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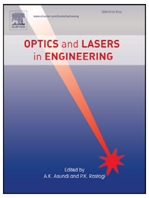

# Phase-shifting optical fiber sensing with rectangular-pulse binary phase modulation

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## ABSTRACT

We propose and demonstrate a new method of phase-shifting optical fiber sensing, wherein rectangular-pulse binary phase modulation is imposed on the laser source of an interferometric fiber optic sensor to generate three phase-shifting steps of $-\pi/2$, 0, and $\pi/2$ radians at the output, and the phase shifts that carry the vibration signals are demodulated with an orthogonal demodulation algorithm. This approach offers the advantages of high efficiency and low complexity because it is simple in design and implementation. Moreover, this method can be applied to successfully realize the demodulation of multiplexed systems based on different multiplexing techniques. The techniques are theoretically analyzed and experimentally demonstrated with recovering the sinusoid wave applied to the sensor. Also, in this paper, a simple multiplexed system is proposed and discussed.

## 1. Introduction

Fiber optic sensors have attracted considerable attention because of their high sensitivity, immunity to electromagnetic interference, high-temperature performance and ease of application to networking and multiplexing for tens of years [1–8]. In particular, interferometric fiber optic sensors (IFOSs) have been widely used in earthquake forecasting, oil exploration and security monitoring for their high sensitivity [9–19].

In IFOSs, the methods of detecting the relative optical phase shifts between the signal and reference arms form a very important part of sensing. In this regard, researchers have developed several detection techniques such as the phase-generator carrier (PGC) homodyne or heterodyne techniques [20–22], path-matched differential interferometry (PMDI) [23,24], and 3 × 3 coupling multi-phase detection [25,26]. The PGC technique and PMDI technique provide the advantages of high sensitivity and are easy to be employed for the multiplexing technology, but they require relatively complex demodulation. The 3 × 3 coupling multi-phase detection can meet the demand of large signal demodulation, but it is complex when used in multiplexed system, because there are three outputs per sensor.

In this scenario, we propose a new method of phase-shifting optical fiber sensing. The key element here is the rectangular-pulse binary phase modulation imposed on the laser source of the IFOS, through which we can realize three phase-shifting steps of $-\pi/2$, 0, and $\pi/2$ radians at the output, and subsequently, we can obtain the phase shifts that carry the vibration signals via an orthogonal demodulation algorithm [27,28]. To the best of our knowledge, this is the first time that such a phase modulation has been applied in the IFOS. It is simple in design and implementation because there are no any extra elements needed. Our approach offers the advantages of high efficiency and low complexity. In addition, the rectangular-pulse signal is advantageous for high-speed modulation.

## 2. Structure principle and experiment analysis

The schematic of the proposed method is shown in Fig. 1. A laser with a narrow line-width and continuous output is used as the light source. The isolated continuous light from the source is modulated by a phase modulator (PM). A stable rectangular pulse signal is generated by the PM driven by a high-frequency signal generator. Subsequently, the light beam transfers along the reference and signal arms through a 2 × 2 coupler. Both sets of signals are reflected by Faraday rotator mirrors (FRMs 1 and 2), and the reference and signal light beams interact with each other at the output of the 2 × 2 coupler. Finally, the interference light intensity signal is acquired by a photo-detector (PD) and processed by an oscilloscope (OSC). At the same time, there is a reference pulse transmitted directly to the OSC for demodulation.

The complex amplitude of the light source that is modulated by the PM is represented by $E$ with the amplitude $A_0$ can be expressed as [29]

$$E = A_0 \exp(-j2\pi \upsilon t + \varphi(t)), \tag{1}$$

where $j$ denotes the imaginary unit, $\upsilon$ the center frequency of the light source, and $\varphi(t)$ the modulated phase. This last parameter can be

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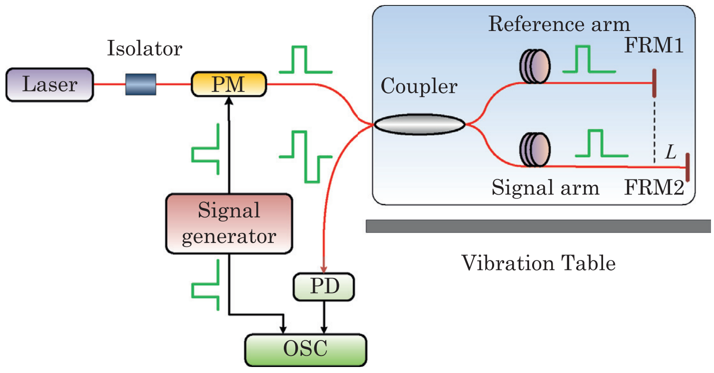

**Fig. 1.** Schematic of the fiber optic interferometer.

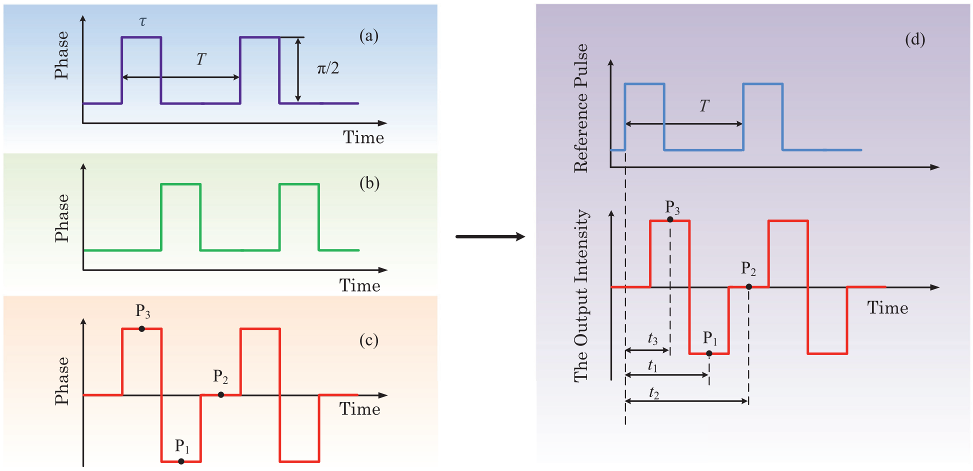

**Fig. 2.** Time and phase relationships between the modulated phase terms and reference pulse $\varphi(t)$, $\varphi(t-\tau)$, and $\varphi(t)-\varphi(t-\tau)$. (a) $\varphi(t)$; (b) $\varphi(t-\tau)$; (c) $\varphi(t)-\varphi(t-\tau)$; (d) Time intervals $t_1, t_2, t_3$, between the three points P1, P2, P3 and the rising edge of reference pulse.

written as

$$\begin{aligned}&\varphi(t)=\pi/2, kT\le t<\tau+kT,\\&\varphi(t)=0, \tau+kT\le t<(k+1)T,\end{aligned}\tag{2}$$

where $k$ represents a non-negative integer, $T$ the cycle of the rectangular pulse, $\tau$ the duration of the rectangular pulse, and $3\tau\le T$.

The phase of the modulated light source is shown in Fig. 2(a). After modulation, the light beam is split along the signal and reference arms via the $2\times 2$ coupler. The length difference of the two arms is $L$. Further, we have $\tau=2nL/c$, where $n$ denotes the refractive index of the fiber and $c$ the speed of light. The electric fields of the reference ($E_r$) and signal ($E_s$) light beams can be written as

$$\begin{aligned}&E_r=A_r\exp(-j2\pi\upsilon t+\varphi(t)+\varphi_r),\\&E_s=A_s\exp(-j2\pi\upsilon(t-\tau)+\varphi(t-\tau)+\varphi_s),\end{aligned}\tag{3}$$

where $\varphi(t)$ and $\varphi(t-\tau)$ represent the modulated phase terms. The phase waveform corresponding to $\varphi(t-\tau)$ is shown in Fig. 2(b). Parameters $\varphi_r$ and $\varphi_s$ represent the phase shifts in the reference and signal arms, respectively, as generated by the vibration. The combined amplitude at the output can be expressed as $E_O=E_r+E_s$, and the output light intensity $I$ is expressed as follows [29]:

$$I=E_0E_0^*=A+B\cos(\varphi(t)-\varphi(t-\tau)+\varphi_1+\varphi_0),\tag{4}$$

where $A$ and $B$ are proportional to the optical power, and $B$ also depends on the mixing efficiency of the interferometer. Further, $\varphi(t)-\varphi(t-\tau)$ represents the modulated term, whose phase waveform is shown in Fig. 2(c). In addition, $\varphi_1=\varphi_r-\varphi_s$ represents the phase shifts caused by the vibration, and $\varphi_0=2\pi\upsilon\tau$ the initial phase term.

Upon assuming $\theta=\varphi_1+\varphi_0$, the total intensity $I$ can be divided as follows:

$$\begin{aligned}&I_1=A+B\cos(\theta-\pi/2), \tau+kT\le t<2\tau+kT,\\&I_2=A+B\cos(\theta), 2\tau+kT\le t<(k+1)T,\\&I_3=A+B\cos(\theta+\pi/2), kT\le t<\tau+kT,\end{aligned}\tag{5}$$

Assuming that the period of the vibration signal is $T_1$, in the practical case, we have $T\ll T_1$, and thus, it can be considered that the vibration signal remains unchanged over the time period $0<t<T$. The OSC receives the output intensity and the reference pulse. Subsequently, we obtain the three light intensities $I_1$, $I_2, I_3$, corresponding to the three points P$_1$, P$_2$, and P$_3$ according to the calibration of $t_1$, $t_2, t_3$ which represent the time intervals between the three points P$_1$, P$_2$, P$_3$ and the rising edge of reference pulse shown in Fig. 2(d). The scheme of orthogonal demodulation algorithm is shown in Fig. 3. Using the orthogonal demodulation algorithm and removing the constant terms $A$ and $B$, we obtain $\theta$ as follows [27, 28]:

$$\theta=\arctan(I_s/I_c),\tag{6}$$

where $I_s=I_1-I_3$ and $I_c=2I_2-(I_1+I_3)$. After elimination of the initial phase term $\varphi_0$, the vibration signal $\varphi_1$ can be demodulated. The process of data acquisition is not complex and we just need three sampling points in one modulation cycle $T$.

We next tested the validity of our proposed IFOS via experiments. A laser source (developed independently by our laboratory, the center wavelength of 1552.596 nm and the line-width smaller than 1000 Hz) was used to generate a continuous light beam. A phase modulator (JDSU Inc. PM–150–005) driven by a Tektronix signal generator was used to generate high-frequency rectangular pulses with 28-ns duration