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Eliminating additional laser intensity modulation with an analog divider for fiber-optic interferometers

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ABSTRACT

Additional laser intensity modulation (LIM) will degrade performance of fiber-optic interferometric sensors in which phase generated carrier demodulation techniques are utilized. In this paper, a new method to eliminate the additional LIM of a sinusoidal modulated fiber ring laser through an analog divider is presented. Experimental results show not only LIM but also intensity noise peak caused by relax oscillation are eliminated simultaneously by the analog divider. System becomes more stable, and gets a higher performance with adoption of this method. Factors influencing system performance are also analyzed.

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1. Introduction

Phase generated carrier (PGC) demodulation scheme is widely used in fiber-optic interferometric sensing system due to its high sensitivity, large dynamic range and good linearity [1,2]. With a frequency modulated laser source, the sensing head can work in passive mode. However, a normal PGC demodulation circuit or program cannot operate correctly because the laser source is often attached with laser intensity modulation (LIM). Several solutions have been proposed: A. Dandridge tried to reduce intensity noise and additional LIM with balanced detectors [3], J. Cao selected a laser diode with low additional intensity modulation [4], and Y. Liu dealt it with PGC-atan algorithm, which could reduce its influence to some extent [5]. Q. Shi eliminated LIM of a sinusoidal modulated semiconductor laser illuminating system, by dividing the interferometer output signal with the directly detected light intensity signal which was prestored in computer [6]. These methods can reduce or eliminate the impact of LIM in their specified application. However, Erbium-doped fiber ring laser, which has a good prospect in interferometric systems operated with large optical path difference (OPD), has several order of harmonics in its LIM spectrum even modulated by a simple sinusoidal signal, and system performance may degrade more or less even if dealing with the above options.

In this paper, a new method, which adopts an analog divider to divide interferometric signal with laser intensity signal to eliminate LIM, is shown. The performance of a modulated Erbium-doped fiber ring laser illuminating interferometer with PGC demodulation system is also shown.

2. Theoretical analysis

In an ideal case, there is no LIM for a normal Michelson or Mach–Zehnder interferometer illuminated by a modulated laser source, its output signal can be expressed as [1]

$$I = A + \kappa A\ \cos[C\cos(\omega_0 t) + \phi(t)]. \tag{1}$$

Here, constant A represents laser intensity, κ is mixing efficiency, ω_0 is modulation frequency, $C\cos(\omega_0 t)$ is phase carrier, $\varphi(t)$ is phase difference, including fixed phase difference introduced by interferometer OPD between two arms, signals to be detected, undesired environmental noises, and phase noise introduced by laser source frequency jitter.

In order to get the spectrum of Eq. (1), expand it in terms of Bessel function:

$$I = A + \kappa A \left\{ \begin{array}{l} \left[J_0(C) + 2\sum_{k=1}^{\infty} (-1)^k J_{2k} \cos 2k\omega_0 t \right] \cos\phi(t) \\ - \left[2\sum_{k=0}^{\infty} (-1)^k J_{2k+1} \cos(2k+1)\omega_0 t \right] \sin\phi(t) \end{array} \right\}. \tag{2}$$

Mix Eq. (2) with $G\cos\omega_0 t$ and $H\cos 2\omega_0 t$ respectively, a pair of quadrature signals, $\sin\varphi(t)$ and $\cos\varphi(t)$, can be obtained. And signal under detected can be obtained after a series of further treatment:

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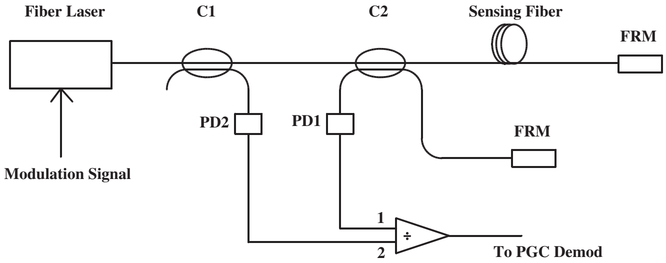

Fig. 1. System configuration schematic diagram.

time derivative, cross multiplication, subtraction, integral and high pass filtering. This demodulation scheme is described in detail in Ref. [1].

However, when the laser source is a sinusoidal modulated fiber ring laser, unwanted LIM is also introduced, and then laser intensity A in Eq. (1) can be expressed as

$$A = A_0 + \sum_{m=1}^{\infty} A_m \cos\omega_0 t. \tag{3}$$

Here, A_0 is DC component of optical intensity, A_m is the amplitude of the m-order harmonic, and in fact it may vary with time because of environmental disturbances. So, in this condition, the output of interferometer becomes

$$I' = \left(A_0 + \sum_{m=1}^{\infty} A_m \cos\omega_0 t\right)(1 + \kappa\ \cos[C\cos(\omega_0 t) + \phi(t)]). \tag{4}$$

In order to simplify the calculation, but not losing of generality, we will neglect 6th and higher order harmonic of modulation frequency in Eqs. (2) and (3). If Eq. (4) is still mixed with $G\cos\omega_0 t$ and $H\cos 2\omega_0 t$ respectively, it gets

$$\begin{aligned}\frac{A_1 G}{2}(1+\kappa J_0) &+ \frac{\kappa G}{2}[-2A_0 J_1 - A_2 J_1 + A_2 J_3 - A_4 J_5]\sin\phi(t)\\ &+ \frac{\kappa G}{2}[-2A_1 J_2 - A_3 J_2 + A_3 J_4 - A_5 J_4]\cos\phi(t),\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{A_2 H}{2}(1+\kappa J_0) &+ \frac{\kappa H}{2}[-A_1 J_1 - A_3 J_1 + A_1 J_3 + A_5 J_3 - A_3 J_5]\sin\phi(t)\\ &+ \frac{\kappa H}{2}[-2A_0 J_2 - A_4 J_2 + A_2 J_4]\cos\phi(t).\end{aligned} \tag{6}$$

From Eqs. (5) and (6), we can see that the outputs become very complicated: they contain extra DC components and are no longer in quadrature. These deviations will get more obvious with a stronger LIM harmonics. As a result, signal fading will be unable to be eliminated thoroughly after the PGC demodulation process, and system performance will degrade. In fact, obvious signal fading can be observed in experiments.

It can also be seen from Eq. (4) that a simple but effective method to eliminate LIM is to divide the interferometer output signal Eq. (4) with laser intensity signal Eq. (3). The output of the divider is sent to a normal PGC demodulation circuit or program, and signal to be detected can be recovered without fading.

3. Experimental setup and results

The proposed system configuration to eliminate LIM mentioned above is shown in Fig. 1. An extra 3 dB coupler (C1) is introduced in the polarization independent Michelson interferometer illuminated by an Erbium-doped fiber ring laser, which has been discussed in detail in Refs. [7,8]. C2 is another 3 dB coupler. Two 90° Faraday rotating mirror (FRM) is used to reflect light and ensure the two reflected beam to interference with polarization aligned. PD1, and PD2 are photodetectors. PD1 is used to detect the interferometric signal and PD2 is used to detect laser intensity signal. The output of PD1 is divided by the output of PD2 with an analog divider fabricated by AD734. At last, we send the output of the divider to a normal PGC demodulation circuit and get the final result.

As shown in Fig. 1, the fiber laser is modulated by an external 40 kHz sinusoidal signal, which is used to generate the desired frequency dither, however undesired LIM is also added. The output waveform of PD2 and its spectrum are shown in Figs. 2 and 3, respectively. It can be seen that there is an obvious LIM whose spectrum has not only fundamental modulation frequency but also several orders of harmonics. The noise around 35 kHz is a result of laser relax oscillation. In fact, because the fiber ring laser has a relative long cavity (of

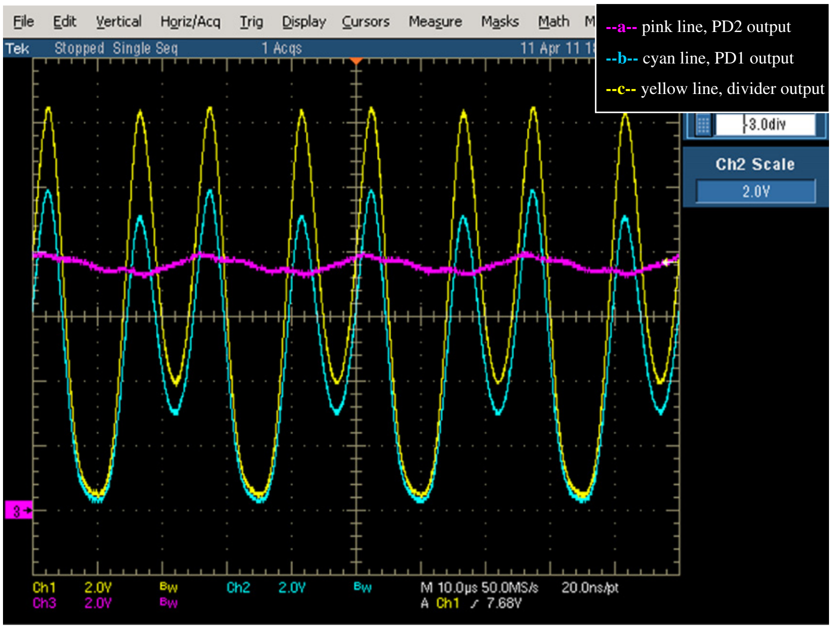

Fig. 2. Output waveforms of PD1, PD2, and the analog divider.

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