Distributed optical fiber sensor using Sagnac for acoustic detection

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Abstract: A distributed optical fiber acoustic sensor based on in-line Sagnac is presented. After clockwise and counterclockwise light waves are recombined, interference in 3×3 coupler is produced. The acoustic sensor uses photo detector (PD), data acquisition card, filter and amplification to realize photo electric conversion and recover acoustic signal. To study the performance of this acoustic sensor, localization principle based on null frequency is analyzed. To reveal null frequencies from the acoustic disturbance position, a fast Fourier transform (FFT) is applied to transform time domain signal data into frequency domain signal. The results demonstrate that the Sagnac distributed optical fiber sensor can retransmit acoustic signal and the location performance is verified by simulation and experiment.

Key words: Sagnac; acoustic sensor; null frequency; localization

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Optical fiber sensors have been widely used because of its outstanding advantages of flexible length, corrosion resistance, light weight and immunity to electromagnetic interference (EMI) [1-2]. In recent years, fiber-optic acoustic sensors have been successfully designed and applied to remote sensing, oil exploration, underwater communications and structural health monitoring[3-4]. Fiber-optic acoustic sensors can be divided into point, quasi-distributed and distributed acoustic sensors. Distributed fiber-optic acoustic sensing technology can provide fully distributed acoustic information along the entire fiber link, and thus external acoustic signals from an arbitrary point can be detected and located. Several distributed optical acoustic detection technologies have been proposed including Mach-Zehnder interferometer (MZI)[1], Michelson interferometer (MI)[5] and Sagnac interferometer[6-7]. Compared with other interferometers, Sagnac interferometer is more practical and cheaper for acoustic sensor owing to its insensitivity to temperature variation and low expectation for light source[8-9].

The objective of this paper is to demonstrate that Sagnac distributed fiber-optic acoustic detection system can effectively retransmit the sounds. This Sagnac interferometer can avoid the situation that half of the fiber needs to be isolated from the physical fields in practical measurement, which decreases the cost in the loop configuration and inherits the advantages of zero-path-length mismatched characteristic. This study offers a detailed analysis of location principles. In addition, the effect of the sound propagation is investigated. Finally, the location performance is verified by simulation and experimental results.

The rest of this paper is organized as follows: Operation principle of the distributed optical fiber sensor based on in-line Sagnac is described in Section 1. Sec-

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tion 2 presents the simulation and experimental results. Finally, conclusion is given in Section 3.

1 Operation principle

The schematic of the Sagnac distributed optical fiber acoustic detection system is shown in Fig. 1. Once the laser is injected into a 3×3 coupler, it is split into clockwise (CW) and counterclockwise (CCW) light beams. The CW light beam goes through a 3×3 coupler, a delay coil and a 2×1 coupler. However, the CCW light beam goes through a 3×3 coupler and a 2×1 coupler. Both of the light beams continue passing through sensing fiber (SF) and 1×2 coupler. When vibration occurs on the sensing fiber, the phase of the light transmitting in the fiber will change. A photo detector (PD), which is connected to one terminal of the 3×3 coupler, receives the change and makes photoelectric transformation. The 1×2 coupler is used to form line-based configuration. Because of optical paths, four forms of transmission channels for light beams will be got. Their propagation paths are as follows:

a) 1-3-Delay coil-5-7-8-9-8-7-6-4-2.

b) 1-4-6-7-8-9-8-7-5-Delay coil-3-2.

c) 1-3-Delay coil-5-7-8-9-8-7-5- Delay coil -3-2.

d) 1-4-6-7-8-9-8-7-6-4-2.

According to principle of optical interference, only paths (a) and (b) can stably interfere at 3×3 coupler. When single intrusion is applied on the SF, the intrusion signal could be described as the superposition of different sine waves with different frequencies and magnitudes.

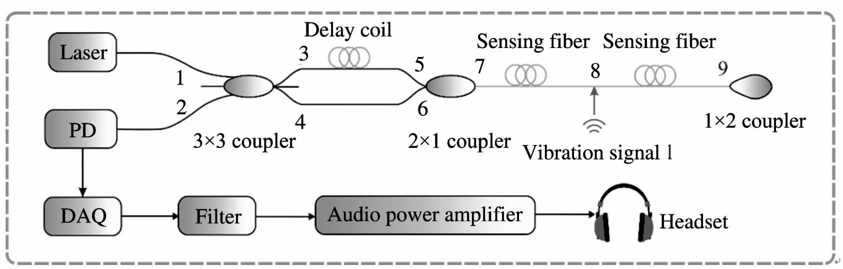


Fig. 1 Schematic of Sagnac distributed optical fiber acoustic detection system

The phase change of the injected light $\varphi(t)$ is[8]

$$\varphi(t) = \sum_{i=1}^{W} \psi_i \sin(\omega_i t + \phi_i), \quad (1)$$

where ψ_i is the amplitude of each single sine component; ω_i is the frequency; ϕ_i is the initial phase; and W is a positive integer. For the sine wave whose frequency is ω_i, both the injected lights in path (a) and path (b) are modulated twice. The phase difference between path (a) and (b) caused by the intrusion can be obtained on the basis of Eq. (1), namely[8]

$$\Delta\varphi_i(t) = \psi_i \{\sin[\omega_i(t+\tau_D)+\phi_i] + \sin[(\omega_i(t+\tau_D+T)+\phi_i]\} -$$

$$\psi_i\{\sin(\omega_i t+\phi_j)+\sin[(\omega_i(t+T)+\phi_i]\} = 4\psi_i \sin\left(\omega_i \frac{nL_d}{2c}\right)\cos\left(\omega_i \frac{nL}{c}\right)\cos\left[\omega_i\left(t-\frac{n(2L_0+L_d)}{2c}\right)+\phi_i\right], \quad (2)$$

where τ_D and T are the time consumptions that the injected light travels through delay coil and 8-9-8 in path (a), respectively; L_0 and L_d are the lengths of SF and the delay coil, respectively; L is the distance between the intrusion point and 1×2 coupler; n is the refractive index of the fiber and c is the light speed in vacuum.

When $\sin(\omega_i nL_d/(2c))\cos(\omega_i nL/c)$ is equal to zero, the frequency components satisfied it will disappear in the spectrum of the phase difference signal. These frequencies are called null frequencies. There are two possible reasons that $\sin(\omega_i nL_d/(2c)) \times \cos(\omega_i nL/c)$ equals zero or $\cos(\omega_i nL/c)$ equals zero. In this lase, $\omega_i nL/c$ is equal to $k\pi+\pi/2$. Thus, the null frequency f_{null} can be given by[10]

$$f_{null} = \frac{\omega_i}{2\pi} = \frac{(2k-1)c}{4nL}. \quad (3)$$

The other is $\sin(\omega_i nL_d/(2c))$ is equal to zero. In this case, $\omega_i nL_d/(2c)$ is equal to $k\pi$. Therefore, the null frequency $f_{null'}$ satisfies

$$f_{null'} = \frac{\omega_i}{2\pi} = \frac{(k-1)c}{4nL_d}. \quad (4)$$

When L_d is short enough, the value of null frequency $f_{null'}$ is so big that its effect can be ignored. Thus, by using fast Fourier transform (FFT) for $\Delta\varphi(t)$ to demodulate the interference light intensity, the frequency spectrum with obvious period signal could be obtained. After the values of the null frequencies are picked out, the intrusion location could be obtained according to Eq. (3)[11] as

$$L = \frac{(2k-1)c}{4nf}. \quad (5)$$

2 Experimental results

The linear Sagnac distributed optical fiber acoustic detection system is built as shown in Fig. 2.

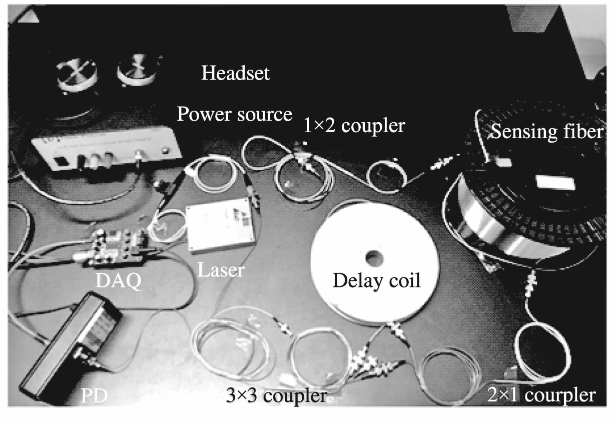
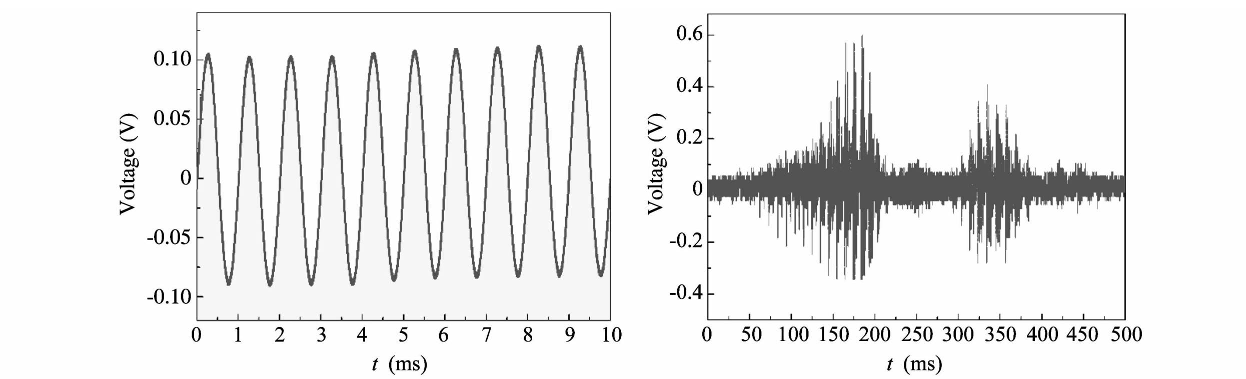


Fig. 2 Linear Sagnac distributed optical fiber acoustic detection system

The total length of the sensing fiber is 6.2 km. To detect the ability of the retransmit acoustic signal of the optical fiber acoustic detection system, sinusoidal sound signal whose frequency is 1 kHz is used in the system. The testing result is shown in Fig. 3.



(a) 1 kHz sinusoidal signal (b) Irregular sound signal of "Hello"

Fig. 3 Experimental results applying different signals to linear Sagnac distributed optical fiber acoustic detection system

As seen in Fig. 3(a), the sinusoidal signal period is 1 ms. The distributed optical fiber acoustic detection system can detect periodic acoustic signal, which is consistent with the signal imposed. From Fig. 3(b), it can be observed that the distributed optical fiber acoustic detection system can detect acoustic irregular which is irregular.

To further evaluate the acoustic detection ability of the system, the frequency of the sound is changed. The response results of this fiber acoustic detection system are shown in Fig. 4.

As demonstrated in Fig. 4, when frequency is changed from 20 Hz to 20 kHz, all of them can be detected. It can be concluded that linear Sagnac distributed optical fiber acoustic detection system can detect acoustic signals with different frequencies well.

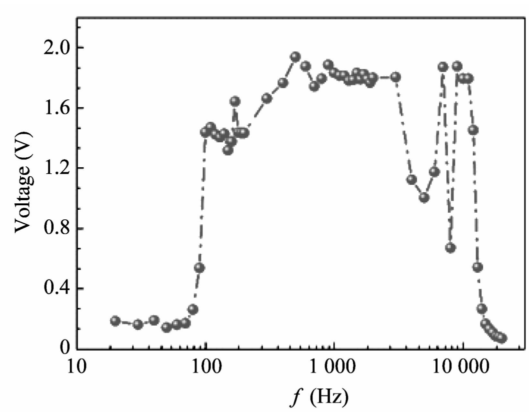


Fig. 4 Experimental results applying signals with different frequencies

In the experimental process, piezoelectric transducer driven by an electrical signal generator applys a pulse signal to the end of the fiber. The frequency of the electrical signal generator changes from 1 kHz to 60 kHz. The distance between vibration position and the end of the sensing fiber is 6.2 km. The spectra curves of simulation and experimental results are presented in Fig. 5.

As shown in Fig. 5, the results of this experiment conform to that of the simulation. The value of the actual null frequency is close to the theortical value and the vibration position can be calculated by null frequency, which demonstrates that locating position by null frequency is feasible. Additionally, there are multiple null frequencies in the spectra curves and the frequency of the null frequency is a arithmetic progression tolerance. These results conform to Eq. (5) and these observed null frequencies are countable.

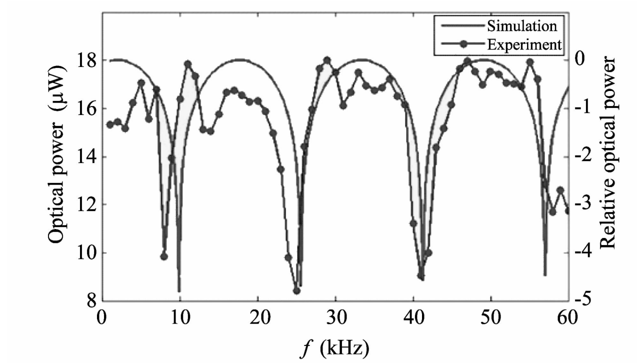


Fig. 5 Spectra curves under different frequencies

The detailed results are tabulated in Table 1.

The average values of the localization error is 105 m.

Table 1 Localization results for optical fiber acoustic detection system

Index	1st null frequency	2nd null frequency	3rd null frequency	4th null frequency
Frequency (kHz)	8	25	41	58
Locating position (m)	6 465	6 206	6 307	6 242
Localization error (m)	265	6	107	42

3 Conclusion

In this paper, a distributed optical fiber acoustic detection system based on Sagnac is presented. The localization method for this interferometer acoustic detection system is investigated. The discussion of the working principles and analysis of the localization method are completed. Theory analysis and experiment results demonstrate that the proposed method can realize the acoustic signal detection and location accurately. The results show that this optical fiber sensor has promising potential in the application of acoustic localization.

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基于 Sagnac 的分布式光纤传感声学传感器

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摘　要： 介绍了一种基于 Sagnac 的分布式光纤声学传感器。这种声学传感器通过光电探测器、数据采集卡、滤波器和音频放大将 3×3 耦合器处干涉的光信号转换为电信号且实现音频信号的还原。为了研究此分布式光纤声学传感器的性能，分析了基于零频点实验声源扰动定位的原理，并运用快速傅立叶变换将时域信号转化为频域信号显示声源扰动产生的零频点。实验结果表明，基于 Sagnac 的分布式光纤声学传感系统可以很好地实现声音信号的还原和定位。

关键词： Sagnac；声音传感；零频点；定位

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