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RESEARCH ARTICLE

A simple method for measuring dynamic phase changes in a homodyne interferometric fiber-optic sensor

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Abstract A simple but reliable measurement method for the dynamic phase shift in a passive homodyne interferometric fiber-optic sensor is proposed. The amplitude of the dynamic phase shift is calculated directly from the photodetector output. A Mach-Zehnder interferometer with a PZT, which is used to generate the simulation signal, is constructed. The experimental results obtained using this simple method are well in agreement with the results given by the standard phase generated carrier (PGC) method, which shows the validity of the results. This new method has the advantages of simplicity of operation, no active element in the sensing head, no modulation to the laser, large dynamic range and working bandwidth, etc. It can be used for the dynamic phase shift measurement of various interferometric fiber-optic sensors.

Keywords fiber-optic sensor, interferometer, fiber-optic hydrophone, acoustic sensitivity, phase generated carrier (PGC) demodulation, heterodyne

1 Introduction

Interferometric fiber-optic sensors have shown high sensitivity and large dynamic range in their response to applied strain, temperature, and electric and magnetic fields [1,2]. The output of an interferometric sensor is a nonlinear and cosinusoidal function of the phase difference between the optical waveguides in the two arms. Hence, a linear measurement of the signal's phase shift from the photodetector output is not possibly direct. The phase difference may be divided into two components: a slowly changing random phase shift induced mainly by ambient temperature fluctuations, and a rapidly changing dynamic phase modulation induced by a harmonically varying measurand [3]. The amplitude of the output signal will vary unpredictably due to the random phase shift, which makes the readout of the dynamic phase shift in an interferometric fiber-optic sensor more difficult [4–8].

To recover the dynamic phase shift, many methods have been developed [2–18]. These schemes mainly include phase tracking and compensating methods, a passive homodyne method using a 3 × 3 directional coupler, phase generated carrier (PGC) modulation and demodulation, and various heterodyne methods. Among these methods, phase tracking and most of the heterodyne methods have the advantage of simplicity. However, the use of a bulky piezoelectric transducer for phase compensation and the additional use of an acousto-optic or integrated optic frequency shifter in one arm of the fiber interferometer in various heterodyne methods are undesirable in many applications. A passive homodyne method can be achieved by using PGC or a 3 × 3 directional coupler, but the signal demodulation of PGC is very complicated and a high performance 3 × 3 directional coupler must be required in the latter. In several applications, there is a need for a simple, passive and reliable method of measuring the signal's phase shift.

In this paper, a simple passive homodyne method is proposed. The dynamic phase shifts in an interferometric fiber-optic sensor are obtained directly from the photodetector output. This phase measurement technique has the advantages of simplicity, no-feedback, large dynamic range and working bandwidth, etc. It is feasible to apply the optical interferometer generally for the measurement of dynamic sinusoidal displacements.

2 Principles

The instantaneous voltage at the photodetector output can be written as

$$V(t) = A + B\cos[x\sin(\omega_s t + \varphi_s) + \varphi_0(t)], \tag{1}$$

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where $A = 2\upsilon$ and $B = 2\upsilon b$ (with υ the voltage due to either of the fiber outputs and b the interferometer mixing efficiency), x is the modulation depth, ω_s is the angular frequency of the signal phase shift, φ_s is a phase constant, and $\varphi_0(t)$ is the slowly varying random phase due to ambient temperature and pressure variations. Expanding the cosinusoidal function in Eq. (1) in terms of the first kind of Bessel function $J_n(x)$ as follows

$$\begin{aligned} V(t) &= A + BJ_0(x)\cos\varphi_0(t) \\ &- \left\{2B\sum_{k=1}^{\infty} J_{2k-1}(x)\sin[(2k-1)(\omega_s t + \varphi_s)]\right\}\sin\varphi_0(t) \\ &+ \left\{2B\sum_{k=1}^{\infty} J_{2k}(x)\cos[2k(\omega_s t + \varphi_s)]\right\}\cos\varphi_0(t). \end{aligned} \quad (2)$$

After passing through a low-pass filter which can eliminate components above the fundamental frequency, $V(t)$ becomes

$$\begin{aligned} V(t) &= A + BJ_0(x)\cos\varphi_0(t) \\ &-2BJ_1(x)\sin\varphi_0(t)\sin(\omega_s t + \varphi_s). \end{aligned} \quad (3)$$

From Eq. (3), we can see that $V(t)$ is approximately a sinusoidal signal with a frequency ω_s, and a DC component for the varying rate of $\varphi_0(t)$ is far slower than ω_s. The amplitudes of the DC and AC components of $V(t)$ are given by

$$V_{DC} = A + BJ_0(x)\cos\varphi_0(t), \quad (4)$$

$$V_{AC} = 2BJ_1(x)\sin\varphi_0(t). \quad (5)$$

From Eqs. (4) and (5), Eq. (6) can be obtained using the basic relation of $\sin^2 x + \cos^2 x = 1$ as

$$G^2J_0^2(x) + H^2J_1^2(x) = J_0^2(x)J_1^2(x), \quad (6)$$

where, $G = V_{AC}/(2B)$ and $H = (V_{DC} - A)/B$. All the nonzero solutions of Eq. (6) over a given range of x can be given by the numerical method, and are labeled as $x_1, x_2, ..., x_n$, respectively. A corresponding $\varphi_{0N}(t)$ can be obtained by substituting x_N into Eq. (4) or (5), where $N = 1,2,...,n$. Then n matching functions can be constructed using the n groups of parameters (x_N, $\varphi_{0N}(t)$) as follows:

$$V_N(t) = A + B\cos[x_N \sin\omega_s t + \varphi_{0N}(t)], \quad N = 1,2,...,n. \quad (7)$$

The correlation coefficients of each matching function $V_N(t)$ with $V(t)$ also can be given by the numerical method, and are labeled as $c_1, c_2, ..., c_n$, respectively. Assume that the biggest one is c_I, and the corresponding group of parameters is (x_I, $\varphi_{0I}(t)$), therefore the amplitude of the dynamic phase shift, i.e., the modulation depth x, is equal to x_I.

3 Experiments

To test the novel dynamic phase measurement method described above, a homodyne Mach-Zehnder interferometer which uses panda polarization maintaining fiber is constructed, as shown in Fig. 1. About five meters of fiber are wound on a PZT cylinder forming the signal arm, and an AC voltage is applied from a function generator, which works at 1 kHz. A fiber ring laser with a center wavelength 1550 nm is used as a light source. The output signal from the photodetector is amplified and fed to a digitizing oscilloscope, which samples the analog output of the photodetector. The digitizing oscilloscope (type of TDS5000B, Tektronix, USA) is able to capture the signal in such a short time period that the variation of $\varphi_0(t)$ can be neglected, and which implies that $\varphi_0(t)$ can be regarded as a constant for each single measurement. A personal computer is used to store the data and perform digital signal processing, which includes fast Fourier transform (FFT), low-pass filtering, and calculations for the amplitude of the dynamic phase shift x, as shown in Eqs. (3)–(7). From the principle introduced above, we can see that A and B must be known for calculating the modulation depth x. To obtain A and B, a large amplitude (ensure $x > \pi$), high frequency, and linear voltage are applied to PZT, and the photodetector output is a cosinusoidal signal approximately. Find a neighboring group of maximum and minimum $V(t)$, marked as V_{max} and V_{min}. From Eq. (1), we know that $V_{max} = A + B$ and $V_{min} = A - B$, therefore

$$A = (V_{max} + V_{min})/2, \quad (8)$$

$$B = (V_{max} - V_{min})/2. \quad (9)$$

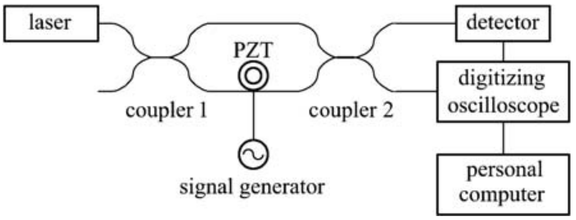

Fig. 1 Experimental setup showing fiber-optic Mach-Zehnder interferometer

To show the validity of the results obtained by the simple method described above, a comparison is done with the results obtained by the standard PGC method, as shown in Fig. 2. From the figure, it can be shown that the results given by the simple method are well in agreement with the results given by the PGC method, and the

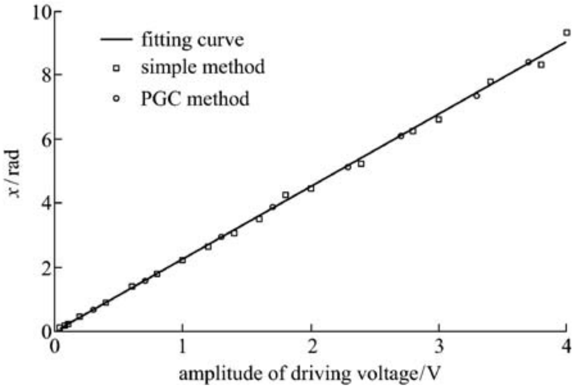

Fig. 2 Experimental phase shift as a function of voltage applied to PZT at 1 kHz

modulation depth x is a linear function of the voltage applied to the PZT, as expected. The phase modulation coefficient of the PZT (the phase shift per unit applied voltage) is calculated from Fig. 2 to be about 2.25 rad/V.

4 Conclusions

In conclusion, a simple and reliable measurement method for the dynamic phase shift in a homodyne interferometric fiber-optic sensor is demonstrated. The amplitude of the dynamic phase shift is calculated directly from the photodetector output. This novel method has the advantages of simplicity of operation, no active element in the sensing head, no modulation to the laser, a large dynamic range and working bandwidth, etc. It can be used for the dynamic phase shift measurement of various interferometric fiber-optic sensors.

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