigated. The disturbance causes a phase modulation and can be detected by the Sagnac interferometer. The proposed sensor includes three Sagnac interferometers merged sharing one broad-band source (BBS). The interference signal is acquired by two photo detectors (PDs) respectively. Since the coherent length of the source is too short for the lightwave propagating along different optical paths to interfere, there are only three paths of the light can interfere. One of the PDs detects the summation of the signals from two Sagnac interferometers which have the same loop length. The other PD measures the interference lightwave from the interferometer comprise of the Faraday rotator mirror (FRM) and the sensing fibers. The disturbance can be located by conducting mathematical operations to the detected signals. The experimental results show that the proposed sensor can locate the disturbance. The maximum location error is 370 m and the average location error is 270 m during 10 times experiments.

Key words: fiber-optic distributed disturbance sensor;　Sagnac interferometer;　fiber delay loop; intrusion detection

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基于 Sagnac 组合型干涉仪的光纤分布式扰动传感器

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摘　要： 提出并研究了基于 Sagnac 组合型干涉仪的光纤分布式扰动传感器。扰动作用在传感光纤上引起传输光波相位的变化，可以通过 Sagnac 干涉仪进行检测。所提出的光纤传感器包括三个 Sagnac

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干涉仪，它们共用一个宽带光源(BBS)，并通过两个光电探测器(PD)检测干涉信号。由于宽谱光源的相干长度很短，因此只有经历相同路径的两束光会发生干涉，这样的路径存在三条。其中一个光电探测器检测有着相同环路长度的两个 Sagnac 干涉仪的信号之和，另一个光电探测器检测由法拉第旋光镜和传感光纤组成的干涉仪中的干涉光强。通过对探测器接收到的信号进行数学运算可以对扰动进行定位。实验结果表明，所提出的传感器可以检测并定位扰动。10 次实验的最大定位误差为 370 m，平均定位误差为 270 m。

关键词：光纤分布式扰动传感器； Sagnac 干涉仪； 光纤延迟环； 入侵探测

0 Introduction

Fiber-optic distributed disturbance sensors (FDDS) can detect and locate the disturbances along the whole length of the sensing fiber. It has the unique advantages in high sensitivity, intrinsic safety, electrical insulation, anti-electromagnetic interference, corrosion resistance and full range distributed measurement[1-3]. It attracts increasing attention in the field of security and is extensively used for monitoring and securing national borders, prison perimeters, oil and gas pipelines, structural health and communication links. The configurations of current interferometer based FDDS mainly include Mach-Zehnder interferometer, Sagnac interferometer, Michelson interferometer and the combined configurations of the interferometers[4-18].

The FDDS based on Sagnac interferometer merged with Mach-Zehnder or Michelson interferometer has several disadvantages[19]. For instance, the high noise background due to the Mach-Zehnder or Michelson interferometer with long fiber under the complicated outdoor conditions and all phase changes along the fiber could sum up and produce a strong noise background. In contrast, the Sagnac interferometer is a well balanced reciprocity insensitive interferometer and the output has a much higher signal-to-noise ratio (SNR) accordingly. In addition, a low coherent light source can work well in the Sagnac interferometers. However, an expensive highly coherent laser source needs to be employed in the Mach-Zehnder or Michelson interferometer. In general, Sagnac interferometer based FDDS attracts more attention of the researchers and engineers than Mach-Zehnder or Michelson interferometer based ones. In spite of this, there are still some problems of current Sagnac interferometer based FDDS, such as the high cost for two optical sources, modulators with different frequency for two mode system and WDMs for dual-wavelength system, and difficulty of complexity of location algorithm for single Sagnac based sensor, which prevent the further practical applications.

The paper describes a merged Sagnac interferometers based FDDS. The sensing configuration includes three Sagnac interferometers sharing the sensing fiber. The two Sagnac interferometers are almost the same length and another one contains a Faraday rotation mirror (FRM). The sensor requires only a broad-band optical source. The signals received by the two photo-detectors (PD) are analyzed and the location method is presented. Furthermore, the feasibility and performance of the proposed sensor is experimentally investigated.

1 Theory

The Sagnac interferometer is a common-path interferometer in which the two light beams travel the same optical path in the opposite directions, and create the interference pattern when recombining on the coupler. The proposed FDDS based on the merged Sagnac interferometers is illustrated in Fig.1. The light from a broad-band source (BBS) S is divided into two paths with the same optical power by the coupler C_1. The light waves propagating along the clockwise path and the counterclockwise path are received by the photo-detectors PD_1 and PD_2. The optical fiber loop D_1 and D_2 are used to form the time delays. Since the coherent length of the source is too short for the lightwave propagating along different optical paths to interfere, the paths of the coherent light are as follows:

(1) $C_1-C_2-L_1-C_3-L_3-D_1-C_1$ and $C_1-D_1-L_3-C_3-L_1-C_2-C_1$

(2) $C_1-C_2-L_2-C_3-L_3-D_1-C_1$ and $C_1-D_1-L_3-C_3-L_2-C_2-C_1$

(3) $C_2-L_1-C_3-D_2-FRM-D_2-C_3-L_2-C_2$ and $C_2-L_2-C_3-D_2-FRM-D_2-C_3-L_1-C_2$

The light waves traveling along path (1) and path (2) interfere in the coupler C_1 and the superposed coherent light is detected by PD_1. The light transmitting along the path (3) interferes in the coupler C_2 and the coherent light is detected by PD_2. The loop length of the path (1) and (2) are approximately equal. The disturbance is applied at point P in the sensing region L1, and the signals detected by PD_1 and PD_2 are expressed as:

$$I_1(t)=\frac{I_0}{2}\{1+\cos[\Delta\phi_1(t)+\varphi_1]\}+\frac{I_0}{2}[1+\cos(\varphi_1')] \quad (1)$$

$$I_2(t)=\frac{I_0}{2}\{1+\cos[\Delta\phi_2(t)+\varphi_2]\} \quad (2)$$

where

$$\Delta\phi_1(t)=\phi(t-\tau_1)-\phi(t-\tau_2) \quad (3)$$

$$\Delta\phi_2(t)=\phi(t-\tau_3)-\phi(t-\tau_4) \quad (4)$$

The time delay are given as:

$$\tau_1=\frac{nz}{c} \quad (5)$$

$$\tau_2=\frac{n(2L+D_1-z)}{c} \quad (6)$$

$$\tau_3=\tau_1=\frac{nz}{c} \quad (7)$$

$$\tau_4=\frac{n(2L+2D_2-z)}{c} \quad (8)$$

where I_0 is determined by the input optical intensity; φ_1, φ_1' and φ_2 are the initial phases induced by the non-reciprocal factors; $\phi(t)$ is the phase modulation caused by the disturbance; $\Delta\phi_1(t)$ and $\Delta\phi_2(t)$ are the phase differences; τ_1, τ_2, τ_3 and τ_4 are the propagating time delay to the PDs in the interferometers; L is the length of the optical fiber L_1, L_2 and L_3; z is the distance from the perturbation to the coupler C_1, D_1 and D_2 are the length of the two optical fiber loops individually; c is the speed of light in a vacuum; and n is the reflective index of the fiber. The time delay loops are intended to eliminate the dead zones of the sensing region and increase the sensitivity of the sensor.

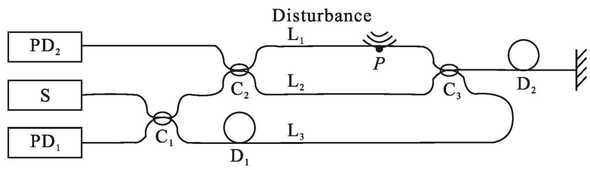

Fig.1 Schematic illustruation of merged Sagnac interferometer based FDDS

The phase differences $\Delta\phi_1(t)$ and $\Delta\phi_2(t)$ can be calculated from the Taylor expansion with the higher-order terms neglected:

$$\Delta\phi_1(t)=\frac{n(2L+D_1-2z)}{c}\frac{d\phi}{dt} \quad (9)$$

$$\Delta\phi_2(t)=\frac{2n(L+D_2-z)}{c}\frac{d\phi}{dt} \quad (10)$$

Eq.(9) and (10) are substituted in Eq.(1) and (2), the disturbance location z and the phase modulation ϕ are determined.

After AC coupling and lowpass filtering, Eq.(1) and (2) can be derived as:

$$I_3(t)=\frac{I_0}{2}\cos[\Delta\phi_1(t)+\varphi_1] \quad (11)$$

$$I_4(t)=\frac{I_0}{2}\cos[\Delta\phi_2(t)+\varphi_2] \quad (12)$$

Eq. (11) and (12) are deduced by Hilbert transform[20-21] and can be given by:

$$I_5(t)=\frac{I_0}{2}\sin[\Delta\phi_1(t)] \quad (13)$$

$$I_6(t)=\frac{I_0}{2}\sin[\Delta\phi_2(t)] \quad (14)$$

According to the theory of calculus, we can obtain:

$$\frac{I_3}{I_4}=\frac{\frac{dI_5}{dt}}{\frac{dI_6}{dt}}\frac{\frac{d\Delta\phi_2(t)}{dt}}{\frac{d\Delta\phi_1(t)}{dt}} \quad (15)$$

Let

$$K=\frac{I_3}{I_4}\frac{\frac{dI_6}{dt}}{\frac{dI_5}{dt}} \quad (16)$$

The position of the disturbance can be deduced as:

$$z=L-\frac{2D_2-KD_1}{2(K-1)} \quad (17)$$

2 Experiment and discussion

To verify the feasibility of the proposed sensor experimentally, the setup of the prototype system is built and illustrated in Fig.2. In general, the setup includes a continuous BBS super luminescent diode (SLD), three couplers, two photo detectors, a FRM, an amplifier circuit, a data acquisition card (DAQ), a computer, and several optical fiber loops utilizing for sensing, transmitting and time delay. The central wavelength of the source is 1 310.0 nm, the maximum output power is about 5 mW, and the spectral width is about 40 nm。 The length of the sensing fiber L_1 and the transmitting fiber L_2 and L_3 are all 20 km. The length of time delay loops D_1 and D_2 are both 2 km. The sampling frequency is 1 MHz.

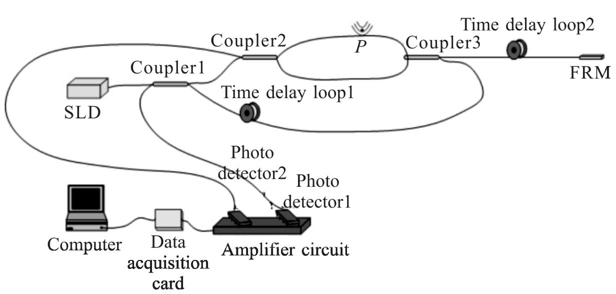

Fig.2 Schematic illustration of experimental setup

The perturbation is imposed on the sensing fiber L_1 at the 10 km position and the detected signals with a disturbance and without disturbances received by PD_1 are shown in Fig.3. The waveform of the signals with the disturbance is quite different from it is without disturbances, which means the proposed sensor is able to detect the disturbance event. Then the perturbation is applied on ten different positions to test the function of distributed sensing and location of the disturbance. The measured and actual location of the disturbance is illustrated in Fig.4, from which it is clear that the average error is 270 m and the maximum error is 370 m.

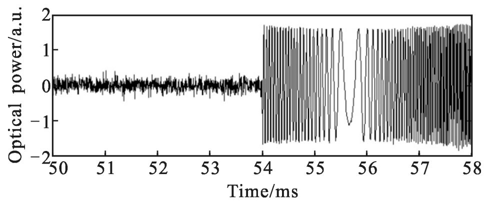

Fig.3 Detected signal induced by perturbation at the position z=10 km

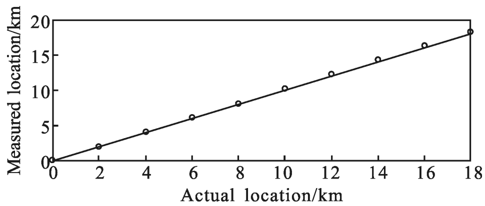

Fig.4 Measured versus actual location of disturbance

3 Conclusion

The merged Sagnac interferometers based fiber-optic sensor is demonstrated in the paper, which is able to detect the disturbance event in the sensing region and locate the event. The sensor has much higher SNR than the Mach-Zehnder or Michelson interferometers based FDDS. Compared with current Sagnac interferometer based FDDS, it requires only one BBS without other expensive components and effectively reduces the cost accordingly. The experimental results confirm the design and the theoretical analysis. The location performance of the proposed sensor is investigated in the laboratory in the paper and the future investigation will be focused on testing the sensor in the field and developing the sensor in the practical applications.

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