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Crosstalk and phase-noise reduction in time-division multiplexing of polarization-insensitive fiber optic Michelson interferometric sensors

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ABSTRACT

The multiplexing system of fiber optic interferometric sensors suffers from crosstalk and noise, and the performance degrades. The crosstalk of TDM of the fiber optic interferometric sensor includes lead fiber crosstalk, sensor crosstalk for optical gate with finite extinction ratio (ER) and delay fiber crosstalk. In this paper, the laser emission time difference of each interference term of the TDM-PIFOMI system was utilized to reduce the crosstalk and noise by using laser diode high frequency modulation. The temporal characteristics of the crosstalk and the noise of the TDM-PIFOMI system were analyzed, and the theoretical sensor crosstalk, A_{sensor}, is $-4\,\text{ER(dB)}$ by using laser diode high frequency modulation. According to the PGC demodulation process, the minimum frequency of the laser diode modulation was estimated to be larger than nine times of the carrier frequency of the PGC demodulator.

In our experimental results, the improvements of the sensor crosstalk were from 8.3 to 15.5 dB, and the improvements of the delay fiber crosstalk were 15.7 and 14.6 dB by using laser diode high frequency modulation. The phase noise was reduced from 2 dB to 3.9 dB. Using laser diode high frequency modulation to decrease the crosstalk and the noise of the TDM-PIFOMI system is effective and cheap.

1. Introduction

Fiber optic interferometric sensors (FOIS) have a lot of advantages and have been developed for many applications [1]. An important feature of FOIS is its multiplexing capability [2]. Various interferometric sensor multiplexing have been reported, such as time-division multiplexing (TDM) [3–5], combinations of TDM and WDM [6,7], frequency-division multiplexing (FDM) [8–10], and coherence multiplexing [11]. TDM of FOIS has been shown to have advantages of low crosstalk and high sensitivity. Polarization fading is one of the important problems of FOIS. This problem becomes complicated in the interferometric sensor arrays, which is due to the polarization state of individual optical paths changes independently. Polarization-insensitive fiber optic Michelson interferometer (PIFOMI) has been demonstrated [12]. This sensor includes the Faraday rotator mirror (FRM) which eliminates the polarization fading by compensating the birefringence effect in a retraced fiber path [13,14]. A TDM array based on this concept was suggested by Marrone et al. [15]. The TDM of polarization-insensitive fiber optic Michelson interferometric sensors (TDM-PIFOMI) has been reported to solve the polarization fading problem by using FRM and generate the interference signals by using optical path matching compensation interferometer [5].

Generally, most multiplexing system of the FOIS suffers from the crosstalk and the noise between sensors, and the performance of the sensor system degrades. The inherently superior performances of the FOIS systems are high sensitivity and wide dynamic range. Therefore, suppression of crosstalk and noise in multiplexing system of the FOIS is required to achieve the high performance. A direct laser diode high frequency modulation has been used in coherence multiplexing of fiber optic sensor to reduce the excess phase noise and improve the minimum phase detection sensitivity (MPDS) [16]. The crosstalk of TDM of the FOIS comes from (a) lead fiber crosstalk, (b) sensor crosstalk for optical gate with finite extinction ratio, and (c) fiber crosstalk by Rayleigh backscattering [5,17,18]. There are many crosstalk suppression methods, such as the modulating technique which needs extra optical phase modulation system and results in complicated control procedure [19,20]. In this paper, the temporal characteristics of the crosstalk and the noise of the TDM-PIFOMI system were analyzed and successfully suppressed by using the laser diode high frequency modulation technique.

2. Theory

Fig. 1 shows the TDM-PIFOMI system with two sensors. The unbalanced Michelson interferometer of the first sensor (SI_1) consists of coupler FC_1, Faraday rotator mirrors FRM_1 and FRM_2. The second sensor (SI_2) consists of FC_2, FRM_3 and FRM_4. The

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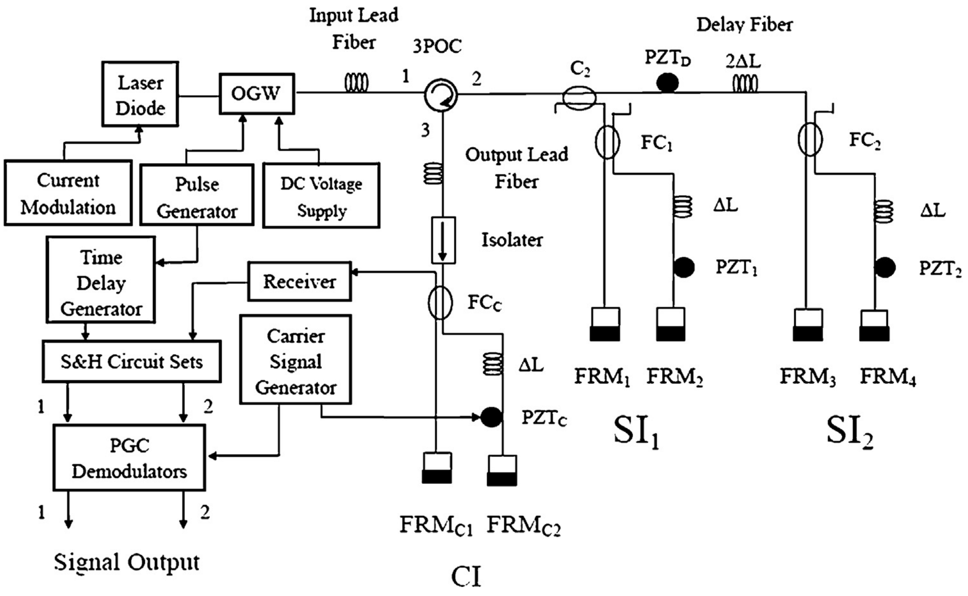

Fig. 1. The array configuration of TDM-PIFOMI system with two sensors.

compensating interferometer (CI) consists of FC_C, FRM_{C1} and FRM_{C2}. The path difference between two unbalanced arms of the above SI_1, SI_2 and CI are ΔL_{S1}, ΔL_{S2} and ΔL_{CI}, respectively. Ideally, the matched optical path between CI and all sensors is required, i.e., $\Delta L_{S1} = \Delta L_{S2} = \Delta L_{CI} = \Delta L$. The effective optical path difference (OPD) of SI_1 and SI_2 are $2n|\Delta L_{S1} - \Delta L_{CI}|$ and $2n|\Delta L_{S2} - \Delta L_{CI}|$, respectively, where n is the refractive index of fiber core. The continuous-wave laser diode was externally modulated by the optical-guided-wave intensity modulator (OGW) to generate optical pulse [21]. The output optical pulse of the OGW with high extinction ratio (ER) is a key to reduce the sensor crosstalk [5], and the maximum ER of the optical pulse can be automatically adjusted to the optimum condition [22]. In Fig. 1, we can see that the input lead fiber (ILF) is between the OGW and the 3-ports optical circulators (3POC), and the output lead fiber (OLF) is between the 3POC and the optical isolator. The 3POC and the optical isolator were used to avoid the crosstalk and the noise which came from the Rayleigh backscattered light from the input and output lead fibers [23]. A delay fiber (DF) is between the coupler C_2 and coupler FC_2. Piezoelectric (PZT) phase modulators PZT_1, PZT_2 and PZT_D were used to generate the sensing phase simulation signals of SI_1, SI_2 and DF, respectively. The PZT_C was used to generate the carrier signal of CI. The output interference signals of SI_1 and SI_2 were obtained by the sample hold circuits with proper triggers from the time delay generator, respectively. The polarization fading problem of the output interference signals of SI_1 and SI_2 can be solved by FRMs, as shown in Fig. 1 [5]. The sensing phase signals of SI_1, SI_2 and DF can be demodulated from the interference signals by using the PGC demodulation with the optimum condition that the amplitude of the carrier signal is 2.37 rad [24,25]. In this paper, the amplitudes of the sensing phase simulation signals of SI_1 and SI_2 were assumed to be 1 rad which is convenient for analysis.

Generally, the coherence length of the laser diode in TDM-PIFOMI system is quite long to reduce the excess phase noise of SI_1 and SI_2, which comes from the effective optical path difference of the main interference signals SI_1 and SI_2. However, the unwanted interference signals caused by lead fiber, optical gate with finite extinction ratio, and Rayleigh backscattering generate crosstalk and noise. Each interference signal is generated by two reflective optical pulses with different laser emission time. For example, the emission time difference of the main interference signal SI_1 is $2n|\Delta L_{S1} - \Delta L_{CI}|/c$, where c is the light velocity. Especially, the laser emission time differences of the interference signals due to a low level optical pulse (OGW at off condition) and a high level optical pulse (OGW at on condition) are very large (the multiples of $2n\Delta L/c$). Utilizing the direct laser diode high frequency modulation in TDM-PIFOMI system, the laser emission time difference is important for the crosstalk and noise, which is proved in this paper.

The effective OPD of SI_1 is $2n|\Delta L_{S1} - \Delta L_{CI}|$. The laser diode was modulated by a high frequency current signal $\Delta i_h \sin\omega_h t$ and generated a high frequency phase signal $\Delta\phi_h(t)$ [24] as the following equation,

$$\Delta\phi_h(t) = \left(\frac{4\pi|\Delta L_{S1} - \Delta L_{CI}|n}{c}\right)\Delta i_h\left(\frac{\delta\nu}{\delta i}\right) sin\omega_h t = \Delta\phi_h \sin\omega_h t \tag{1}$$

$\Delta\phi_h = ((4\pi|\Delta L_{S1} - \Delta L_{CI}|n/c)\Delta i_h(\delta\nu/\delta i))$ represents the amplitude of phase carrier signal, where $\delta\nu/\delta i$ is the effective current to frequency conversion factor of the laser diode. The main interference signals $I_1(t)$ of SI_1 can be expressed as,

$$I_1(t) = b\{1 + k\cos[\phi_T(t) + \Delta\phi_h \sin\omega_h t]\} \tag{2}$$

where $\phi_T(t)$ represents all the phase signals excluding high frequency signal, b is a coefficient proportional to the optical power, and k is the fringe visibility of the interference signal output. The $I_1(t)$ can be expressed as,

$$I_1(t) = b\left\{1 + k\left[J_0(\Delta\phi_h) + 2\sum_{n=1}^{\infty} J_{2n}(\Delta\phi_h)\cos 2(n\omega_h t)\right]\cos\phi_T(t) - k\left[2\sum_{n=0}^{\infty} J_{2n+1}(\Delta\phi_h)\sin((2n+1)\omega_h t)\right]\sin\phi_T(t)\right\} \tag{3}$$

Matched optical path between CI and all sensors is required in the TDM-PIFOMI system, i.e., $\Delta L_{S1} \approx \Delta L_{CI}$, therefore $\Delta\phi_h \approx 0$ and $J_0(\Delta\phi_h) \approx J_0(0) = 1$. Utilizing the low pass filter to signal $I_1(t)$, and the output $I_{1,\mathrm{low}}(t)$ of $I_1(t)$ can be expressed as,

$$I_{1,\mathrm{low}}(t) = b[1 + kJ_0(\Delta\phi_h)\cos\phi_T(t)] \approx b[1 + k\cos\phi_T(t)] \tag{4}$$

We can see that the $I_{1,\mathrm{low}}(t)$ approaches the main interference signal of SI_1 without high frequency current modulation, which means the demodulation sensing phase signal and noise of the main interference signals of SI_1 were not affected by the high frequency current modulation.