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Low coherence fiber differentiating interferometer and its passive demodulation schemes

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ABSTRACT

In this paper, a low coherence fiber differentiating interferometer and its passive demodulation schemes are presented and experimentally demonstrated. The interferometer which adopts a broadband light resource and balanced detection is a hybrid configuration of Mach–Zehnder and Sagnac interferometer. The two passive demodulation schemes employ an approximate method and a differential-and-cross-multiply (DCM) method to obtain the vibration signal. The phase measurement resolution (PMR) of both methods can reach 6×10^{-5} rad. Comparing with the approximate method which is usually adopted to restore weak signal, the experiment results demonstrated the dynamic range of the DCM demodulation method has increased 30 dB, which extends the measurement range and can be used widely in various physical fields.

1. Introduction

Interferometer fiber sensor can be used to detect many kinds of physical parameters; for example, temperature, pressure, magnetic field, acoustics, etc. [1–3]. There has been of considerable interest recently in the development of fiber optic sensors based on white light interferometer [4–6].

Low-coherence interferometer is very promising to be used in long-distance and large-area monitoring applications, such as the security inspection of communication trunk, power transmission line, and oil and natural gas pipelines [5,7]. It has many advantages over conventional interferometric systems: the sensing system is insensitive to low frequency phase disturbance and polarization disturbance, the demodulation process is relatively simple, and this system is of low cost and stable [2,8]. Fiber-optic sensors based on the white-light interferometry proved to be convenient devices provide the combination of absolute measurements with a large dynamic range and high accuracy [9].

Signal demodulation plays an important role in fiber optic interferometer sensor technology. So far, several demodulation approaches have been reported, including a true heterodyne scheme [10–12], active homodyne scheme using phase generated carrier (PGC) and differential-and-cross-multiply (DCM) approach [13–15], as well as a passive homodyne scheme with a 3 × 3 fiber coupler [16,17].

Recently fiber differentiating interferometer based on phase compress is commonly used in order to obtain the measurement signal [18,19]. The approximation equation $\sin\varphi \approx \varphi$ and $\arcsin\varphi$ are usually used [20]. Both of them can obtain the signal under test, but they also have many disadvantages. The result of approximation is intolerable if the modulation φ is too large. That is to say, the linear range and dynamic range can be limited. An arcsine function can be applied to the output signal resulting in a linear relationship between the measured and output phase from $-\pi/2$ to $\pi/2$. If the phase change exceeds one interference fringe, this method will not make sense. In this paper, in order to extend the dynamic range of signal demodulation, a hybrid configuration of Mach–Zehnder and Sagnac interferometers which was composed of a 3 × 3 coupler and balanced detection system is adopted. Coincide with a new passive demodulation algorithm, the large dynamic range of signal demodulation is realized.

2. Optical setup

The optical setup of the differentiating fiber-optic interferometer adopting 3 × 3 coupler is shown in Fig. 1. It was a hybrid configuration of Mach–Zehnder and Sagnac interferometers with Amplified spontaneous emission (ASE) light source as the broadband source. The interferometer was composed of a 3 × 3 coupler and a 2 × 2 coupler. C1 is 3 × 3 coupler and C2 is a 2 × 2 coupler. The signal generator was connected to columnar piezoelectric modulator (PZT) to simulate vibration on sensing fiber. And the three terminals of the 3 × 3 coupler were connected to a source

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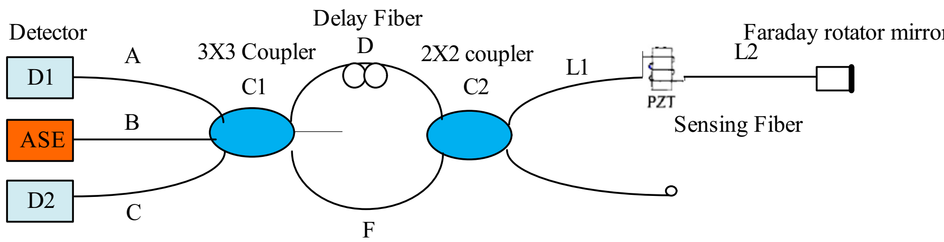

Fig. 1. The schematic diagram of the optical path in the system.

and two detectors respectively. One terminal of the 2×2 coupler was connected to a sensing fiber before Faraday rotator mirror which is used to eliminate decline of the polarization state; the other terminal was looped to eliminate the reflected light. Two terminals between 3×3 coupler and 2×2 coupler were directly connected; the other two are connected through delay fiber D.

Fig. 1 is the schematic diagram of the optical setup. There are four different optical paths from the light to the detector D1, which are expressed as follows

Path1 B-D-L1-L2-L2-L1-F-A
Path2 B-F-L1-L2-L2-L1-D-A
Path3 B-D-L1-L2-L2-L1-D-A
Path4 B-F-L1-L2-L2-L1-F-A

In the experiment, we adopt a fiber ASE source as the light source, and the hybrid interferometer is not an equi-arm interferometer, so the optical path difference between path 3 and 4 is too large to interfere. Paths 1 and 2 have the same optical length but travel different direction. These two lights meet interference condition and can interfere. So, we can adopt a low coherence light source in the setup. According to the linear symmetric coupler theory, for a 2×2 lossless 3 dB coupler, the phase at the uncoupled output fiber is $\pi/2$ rad ahead that of its coupled counterpart. And the coupled output fiber of 3×3 coupler will introduce $2\pi/3$ rad. According to the hybrid interferometer theory analysis [5], the photo current of D1 can be written as follows

$$I_1 = \frac{\eta e}{h\nu}\left\{4E^2 + 2E^2 \cos\left[4\phi_m \sin\omega_s\left(\frac{\tau_d}{2}\right)\cos(\omega_s\tau_x)\cdot\cos\omega_s\left(t-\frac{\tau_t}{2}\right) - \frac{2\pi}{3}\right]\right\} \tag{1}$$

where

$$\tau_T = n(\mathrm{F} + 2L_1 + 2L_2 + D)/C$$

$$\tau_d = [(D - \mathrm{F})n]/C$$

$$\tau_x = (nL_2)/C$$

where E is 1/36 of the intensity of the light source, ω_s is the angular frequency of the sound signal, ϕ_m is the amplitude of the vibration, η is the quantum efficiency of the photodiode, e, h and ν represent electronic charge, Planck constant and laser frequency.

Let

$$t' = t - (\tau_T/2)$$

$$\phi_s(t') = 4\phi_m \sin\omega_s(\tau_d/2)\cos(\omega_s\tau_x)\cos\omega_s(t') \tag{2}$$

When the drive frequency is low and the length of delay fiber is not very long.

$$\sin\omega_s(\tau_d/2) \approx \omega_s(\tau_d/2)$$

$$\cos(\omega_s\tau_x) \approx 1.$$

Then (2) can be expressed as follows

$$\phi_s(t') \approx 4\phi_m(\tau_d/2)\omega_s \cos\omega_s(t') \tag{3}$$

where $4\phi_m(\tau_d/2)$ is a constant, $\phi_s(t')$ is the differentia form of the test signal. And $\phi_s(t')$ is a phase compressed by the setup. That is why the optical setup is called differentiating interferometer [19]. After integration, we can obtain the test signal. Furthermore, from the equation Eq. (3), we can see if the frequency is low, the value of $\phi_s(t')$ is too small to detect. So, the sensing system is insensitive to low frequency phase disturbance, while the interferometers with lasers are deeply influenced by low frequency disturbances such as environmental vibration and temperature variation.

Then (1) can be expressed as

$$I_1 = \frac{\eta e}{h\nu}\left\{4E^2 + 2E^2\cos\left[\phi_s(t') - \frac{2\pi}{3}\right]\right\} \tag{4}$$

Similarly, the light intensity which inputs the detector 2 can be expressed as follows

$$I_2 = \frac{\eta e}{h\nu}\left\{4E^2 + 2E^2\cos\left[\phi_s(t') + \frac{2\pi}{3}\right]\right\} \tag{5}$$

3. Demodulation method

3.1. Approximate method

Fig. 2 is the schematic diagram of the operating principle. In order to obtain the signal $\phi_s(t')$, we adopted an approximate method firstly.

Calculating Eqs. (4,5), we can get

$$I_1 = \frac{\eta e}{h\nu}\{4E^2 - E^2\cos[\phi_s(t')] + \sqrt{3}E^2\sin[\phi_s(t')]\} \tag{6}$$

$$I_2 = \frac{\eta e}{h\nu}\{4E^2 - E^2\cos[\phi_s(t')] - \sqrt{3}E^2\sin[\phi_s(t')]\} \tag{7}$$

Subtracting I_2 from I_1 gives

$$I_3 = I_1 - I_2 = \frac{\eta e}{h\nu}\{2\sqrt{3}E^2\sin[\phi_s(t')]\} \tag{8}$$

If $\phi_s(t')$ was very small $\sin[\phi_s(t')] \approx \phi_s(t')$. Eq. (8) could be expressed as

$$\frac{\eta e}{h\nu}\{2\sqrt{3}E^2\sin[\phi_s(t')]\} \approx \frac{\eta e}{h\nu}[2\sqrt{3}E^2\phi_s(t')] \tag{9}$$

After integration, the weak signal can be obtained through the above method.

But the operating principle has its own limitations. According to (9), we can see the signal is an approximate result. If the signal is too strong, this method will cause serious signal distortion. In order to solve this problem, we can cut down the length of the delay fiber. According to the Eq. (3), we can find if the delay fiber is shorter, the value of will be smaller, which makes it suitable for measuring strong vibration. Furthermore, we also presented the other demodulation method which we called DCM to obtain strong signal.