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Direct measurement of optical phase difference in a 3×3 fiber coupler

Yi Jiang [a,*], Peng-Juan Liang [a], Tianfu Jiang [b]

[a] School of Optoelectronics, Beijing Institute of Technology, Beijing 10081, China
[b] School of Computer Science, Civil Aviation Flight University of China, Guanghan, Sichuan 618308, China

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ABSTRACT

The precise phase difference in a 3×3 coupler is calculated by using Fourier transform based white-light interferometry. The phase relationships between any two of the three outputs are directly measured, and the result is in agreement with the ideal value. The phase difference of two re-constructed signals in a 3×3 coupler is also measured. In a passive homodyne system, this technique is helpful in removing the distortion of the demodulated signals, which is caused by imperfect properties of the 3×3 coupler.

1. Introduction

Fiber optic interferometric sensors have an advantage of high sensitivity compared with intensity type sensors, fiber Bragg grating sensors, and polarization type sensors [1]. Four of the most widely used two-beam interferometric configurations are: Mach–Zehnder, Michelson, extrinsic Fabry–Perot interferometer (EFPI), and Sagnac. In an interferometric system, a proper demodulation technique is needed to provide automatic linearized and real-time output. The demodulation techniques may be classified as passive homodyne, active homodyne, and heterodyne. The passive homodyne demodulation provides two interferometric outputs with 90° phase difference or three outputs with 120° phase difference. The phase change in an interferometer is directly recovered by detection electronics. This technique is easy to operate, and the operation frequency is only limited by electronics. However, the passive homodyne method requires a special component: a 3×3 fiber coupler [2] or a 4×4 fiber coupler [3]. In particular, 3×3 couplers are widely used in the passive homodyne method, because they are easy to manufacture at a low cost.

In an ideal 3×3 coupler, there is a 120° phase difference between any two of the three output ports. The three outputs can be used to recover the phase shift directly [4,5]. The three outputs can also be re-constructed to obtain two outputs with a 90° phase difference, and a differential cross multipler (DCM) algorithm is used to recover the phase shift [6]. However, the performance of the demodulation technique depends on the characteristics of the 3×3 coupler. It is usually assumed that all three outputs differ in phase by 120° in a symmetric 3×3 coupler. In fact, this assumption is questionable. Zhao et al. [7] and Shih et al. [8] have investigated the distortion caused by the imperfect properties of the 3×3 coupler. If we could measure the phase difference of a 3×3 coupler, the distortion could be compensated [9,10] and we could recover the phase modulation correctly.

Some methods have been proposed to measure the phase difference of a 3×3 coupler. Because the frequency of light is too high to measure, all methods need to construct an interferometer by using a 2×2 coupler and a 3×3 coupler and to measure the phase difference indirectly. Refs. [11–14] deduced the phase difference by measuring the power of the outputs. This method is limited by the splitting ratio fiber loss, and photo-electric amplifier. The phase difference can also be determined from the inclination of the Lissajous figure [10]. The method is realized by measuring the size of the Lissajous figure on the screen, and it achieves only a rough result. In this paper, we measure the phase difference between two output ports directly by using a white-light interferometry based technique. We have demonstrated a spectral domain white-light interferometry, named Fourier transform white-light interferometry [15], in which the phase change in an interferometer caused by the scanning wavelength can be recovered by a Fourier transform based algorithm. In this paper, we demonstrate that the phase difference between any two beams in a 3×3 coupler can be measured directly with high precision in a similar way. Different from the previous work described in Ref. [15], we measured the phase difference between two signals in this paper, and Ref. [15] measured the phase change of one signal. The measured object in Ref. [15] is an extrinsic Fabry–Perot interferometer, and in this paper is a 3×3 coupler.

2. Principle

The experimental setup for investigating the phase difference between two output ports in a 3×3 coupler is shown in Fig. 1. A

* Corresponding author. Fax: +86 10 68913586.
E-mail address: bitjy@bit.edu.cn (Y. Jiang).

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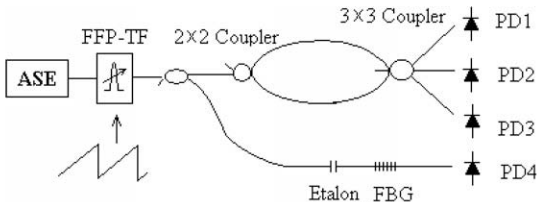

Fig. 1. Measurement setup.

2×2 coupler and a 3×3 coupler are used to construct a Mach–Zehnder interferometer, and an amplified spontaneous emission (ASE) source with wavelength covering 1525–1565 nm and 20 mW of output power is used as a broadband source to illuminate a fiber Fabry–Perot tunable filter (FFP-TF) supplied by Micron Optics Inc. The tunable filter has a bandwidth of 0.325 nm and a finesse of 200, so the free spectrum range is 65 nm. The output of the FFP-TF is a wavelength-scanning light with a bandwidth of 0.325 nm. A sawtooth-wave generator is triggered by a computer to produce a linear-scanning voltage, and the voltage is used to drive the FFP-TF. The wavelength-scanning light is divided into two beams by a coupler. One beam is injected into the 3×3 coupler based Mach–Zehnder interferometer, and three outputs are detected by PD1, PD2, and PD3, respectively. This beam is used to detect the three optical spectra when scanning wavelengths. Another beam is injected into an etalon combined with a fiber Bragg grating, and the transmission light is detected by PD4. This beam is used to obtain the scanning wavelength when the FFP-TF is tuning [16].

The three white-light spectra detected can be expressed as

$$g_k(\lambda) = b_k(\lambda) + c_k(\lambda)\cos\left[\frac{2\pi}{\lambda}nD - \varphi_k\right], \quad k = 1, 2, \text{ or } 3 \tag{1}$$

where k is a labelling index having a value of 1, 2, or 3 and indicates the three outputs, $b(\lambda)$ is the background introduced by the profile of the light source, $c(\lambda)$ is the contrast determined by the polarization state and coupling ratio of the coupler, n is the refractive index, D is the path difference, and thus nD is the optical path difference (OPD). The phase difference between two of the three signals is in fact the phase difference between two output ports in a 3×3 coupler.

Eq. (1) can be rewritten as

$$g_k(\lambda) = b_k(\lambda) + c_k(\lambda)\cos[2\pi f_0\lambda + \varphi_k], \quad k = 1, 2, \text{ or } 3 \tag{2}$$

$$\text{where } f_0 = \frac{nD}{\lambda^2} \tag{3}$$

f_0 is the carrier frequency and is dominated by the OPD. Eq. (2) is firstly Fourier transformed and we obtain Fourier spectra as follows:

$$G_k(f) = B_k(f) + C_k(f - f_0) + C_k^*(f + f_0), \quad k = 1, 2, \text{ or } 3 \tag{4}$$

where $*$ denotes a complex conjugation, and the upper-case letters denote the Fourier spectra. If the OPD is significantly large, the carrier frequency f_0 becomes much larger than the spread of the spectra caused by the variation of $b_k(\lambda)$ and $c_k(\lambda)$, and thus the three spectrum components in Eq. (4) are separated by the carrier frequency f_0. We select one spectrum $C_k(f - f_0)$ from Eq. (4) by a band-pass filter. Then, we compute the inverse Fourier transform of $C_k(f - f_0)$ and obtain the analytic signals

$$g_k(\lambda) = \frac{1}{2}c_k(\lambda)\exp[j(2\pi f_0\lambda + \varphi_k)], \quad k = 1, 2, \text{ or } 3 \tag{5}$$

Then, we calculate a complex logarithm with two signals $g_i(\lambda)$ and $g_j(\lambda)$ as

$$\begin{aligned} h_{ij}(\lambda) &= \ln[g_i(\lambda) * g_j^*(\lambda)] = \ln\left[\frac{1}{4}c_i(\lambda)c_j(\lambda)\right] + j(\varphi_i - \varphi_j) \\ &= \alpha(\lambda) + j\Delta\varphi_{ij}, \quad i \neq j, \text{ and } i, j = 1, 2, \text{ or } 3 \end{aligned} \tag{6}$$

Now, we have the phase difference $\Delta\varphi_{ij}$ between any two outputs in the imaginary part of Eq. (6), which is separated from the unwanted background $b_k(\lambda)$ and amplitude variation $c_k(\lambda)$.

3. Experiments

When the FFP-TF scans the wavelength, we detect three interferometric outputs from the 3×3 coupler and one output from the etalon. The three interferometric signals are used to measure the phase shifts in the 3×3 coupler, and the output from the etalon is used to calibrate the scanning wavelength [16]. One of the interferometric outputs is shown in Fig. 2a, and the other two signals are almost the same except that the phase is different. The horizontal axial in Fig. 2a is the equal-time sampling index. Fig. 2b shows the Lissajous figure between two of the three outputs, in which there is little difference from a conventional Lissajous figure [5]. There are many ellipses in Fig. 2b which are produced by the light source profile. We can roughly deduce that the phase shift of the 3×3 coupler is 120° from the inclination of the Lissajous figure.

The phase differences are measured as wavelength scans from 1530 nm to 1565 nm. One of the results is shown in Fig. 3. We find that the phase difference remains unchangeable when the wavelength is changed. Continuous measurement results for the three phase differences are shown in Fig. 4. The variation in Fig. 4 is ±0.004 rad, or 0.229°. The average phase differences between two

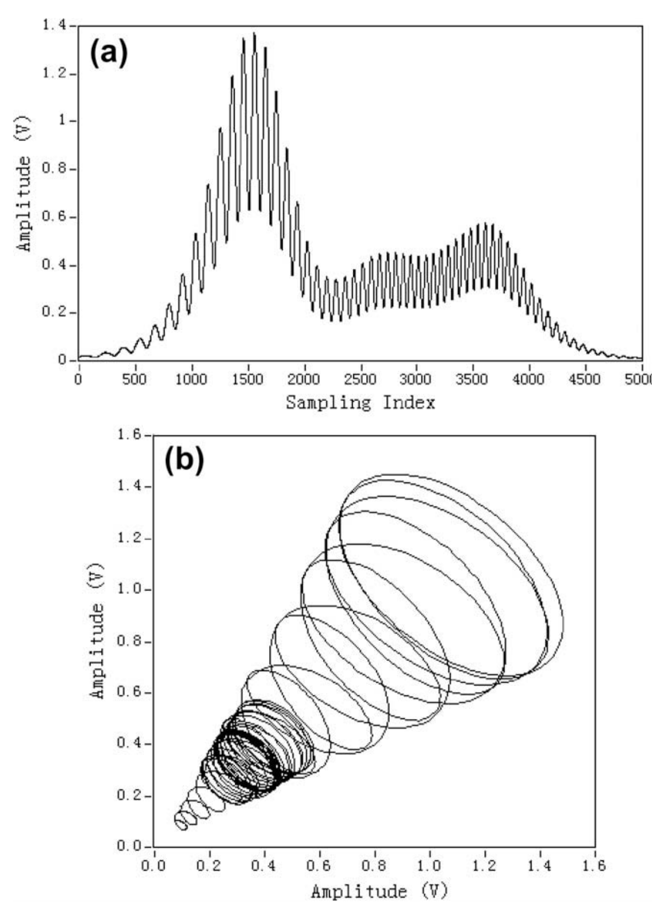

Fig. 2. (a) One of the sampled datum arrays when scanning the FFP-TF. (b) The Lissajous figure between two of the three outputs.