Self-mixing interferometer based on phase modulation technique

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Abstract: *A new self-mixing interferometry based on sinusoidal phase modulation technique is presented. Sinusoidal phase modulation of the laser beam is obtained by an electro-optic modulator (EOM) placed in the external cavity both in free-space and in a fiber. The phase of the interference signal is retrieved by Fourier analysis method. The free-space experimental set-up is applied to measure a displacement of a commercial high precision PZT with accuracy of <10 nm. Moreover, a sensing-oriented all-fiber self-mixing interferometer is devised as well. The sensing scheme is described, experimental results is reported and the overall accuracy is better than λ/10. It indicates that combining the optical fiber EOM with SMI is available and high-accuracy can be achieved.*

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1. Introduction

Self-mixing interference(SMI) in laser diodes has been widely investigated for the last decades and proved to be a promising solution for displacement, vibration, velocity, distance and correlated measurement[1]-[2]. It occurs when a small fraction of the backreflected light from a mirror-liked target is allowed to re-enter the laser active cavity, generating a modulation of both the amplitude and frequency of the lasing field.

SMI was used to measure displacement with an accuracy of λ/2 by counting interference signal peaks. In order to increase the measurement accuracy beyond λ/2, some methods for analysis of SMI signal have been reported[3]-[4]. In this paper, a new self-mixing interferometer based on sinusoidal phase modulating technique is proposed. Firstly, the theoretical model for the phase-modulated self-mixing effect of a laser diode is analyzed and the Fourier transform(FT) phase demodulation method is presented. Secondly, a free-space self-mixing interferometer with phase modulation is proposed and experimentally tested. A free-space EOM situated in the beam path between the facet of the laser diode and the external target is used to introduce phase modulation. The movement of a high-precision commercial PZT is reconstructed and a displacement measurement accuracy of <10nm is obtained. However, it is not always convenient to use this setup in free space for measurement, when the target exists in a severe environment with high temperature, high humidity or strong electromagnetic field. In that case, all-fiber setup has the superiority in comparison with the conventional one. Consequently, an all-fiber self-mixing interferometer is devised with DFB laser as the light source and waveguide-EOM as the phase modulator. Considering the amplitude and frequency of external target, experiments are conducted to reconstruct movements of the target at different parameters.

2. Theoretical Analysis

Theoretical model of a semiconductor laser SMI with phase modulation can be explained by a three-mirror cavity model as in Fig. 1. A linearly polarized laser beam emitted from a laser diode(LD) is subjected to pure phase modulation by an EOM placed in the external cavity and is reflected by a target. A portion of the laser output is allowed to re-enter the laser cavity and mixes with the original light in the laser, forming the self-mixing effect.

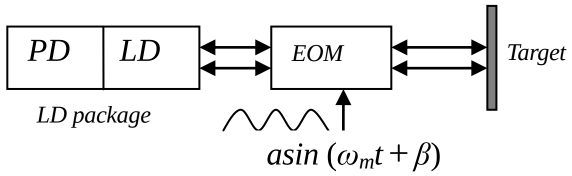


Fig. 1 Theoretical model for SMI LD with phase modulation

Assuming that SMI operates in a low-feedback regime, the output intensity of a SMI LD can be expressed as[5]

$$I = I_0\left[1 + m\cos(\phi)\right] \quad (1)$$

This assumption forms the basis of our subsequent research. An experimentally controlled additive phase $\psi(t) = a\sin(2\pi f_m t + \beta)$ is introduced by an EOM situated in the external cavity, where a is the modulation depth, f_m is the modulation frequency and β is the initial phase of the modulation. Considering that the beam passes through the EOM twice in the external cavity, the modulated interference signal can be written as

$$I(t) = I_0\{1 + m\cos[\phi(t) + 2a\sin(2\pi f_m t + \beta)]\} \quad (2)$$

Expanding Eq. (2) in a Fourier series, harmonics at frequency f_m and $2f_m$ have following expressions:

$$\begin{aligned} I(f_m,t) &= -2mI_0\sin\phi(t)J_1(2a)\sin(2\pi f_m t + \beta) \\ &= A_1(t)\sin(2\pi f_m t + \beta) \end{aligned} \quad (3)$$

$$\begin{aligned} I(2f_m,t) &= -2mI_0\cos\phi(t)J_2(2a)\cos(4\pi f_m t + 2\beta) \\ &= A_2(t)\cos(4\pi f_m t + 2\beta) \end{aligned} \quad (4)$$

Where

$J_n(2a)$ is the nth-order Bessel function . Then we can calculate the phase $\phi(t)$ from $A_1(t)$ and $A_2(t)$ using the subsequent relation:

$$\phi(t) = arc\tan\left[\frac{A_1(t)}{A_2(t)}\cdot\frac{J_2(2a)}{J_1(2a)}\right] \quad (5)$$

The Fourier analysis method is proposed to determine the values of $A_1(t)$ and $A_2(t)$. It mainly takes following steps: (1) taking the Fo urier transform of the interference signal; (2) selecting the first harmo nic $I(f_m)$ and second harmonic components $I(2f_m)$ of the Fourie r spectra with two windows: $f_m/2 < f < 3f_m/2$ and $3f_m/2 < f < 5f_m/2$; (3) taking the inverse Fourier transform of the filtered component, represented by $I_{fm}(t)$ and $I_{2fm}(t)$ respectively ; and (4) computing $A_1(t)$ and $A_2(t)$ using the subsequent relation:

$$A_1(t) = imag\left\{I_{fm}(t)/e^{j(2\pi f_m t+\beta)}\right\} \quad (6)$$

$$A_2(t) = real\left\{I_{2fm}(t)/e^{j(4\pi f_m t+2\beta)}\right\} \quad (7)$$

The phase ϕ obtained using the demodulation technique proposed above is wrapped within the region of $-\pi/2$ and $\pi/2$. After a phase unwrapping process. Then the movement of the external target can be retrieved with the relationship between the phase ϕ and the length of the external cavity shown as:

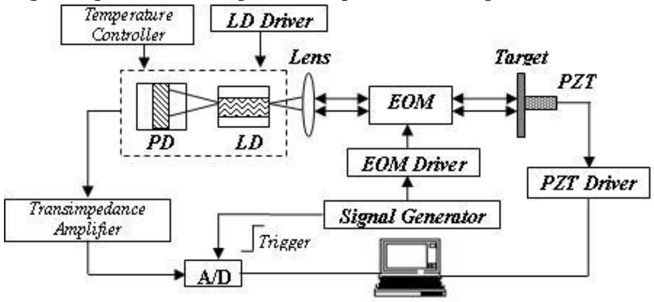
$$L(t) = \frac{\lambda}{4\pi}\phi(t) \quad (8)$$

3 Self-mixing interference with sinusoidal phase modulation in free-space

The experimental setup for free-space SMI with phase modulation is shown in Fig. 2. The light source is a 5mW linearly polarized laser diode (635nm). The external target is fixed on a high-precision commercial PZT(PI, P-841.10) with reflectivity of 0.04 to make SMI operate under very weak regime. The beam emitted from the front mirror of the laser is sent through a collimator lens, an EOM (New Focus, 4002) with axis orientation parallel to the polarization of the laser and then reflected back to the laser cavity by the external target. The interference signal is monitored by a photodiode (PD) accommodated inside a diode laser package. The voltage signal from the PD is amplified, digitized by a data acquisition card and processed by a PC.

Experiments have been done to confirm the validity of the sinusoidal phase modulating self-mixing interferometer and the phase demodulation method. In our experiment the first rising edge of TTL level from the signal generator which drives the EOM driver is introduced to the A/D card as the trigger of data acquisition. Then a sinusoidal phase modulation with the initial phase $\pi/2$ can be obtained.

Fig. 2 Experimental setup for free-space SMI with phase modulation



Firstly, the PZT is controlled to move at a sinusoidal form with frequency 10Hz and amplitude $2\mu m$ (peak to peak). The modulation frequency is 1KHz and the modulation depth is 1.2rad. The sampling rate of the A/D card is 50KHz. Fig. 3(a) is the interference signal obtained by A/D card. Fig. 3(b) is the Fourier spectra of the detected signal in which the first harmonic component centered at 1KHz and the second harmonic component centered at 2KHz. Following the phase extraction steps, the phase is retrieved as in Fig.3(c). After unwrapping the phase and using the relationship between the phase ϕ and the length of the external cavity, the movement of PZT is reconstructed as in Fig. 3(d). In displacement measurement, only the relative value of the two positions is important. So, we examine the peak-to-peak amplitude in Fig. 3(d) and get the displacement measurement accuracy. The peak-to-peak amplitude of the reconstructed waveform in Fig. 3(d) is $2.002\mu m$.

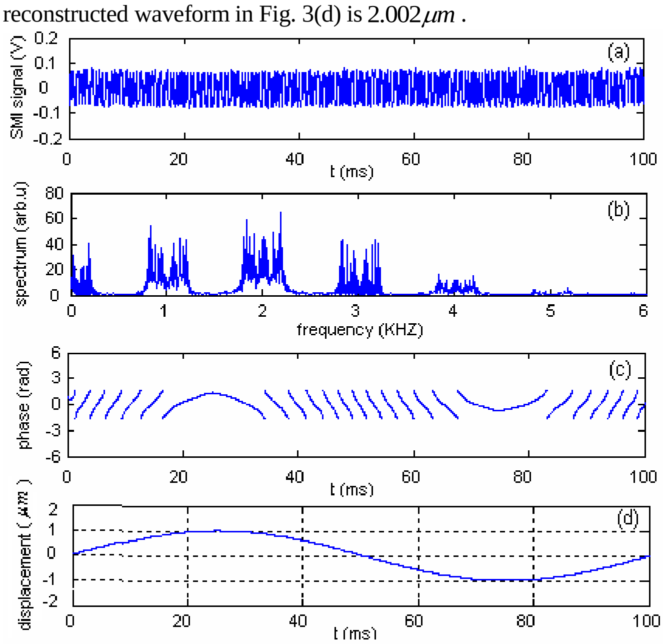


Fig. 3 (a) The obtained SMI signal. (b) Fourier spectra of the SMI signal. (c) Extracted phase (wrapping). (d) Displacement reconstruction result.

Secondly, the PZT is controlled to move at a sinusoidal form with frequency 40Hz and amplitude $4\mu m$ (peak to peak). The modulation frequency is 6KHz and the modulation depth is1.2rad. The sampling rate of A/D card is 100KHZ. The reconstruction result is in Fig. 4 and the max error for displacement measurement is 7nm.

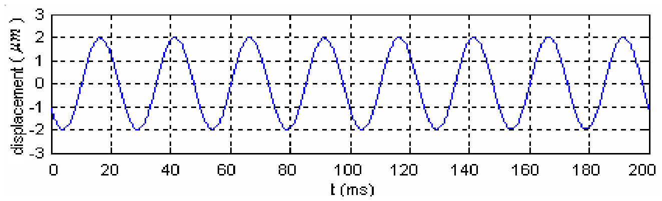


Fig. 4 Displacement reconstruction result of PZT with frequency 40HZ and amplitude of $4\mu m$ (peak to peak).

4 All-fiber self-mixing interference with sinusoidal phase modulation

The experimental setup of all-fiber self-mixing interferometer is shown in Fig. 5. Single longitudinal mode light emitted from the DFB laser(1550nm) travels through a polarization maintaining coupler (PMC), an in-line polarizer (POL), a fiber EOM, and a focusing lens, then reflected back to the laser cavity by a reflector fixed on a PZT translator. The EOM can provide pure phase modulation with extremely low amplitude modulation. The SMI signal is monitored by a photodiode (PD) which is connected to the other end of the coupler. The voltage signal from the PD is acquired by a data acquisition card and then the digital signal is transferred to a PC to be processed.

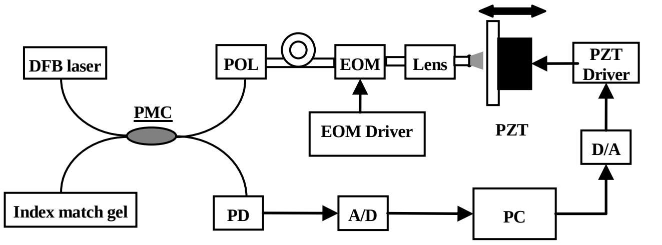


Fig. 5. Experimental setup for all-fiber SMI with phase modulation

Experiments have been performed to demonstrate the sinusoidal phase modulating self-mixing interferometer and the phase demodulation method. The demodulating process of SMI signal is shown in Fig. 6. The PZT is controlled to move at a sinusoidal form with frequency 6Hz and amplitude 3.25 μm (peak to peak). The modulation frequency of EOM is 1kHz, depth 1.2rad. The sampling rate of A/D card is 50kHz. Fig.6(a) is the interference signal obtained by A/D card. Fig.6(b) is the Fourier spectra of detected signal in which the first harmonic component centered at 1kHz and the second harmonic component centered at 2kHz. Fig.6(c) is the demodulated phase. After unwrapping the phase and using the relationship between the phase ϕ and the length of the external cavity, the movement of PZT is reconstructed as in Fig.6(d).

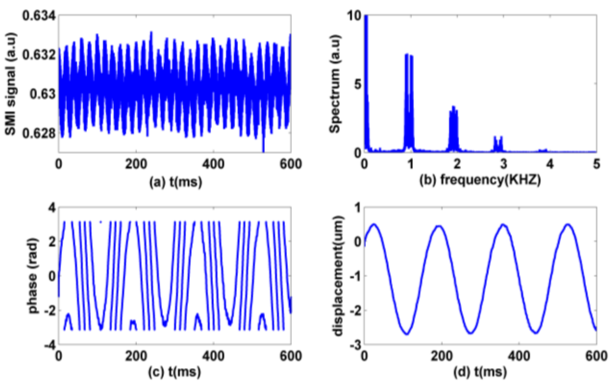


Fig.6. (a)The obtained SMI signal. (b)Fourier spectra of SMI signal. (c)Extracted phase(wrapping). (d)Displacement reconstruction result.

Moreover, we observed the output by changing the parameters of PZT. Fig.7 shows the reconstructed results at different amplitudes of PZT when the frequency is 5Hz. The reference amplitude is 2.40 μm, 4.50 μm, 6.00 μm and the measurement result is 2.35 μm, 4.61 μm, 6.03 μm for a, b and c respectively.

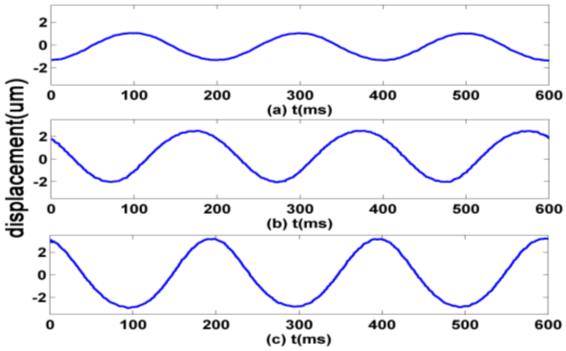


Fig.7 Displacement reconstruction results of PZT with frequency 5Hz , amplitude (a) 2.4 μm, (b) 4.5 μm, (c) 6.0 μm (peak to peak)

Considering that the PZT translator is a high-resolution linear actuator for low-frequency dynamic applications, we change the frequency of PZT from 5Hz to 15Hz in the experiment. Fig.8 shows the reconstructed results at different frequency of PZT when the reference amplitude is 4.50□ m. The measurement results are 4.56□ m, 4.45□ m, 4.48□ m corresponding to the frequency 5Hz, 10Hz, 15Hz, respectively.

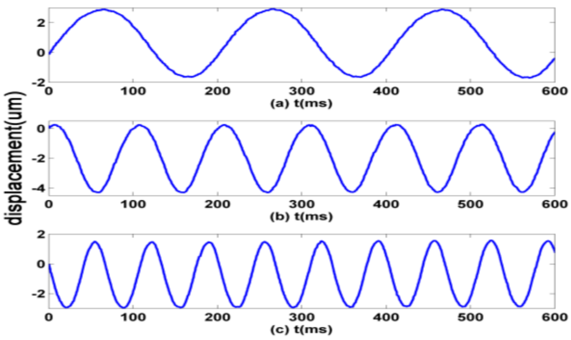


Fig.8. Displacement reconstruction results of PZT with amplitude 4.50 μm, frequency (a) 5Hz, (b) 10Hz, (c) 15Hz

According to the experiments, the maximum error is 0.11μm, less than λ/10. Furthermore, we repeated measurement for 6 times with the amplitude of PZT 6.00 μm. The experimental data show that the average error is 0.102 μm and the standard deviation is 0.1 μm. The results denote the feasibility and validity of all-fiber self-mixing interferometer.

5. Conclusions

The basic theory and experimental results show that the proposed new method can effectively demodulate the phase of the interference signal with high accuracy. The combination of modulation and demodulation decreases the sensitivity of the instrument to fluctuations of the laser power and the noise induced by environment. In free-space experimental setup, experiments are conducted to reconstruct movements of a commercial PZT with precision of <10 nm. Furthermore, An all-fiber self-mixing interferometer based on DFB laser and sinusoidal phase modulation technique is proposed as well. Changing the frequency and amplitude of external target, the different experimental results were obtained , and all of the results show a good agreement with the theory. An accuracy of λ/10 is obtained. Although the measurement accuracy in all optical-fiber SMI system is slightly lower compared with one in free space, the reconstructed movement will not be virtually affected, which indicates that combining the optical fiber EOM with SMI is available and high-accuracy can be achieved.

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