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A modified phase generation carrier technique for fiber-optic distributed disturbance sensor

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ABSTRACT

A modified phase generation carrier technique used in fiber-optic distributed disturbance sensor (FDDS) is proposed and investigated. The FDDS locates the disturbance by dual Mach–Zehnder (MZ) interferometers, however, the initializing phase error of the two MZ interferometer causes the location errors. For the modified PGC technique, a narrow band analog low pass filter is designed, which solves the problem of facilitating the digital narrow band low pass filter in high speed A/D acquisition. In addition, a special demodulation signal is proposed to demodulate higher-order harmonic, compensate the time delay of the long optical fiber and enhance the signal to noise ratio. It is found that the location errors caused by phase drift can be eliminated in our experiments.

1. Introduction

Fiber-optic distributed sensor has attracted a lot of interests due to its long monitoring length, high sensitivity and simple structure with passive sensing element. As a member of the fiber-optic distributed sensor, fiber-optic distributed disturbance sensor (FDDS) can detect, identify and locate the disturbance signal through the Mach–Zehnder (MZ) interferometer. Because of its long monitoring length (60 km) and high accuracy, the FDDS has been widely utilized in intrusion detection and pipeline monitoring [1–20].

The FDDS is realized by dual MZ interferometers. The locating principle is based on the time difference of the two photo detectors. In a MZ interferometer, the non-reciprocity of light path, the polarization variation and environment induced phase noise can produce low-frequency phase drift. This unexpected phase drift will generate variable time difference and result in location errors eventually. In general, several methods can eliminate the effect of the low-frequency phase drift [21–29]:

- 3×3 coupler modulation technique.
- Close-loop operating point control technique.
- Phase generation carrier (PGC) technique.

However, the structure of 3×3 coupler technology is complex, because this technique induces additional phase difference, which is not suitable in the FDDS for locating disturbance. Close-loop operating point control technique is not able to be utilized in practical application because it cannot realize the passive sensing element. The conventional digital phase generation carrier technique is also not effective for MZ interferometer based FDDS, which need to modulate broadband large-signal and locate the disturbance along the long optical fiber. In general, there are three problems for conventional PGC technique for FDDS:

(1) Narrow band low-pass filter of conventional digital PGC is difficult to realize in long-term FDDS with high sampling frequency due to the hardware limit [24–26].
(2) Owing to the long optical fiber used in an FDDS, there is a time delay in the phase modulated carrier, which brings on the location errors. This time delay is expected to be compensated. However, the time delay has not been considered in the conventional digital PGC [24–26] because of its short sensing length.
(3) It needs to use a large dynamic range demodulation algorithm in long-term FDDS due to the frequency and amplitude of the signal. We need to demodulate 5 orders harmonic to assurance real signal, the high signal-to-noise ratio (SNR) and the locating accuracy. However, only fundamental, second and third order harmonics of the carrier are demodulated in the conventional PGC technique [21–29].

We propose a modified PGC technique in this paper to eliminate the low-frequency phase drift in an FDDS. The feasibility of

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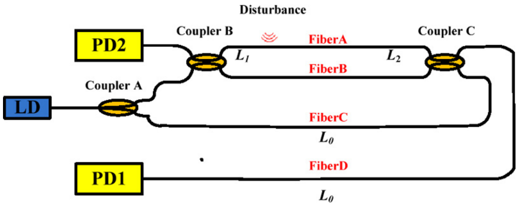

Fig. 1. Schematic illustration of MZ interferometer based FDDS.

the proposed FDDS with modified PGC technique is evaluated via experiments.

2. Principle of FDDS

The schematic diagram of FDDS is shown in Fig. 1.

The light from a laser diode (LD) launches into a 3 dB optical coupler A and splits into two paths: one operates in the clockwise MZ interferometer and the other operates in the counter-clockwise MZ interferometer. Once a disturbance is applied on the Fiber A and Fiber B, a phase change between the two arms of MZ interferometer occurs. The signals received by photo-detectors (PDs) 1 and 2 from the clockwise and counter-clockwise MZ interferometers, respectively, can be expressed as:

$$x_1(t) = I_1\cos[\phi(t - t_1) + \varphi_1(t)] \tag{1}$$

$$x_2(t) = I_2\cos[\phi(t - t_2 - t_0) + \varphi_2(t)] \tag{2}$$

where t_1, t_2 and t_0 are the propagating time of light through the fiber L_1, L_2 and L_0, respectively and are the initial phase of clockwise and counter-clockwise MZ interferometers, respectively. In case of neglecting the low-frequency phase drift induced by the slow time-varying fluctuations, is equal to I_1 and I_2 are determined by the input light intensity of the interferometers and the total loss of the optical fiber. There is a time delay difference τ between the two signals from dual MZ interferometers:

$$\tau = t_2 + t_0 - t_1 = (L_2 + L_0 - L_1) \times \frac{n}{c} \tag{3}$$

Usually, hence the location of the disturbance can be obtained from the time delay difference τ:

$$L_1 = L_0 + L_2 - \tau \cdot \frac{c}{n} = L_0 - \tau \cdot \frac{c}{2n} \tag{4}$$

where c and n are the light speed in vacuum and effective refractive index of fiber core, respectively. By calculating the cross-correlation function of $x_1(t)$ and $x_2(t)$, and finding out the time variable t according to the extremum of the cross-correlation function, τ can be decided [18].

There is no doubt that τ can be calculated exactly in the case of $\varphi_1(t) = \varphi_2(t)$. However, the low-frequency random fluctuations such as temperature or pressure bring on a phase drift so that:

$$\varphi_1(t) \neq \varphi_2(t) \tag{5}$$

In this case, the time delay difference can be expressed as:

$$\tau' = \tau + \Delta\tau \tag{6}$$

where $\Delta\tau$ is the time delay difference variation induced by the low-frequency phase drift when $\varphi_1(t) \neq \varphi_2(t)$. From (5) and (6) it is found that influence of the phase drift, namely $\varphi_1(t) \neq \varphi_2(t)$, produces a time delay difference $\Delta\tau$, due to which, the location error is induced. In order to compensate for the low-frequency phase drift, it is necessary to make use of an effective modified PGC technique to improve the FDDS.

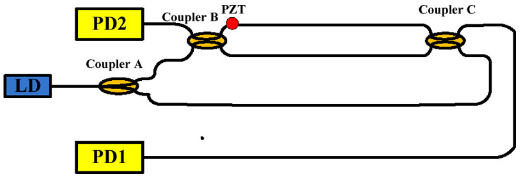

Fig. 2. Schematic illustration of FDDS with a PZT.

3. Proposed phase generation carrier technique

The schematic illustration of an MZ interferometer based FDDS using a PGC technique is shown in Fig. 2. In order to compensate for the phase drift induced by external fluctuations, the phase of the light wave can be modulated through a PZT acting as a phase modulator in the sensing fiber near Coupler B. Hence, the phases of signals $x_1(t)$ and $x_2(t)$, i.e. $\phi(t - t_1)$ and $\phi(t - t_2 - t_0)$ respectively, can be demodulated and the external fluctuations can be compensated.

Let S_m denote the carrier. Assume that:

$$S_m = C\cos(\omega_m t) \tag{7}$$

where C is the modulating amplitude and generally set to 2.37 to minimize the variations of the demodulated signals amplitude, ω_0 is the modulating angular frequency. Modulated signals from MZ interferometers can then be given by:

$$x_1(t) = I_1\cos[C\cos(\omega_m t) + \phi(t - t_1) + \varphi_1(t)] \tag{8}$$

$$x_2(t) = I_1\cos\{C\cos[\omega_m(t - 2t_0)] + \phi(t - t_2 - t_0) + \varphi_2(t)\} \tag{9}$$

To analyze the frequency spectrum of the modulated signals, here we take $x_1(t)$ as an example for illustration. $x_1(t)$ can be calculated from the Bessel function as:

$$x_1(t) = I_1\left\{\left[J_0(C) + 2\sum_{k=1}^{\infty}(-1)^k J_{2k}(C)\cos(2k\omega_m t)\right]\cos\sigma(t) - \left[2\sum_{k=0}^{\infty}(-1)^k J_{2k+1}(C)\cos((2k+1)\omega_m t)\right]\sin\sigma(t)\right\} \tag{10}$$

where k is integer, and $\sigma(t) = \phi(t - t_1) + \varphi_1(t)$.

From (10) it can be clearly seen that the frequency spectrum of the modulated signal consists of the harmonics of the carrier accompanied with the harmonics of the original signal on the sidebands. In order to sample without overlap, a higher sampled frequency is required. However, the higher order frequency components of the modulated signal can be ignored, by a particular choice of the modulating amplitude and an approximation of the higher order terms in the Bessel function. According to the characteristics of the original signal, a low pass filter can be designed to remove the unnecessary harmonics of the carrier and the sidebands, which can simplify the requirement of the sampling. The carrier with the frequency outside of the signal band can be chosen to eliminate the overlaps in the frequency spectrum with the original signal. Hence, it is required that the modulating frequency to be greater than $2k \cdot f_s$, here f_s is the frequency of vibration signal.

The amplitude of the original signal is usually 0.1–3 V and the signal band is generally 2 *k*Hz for FDDS. Considering the distribution of the Bessel function, the harmonic number of the original signal $k = 20$ is assumed, and thus the carrier frequency is chosen to be 80 kHz. In a conventional digital PGC technique, the sampled frequency is determined from the modulating amplitude. However, in our proposed modified PGC technique, the analog multipliers are utilized for mixing, so that we can avoid a high sampled frequency and eliminate the distortions of carrier and original signal. Two carriers expressed as $\cos(\omega_m t)$ and $\cos(2\omega_m t)$ are replaced by