A laser feedback interferometer with an oscillating feedback mirror

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A method is proposed to solve the problem of direction discrimination for laser feedback interferometers. By vibrating the feedback mirror with a small-amplitude and high-frequency sine wave, laser intensity is modulated accordingly. The modulation amplitude can be extracted using a phase sensitive detector (PSD). When the feedback mirror moves, the PSD output shows a quasi-sine waveform similar to a laser intensity interference fringe but with a phase difference of approximately $\pm\pi/2$. If the movement direction of the feedback mirror changes, the phase difference sign reverses. Therefore, the laser feedback interferometer offers a potential application in displacement measurement with a resolution of 1/8 wavelength and in-time direction discrimination. Without using optical components such as polarization beam splitters and wave plates, the interferometer is very simple, easy to align, and less costly.

Keywords: He–Ne laser, laser feedback interferometer, dithering

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1. Introduction

Laser power can be modulated when part of its output light is reflected back into the laser cavity.[1−4] This phenomenon is called optical feedback, or self-mixing interference. In the beginning, laser feedback was thought to be harmful and requiring elimination.[5,6] However, it has attracted great attention in recent years due to its potential application in accurate measurement. A laser feedback interferometer is similar to conventional laser interferometers and can be used to measure displacement,[7−10] velocity,[11,12] vibration,[11,13] etc. However it is more simple and rigid because the reference arm is the laser itself. A laser diode (LD) is a most common source for laser feedback interferometry (LFI) at present due to its advantages in, for example, miniaturization and compactness. In an LD based LFI, direction discrimination is usually achieved by monitoring the switching slope, but there are some inconveniences[14] in, for example, measuring a displacement of less than $\lambda/2$, where λ is the wavelength of the light source. In order to obtain high resolution, an electro-optical modulator (EOM) can be used,[15] but this will increase cost.

One advantage of the He–Ne laser over other types of light sources is its frequency stability, which is on the order of 10^{-9}. There exist, however, two key problems facing ordinary He–Ne laser feedback interferometers at present.[4] One is direction discrimination and the other is resolution improvement. In order to solve these problems, anisotropic elements are introduced into either the internal[16] or external[17] cavity of the He–Ne laser feedback system. An intracavity element not only increases cavity loss but also influences cavity stability, so the latter method is more attractive. However, it would be better if the anisotropic element and polarization beam splitter could be removed. To achieve this goal, a method is proposed and experimental results are given in this paper.

2. Experimental setup

The experimental setup is shown schematically in Fig. 1(a).

A miniaturized internal cavity 632.8 nm He–Ne laser made of monoblock glass ceramics[18] is used whose structure is shown in Fig. 1(b). The laser is 14 cm in length and is filled with Ne^{20} and Ne^{22} dual isotopes. Mode selection diaphragm and Brewster window ensure that only one lasing mode emerges when the frequency is stabilized at gain peak with hill-climbing method. A 50:50 beam splitter splits laser

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output from mirror M_2 into two parts. One part is incident on a photo-electric detector D_1 for frequency stabilization and the other is incident on the feedback mirror M_3 with a reflectivity of about 10%. PZT_1 (piezoelectric transducer) is used to push/pull mirror M_1 to stabilize the laser frequency. The laser output from M_1 is detected by D_2 and sampled into a computer with AD_1 (analog-to-digital converter). The computer program is built with Labview^{TM} workbench. A scanning signal from the SCAN model is applied to PZT_2 via DA_1 (digital-to-analog converter). And meanwhile, a sine signal with small amplitude and high frequency from an oscillator (OSC) is also applied via DA_2. So the feedback mirror M_3 oscillates in the normal direction all the time. As a result, distance between M_2 and M_3 dithers with small amplitude which further makes the laser power oscillating. In the computer program, a low pass filter (LF) is used to eliminate the oscillating part in the laser light intensity and a digital phase sensitive detector (PSD) is used to obtain the induced oscillating amplitude with a frequency identical to the OSC model in the laser light.

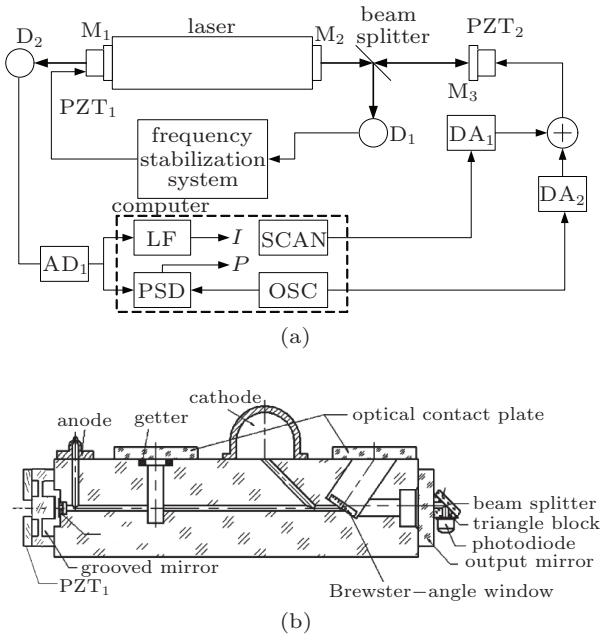


Fig. 1. Experimental setup (a) and the structure of the laser (b).

The principle of PSD is shown in Fig. 2.

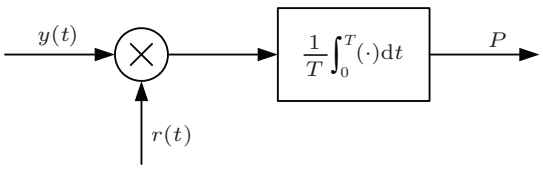


Fig. 2. Principle of PSD.

The PSD consists of a multiplier and an integrator. Let input signal $y(t)$ be

$$y(t) = y_1 + y_2 \sin(\omega t), \tag{1}$$

where y_1 is the component that has no sine signal at frequency ω, $y_2 \sin(\omega t)$ is the oscillating part in $y(t)$, ω is the frequency of the oscillator, and t is time.

Using a reference signal $r(t) = \sin(\omega t + \varphi)$ to multiply $y(t)$, we obtain

$$\begin{aligned} y(t)r(t) &= [y_1 + y_2 \sin(\omega t)] \sin(\omega t + \varphi) \\ &= y_1 \sin(\omega t + \varphi) \\ &\quad - \frac{1}{2} y_2 [\cos(2\omega t + \varphi) - \cos(\varphi)]. \end{aligned} \tag{2}$$

When integrated over time span greater than $2\pi/\omega$, alternating components in $y(t)r(t)$ go to zero and only $\frac{1}{2} y_2 \cos(\varphi)$ is left. In this way, the amplitude of oscillating component in $y(t)$ is obtained. Through tuning φ to zero, we can enhance the sensitivity of PSD to make $\frac{1}{2} y_2 \cos(\varphi)$ maximum. In order to obtain a good signal-to-noise ratio (SNR) for P, a band-pass filter (BPF) can be added in front of the multiplier.

3. Experimental results

First, we investigate the characteristics of laser intensity and PSD. We turn on the laser and frequency stabilization system. In the program, the SCAN model sends a triangular wave and the OSC model sends a sine signal. The frequency and amplitude of the sine signal are 50 kHz and 0.1 V, respectively. Meanwhile, laser intensity is sampled via AD_1 and processed to obtain I and P, which are outputs of LF and PSD. A BPF of 20 Hz bandwidth is used to improve the SNR for P. The update rate of AD and DA is 250 kHz, which is limited by the electric system. The outputs of LF and PSD in the computer program are shown in Fig. 3, where I and P are scaled and shifted along vertical axis so that they can be shown in the same figure. From Fig. 3(a), we know that I and P are in the form of a quasi-sine waveform. Furthermore, I leads to P when PZT voltage is increasing and vice versa when the feedback mirror is driven by PZT_2. The phase difference is approximately $\pi/2$. This phenomenon is very useful for discriminating direction and enhancing resolution from $\lambda/2$ to $\lambda/8$ in measuring displacement, which is 79 nm for the He–Ne laser. The quasi-sine waveform can be reformed into a square wave, as shown in Fig. 3(b).

As an example for application, we measure hysteresis loops of PZT_2 by applying a triangular wave. The results are shown in Fig. 4, where the original result is plotted in dashed lines. We can see small steps due to the $\lambda/8$ resolution. The hysteresis loop is not very clear in Fig. 4(b) due to limited resolution. With an average filter of 15 orders (smooth function in Matlab^{TM}), the curves are smoothed and plotted in solid lines. The smoothed lines are shifted upwards at 0.75 μm in Fig. 4(a) and 0.5 μm in Fig. 4(b) so as to avoid superposition. We can see evident hysteresis loops in the figure.

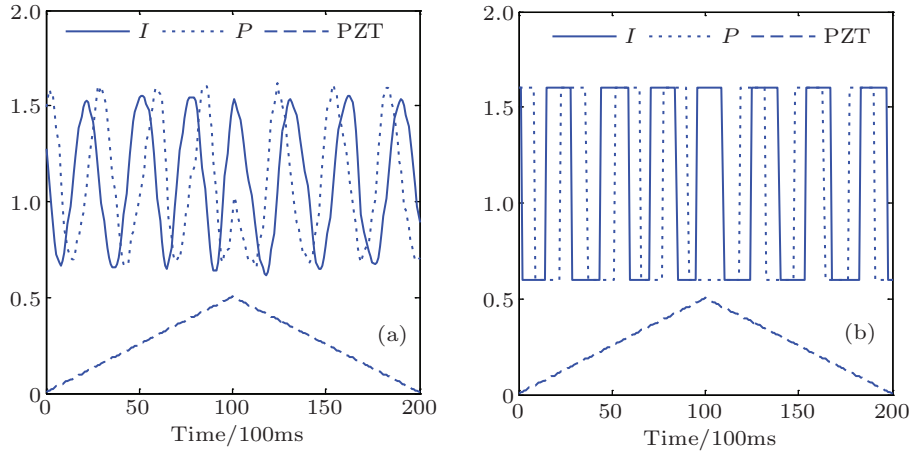


Fig. 3. (colour online) Outputs of LF and PSD (a) and their reshaped wave (b) when the mirror moves under triangular voltage scanning.

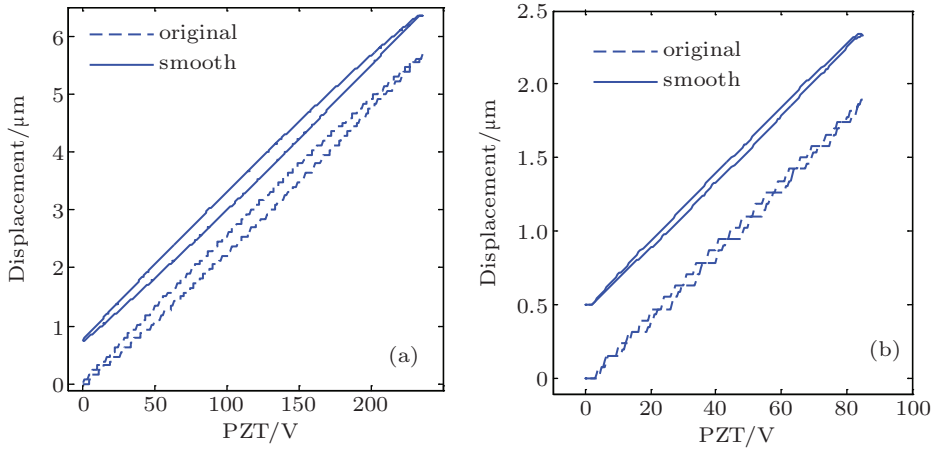


Fig. 4. (colour online) Measured hysteresis loops of PZT_2 using (a) 0–235 V triangular wave and (b) 0–85 V triangular wave.

4. Theoretical analysis

In a typical single mode He–Ne laser, when a small part of light is reflected back into its cavity, the intensity is

$$I = I_0 \left[1 + m \sin (2kl)\right], \tag{3}$$

where I_0 is the initial intensity without feedback, m is the modulation depth, k is the wave number, and l is the distance between the feedback mirror and the laser output mirror, or the external cavity length.

When the feedback mirror is dithering in the normal direction with a small-amplitude sine wave, intensity is changed to

$$I = I_0 \left[1 + m \sin \left(2kl + 2k\Delta l \sin (\omega t)\right)\right], \tag{4}$$

where Δl is the dithering amplitude and ω is the frequency.

Through the equations of trigonometric function, we have

$$\sin \left[2kl + 2k\Delta l \sin (wt)\right]$$

$$= \sin(2kl)\cos[2k\Delta l\sin(wt)] + \cos(2kl)\sin[2k\Delta l\sin(wt)]. \quad (5)$$

According to properties of Bessel's function, we obtain

$$\cos[M\sin(\omega t)] = J_0(M) + 2\sum_{1}^{\infty} J_{2n}(M)\cos(2n\omega t), \quad (6)$$

$$\sin[M\sin(\omega t)] = 2\sum_{0}^{\infty} J_{2n+1}(M)\sin[(2n+1)\omega t], \quad (7)$$

where M is real argument and $\mathrm{J}_n(\cdot)$ is the n-th order Bessel function.

From Eqs. (5)–(7), we know that the base frequency component in $\sin[2kl + 2k\Delta l\sin(\omega t)]$ is $2\mathrm{J}_1[2k\Delta l]\sin(\omega t)$. As a result, after light passes through the PSD module, we obtain $P = I_0\mathrm{J}_1[2k\Delta l]\cos(2kl)\cos\varphi$. If we tune φ to zero in the Labview program, and remove the DC component of I, we can obtain a pair of signals

$$I = I_0\sin(2kl), \quad (8)$$

$$P = P_0\cos(2kl). \quad (9)$$

Equations (8) and (9) are both sine waveforms with a phase difference of $\pi/2$. Combining them, we can measure the displacement of the feedback mirror with a resolution of $\lambda/8$. The method is well known in this field,[8] so we will not express it in detail.

5. Discussion

5.1. Influence of BPF

When the scanning speed of PZT_2 increases, experimental results disagree with theoretical analysis in two aspects, as shown in Fig. 5(a). One aspect is that the reverse direction point lags behind the PZT voltage, which is mainly caused by hysteresis of PZT_2 to the output voltage. Another aspect is that the phase difference between P and I deviates from $\pi/2$ to some extent. It is found that BPF induced time delay mainly accounts for the problem. The PSD module needs some time to perform data processing and introduces time delay. When the scanning speed is fast, this problem becomes remarkable. When we change bandwidth of the BPF from 20 Hz to 200 Hz, the influence of time delay is reduced as shown in Fig. 5(b). The phase difference between P and I is approximately $\pm\pi/2$ but SNR is reduced. Therefore, the time delay of the PSD module is the main limiting factor of this system.

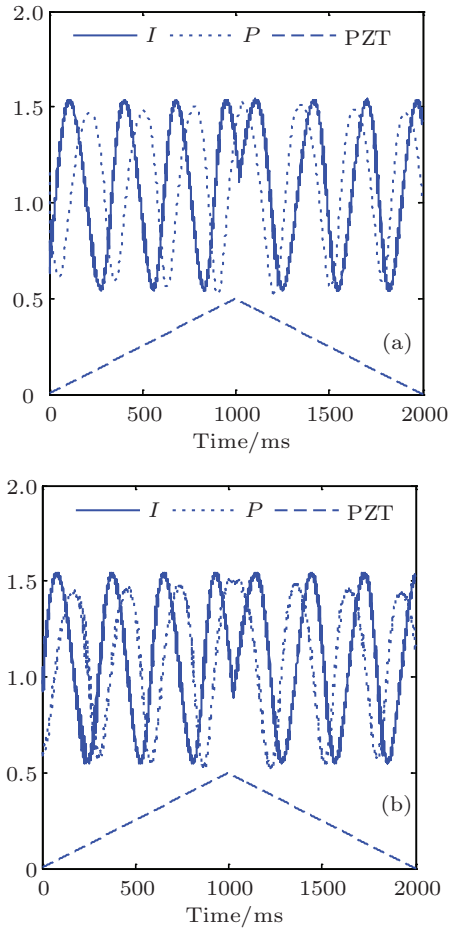


Fig. 5. (colour online) Outputs of LF and PSD with (a) 20Hz BPF and (b) 200 Hz BPF when the mirror moves at higher speed under triangular voltage scanning.

The disadvantages of this method result from PSD module delay, which may reduce the maximum speed of the feedback mirror. With higher oscillating frequency and larger amplitude as well as faster AD and DA, more periods of oscillating signal can be used at a given period in the PSD module so that the SNR can be improved. As a result, a small delay BPF can be used, which allows us to measure objects moving at higher speed.

5.2. Frequency stabilization

In order to achieve stable wavelength, the frequency is stabilized. The laser power tuning curve is shown in Fig. 6, where the slope is caused by a distortion of PZT_1. With the hill-climbing method, the laser can be stabilized at the peak power.

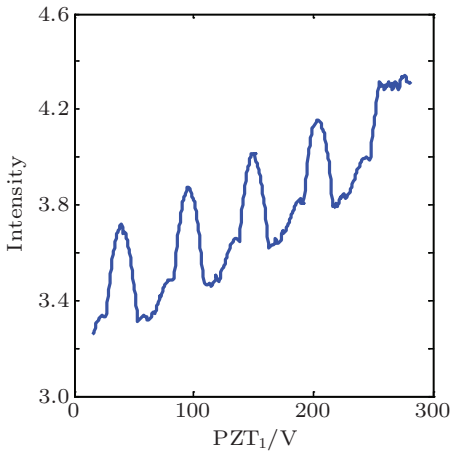


Fig. 6. (colour online) Power tuning of the laser with PZT_1.

The intensity near power peak can be approximately expressed as

$$I = I_{\mathrm{P}}\left[1 - b\left(f - f_{\mathrm{P}}\right)^2\right]\left[1 + m\cos\left(2kl\right)\right], \quad (10)$$

where I_{P} is the maximum intensity, b is the fitting coefficient, f is the laser frequency, and f_{P} is the laser frequency corresponding to peak power. The terms $\left[1 - b\left(f - f_{\mathrm{P}}\right)^2\right]$ and $[1 + m\cos 2kl]$ express the influences of internal cavity length and external feedback, respectively. The influence of external feedback on laser frequency is omitted because it is very small.[19] We can control the feedback level to make m less than 0.1, so its influence on frequency stabilization system is small. From this point of view, the system should be operated in weak feedback condition.

5.3. Influence of strong feedback

When feedback is strong and multiple feedback happens, the waveform of I as a function of $2kl$ will not show a quasi-sine wave.[19,20] When the reflectivity of M_3 is changed to about 0.8, the I and P each as a function of PZT_2 voltage are shown in Fig. 7. It is found that direction discrimination can still be achieved. The phase difference between I and P reaches a deviation of $\pi/2$, which results in unequal subdivision of a fringe. Therefore, it is not suitable for the system to obtain high precision.

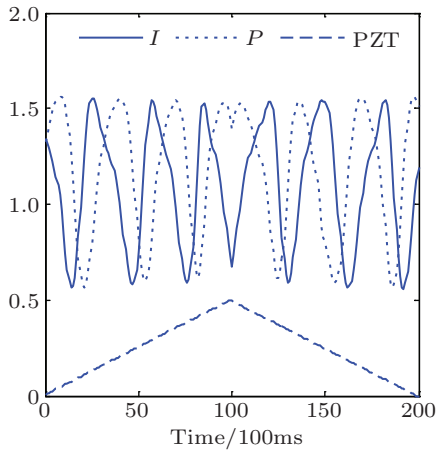


Fig. 7. (colour online) Outputs of LF and PSD with strong feedback.

6. Conclusion

Direction discrimination is a key problem in laser feedback interferometers. Anisotropic feedback is used to obtain a pair of orthogonal signals in Ref. [17]. However anisotropic feedback needs a wave plate and a polarization beam splitter, which complicates the system and alignment. The experimental results in Section 3 show that through vibrating the feedback mirror and using PSD method, a pair of orthogonal signals is obtained. The displacement direction can be easily obtained according to the phase relationship. When the signals are processed with a suitable computer program, a resolution of $\lambda/8$ is achieved. Compared with anisotropic feedback method, this method exploits electric signal processing to simplify the laser feedback system. The laser feedback system only needs a feedback mirror with PZT, so it is simpler and easier to align. In order to make the system achieve a high precision, it is better for the system to operate under weak feedback conditions. The PSD may induce time delay, which limits the maximum speed of the feedback mirror. However, due to advantages such as simplicity, low cost, and easy alignment, this laser feedback interferometer still has many potential applications.

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