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A ultra-small-angle self-mixing sensor system with high detection resolution and wide measurement range

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ABSTRACT

The self-mixing technique based on the traditional reflecting mirror has been demonstrated with great merit for angle sensing applications. Here we demonstrate a modified self-reflection-mixing angle measurement system by combine a right-angle prism to self-mixing angle measurement. In our system, the wavelength is crucial to the angle measurement resolution. For a microchip solid-state laser, the measurement resolution can reach 0.49 mrad, while the resolution for the He-Ne laser is 0.53 mrad. In addition, the ranges in the system with the microchip solid-state laser and He-Ne laser are up to 22 mrad and 24.9 mrad respectively. This modified angle measurement system effectively combines the advantage of self-mixing measurement system with a compact structure, providing interesting features such as of high requisition of resolution and precision.

1. Introduction

Small-angle measurement technology is of importance in a number of applications, such as optical collimation, micro-electro-mechanical system (MEMS), atomic-force microscope imaging, and precision machining. Recently, many different types of small angle measurement methods have been proposed and demonstrated, like mechanical measurement technology, electromagnetic measurement technology, and optical measurement technology. At present, the common optical measurement methods for small-angle measurement include auto-collimatic method, total internal reflection method, ring laser method, and laser interferometry method [1–5]. Among them, the traditional two-beam laser interferometry method is most widely used due to high small-angle measurement precision by measuring the movement of interference fringes.

However, the traditional two-beam laser interferometry has some defects, such as complex optical structure, large size, not easy collimation [6,7] which have been presented in previous research works. It is desired to develop a new method to overcome the above disadvantages. Thus the laser self-mixing interference [8–25] (SMI) technique has been used in the recent years, which avoid defects compared to the traditional two-beam laser interferometry method. Especially, the self-mixing technique is more suitable for the angle-measurement due to its superiority, including compactness, sensitivity, reliability, self-aligned, and easy implementation. Furthermore, the experiment device only has a single optical path and less optical components, thus requiring less space in the small-angle measurement.

For the above reasons, much attention has been drawn to optical measurement of small-angle by measuring the angle of a reflecting mirror based on SMI [26]. The output laser power changes a fringe cycle when feedback light path changes every half-wavelength, which is caused by the change of measured angle. However, this method has also met the inevitable problems of extremely low sensitivity and limited angle measurement range. The main reason is that once the angle measured is slightly larger, the back-reflected light re-enter the laser cavity will be reduced or even disappear. Consequently, it is difficult to produce the enough amplitude of self-mixing signal which determines the measurement sensitivity, when the optical feedback strength is too small. Even if the so called “self-mixing signal” is appears, it is still difficult to distinguish the “self-mixing signal” caused by the optical length difference changed with the angle or the optical feedback strength, which lead to big errors and affect the accuracy of experiment. At the same time, one point should be mentioned the measurement method of rotating the reflecting mirror can only be used

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in the slight-angle measurement, since the light cannot trace the way back while the angle has been changed. So, the traditional self-mixing method of small-angle measurement with a reflecting mirror has a very strict limitation on the location of the incidence point, and a slight change of the incidence point will have an obvious impact on the measurement range and accuracy. Thus, the traditional method with a reflecting mirror will confront lots of unavoidable problems in the process of small-angle measurement.

In this paper, an effective approach is proposed for ultra-small-angle measurement in order to overcome those issues that the traditional SMI method met. In our experiment setup, a right-angle prism is adopted in the experiment system for adjusting experimental device more conveniently. We refer to this novel experiment system as the modified self-reflection-mixing (SRM) angle measurement system. It can generate SMI signal with an arbitrary incidence angle by self-reflection property of right-angle prism. The modified SRM angle measurement system can be used to measure a wider angle range with higher accuracy and sensitivity compared to the traditional method. And the modified SRM angle measurement system also to providing an effective platform to study self-mixing effect with different types of laser source. In Section 2 the theoretical analysis and numerical simulations of the modified SRM angle measurement system are described, and the related experimental results are given in Section 3, which are in good agreement with the theoretical analysis in Section 2. Finally, conclusions are drawn in Section 4.

2. Theoretical analysis of the SRM angle measurement system

During the process of operating the modified SRM angle measurement system, we use a right-angle prism as the key component of the experimental setup. Such a setup ensures that the light can reenter the laser cavity along the original path. We are aware that changing the measuring angle of right-angle prism can lead to the change of external cavity length. In order to get the angle value in our modified SRM angle measurement system, we first discuss the relationship between the optical path and the external cavity length variation. Fig. 1 shows the principle schematic of the modified SRM angle measurement system.

As shown in Fig. 1, the measured angle θ is the angle ∠FBJ. Fig. 1(a) shows the initial position of the prism with θ=0. The line MCDN denotes the light path which incidents vertically on the surface of the prism. Accordingly, Fig. 1(b) illustrates the optical path in the prism with angleθ. It can be realized that ray ME is parallel to ray FN from the characteristics of the right-angle prism. This structure could make the feedback light reenter the laser along the same way.

Based on the theoretical derivation, the angle measurement can be obtained by calculating the length of h_1, h_2, andh_3:

$$h_1 = h - \frac{\sqrt{2}}{2}\left[\rho(\cos\theta - \sin\theta) + \frac{q_1(\cos\gamma + \sin\gamma)\sin\theta}{\cos\gamma}\right] \tag{1}$$

$$h_2 = h - \frac{\sqrt{2}}{2}\left\{\rho(\cos\theta + \sin\theta) - \frac{[\rho(\cos\gamma - \sin\gamma) - q_2(\cos\gamma + \sin\gamma)]\sin\theta}{\cos\gamma}\right\} \tag{2}$$

$$h_3 = \frac{q_1 \sin 45^\circ}{\sin(90^\circ - \gamma)} + \frac{q_2}{\sin(45^\circ - \gamma)} + \frac{[\rho - q_2/\tan(45^\circ - \gamma)]\sin 45^\circ}{\sin(90^\circ + \gamma)} = \frac{\sqrt{2}\rho}{\cos\gamma} \tag{3}$$

where ρ is the side-length of the prism; $\gamma$is the refraction angle.

The optical path difference (include the specific relationship between the external cavity length and the optical path difference) and power of self-mixing signal can be described as Eqs. (4 and 5) respectively [11]:

$$\begin{aligned}\Delta h &= 2\left[(h_1 + h_2 + nh_3) - 2h + \sqrt{2}\rho - \sqrt{2}n\rho\right] \\ &= 2\sqrt{2}\rho\left[1 - n - \cos\theta + \sqrt{n^2 - \sin^2\theta}\right] = 2(L_{ext} - L_0)\end{aligned} \tag{4}$$

$$P = P_0\left(1 + m\exp\left\{-\frac{\delta\nu L_{ext}}{c}\right\}\cos\left(\frac{4\pi\nu L_{ext}}{c}\right)\right) \tag{5}$$

where n is the refractive index of right-angle prism material; P is the output power of laser; P_0 is the initial output power of laser; $m$is modulation coefficient of the interference; $\delta\nu$ is the laser spectral linewidth; L_{ext} is the external cavity length; ν is the output frequency of laser; L_0 is the initial external cavity length. The parameter of the prism side-length $\rho$and its refractive index n used in our simulation and experiment are 2.5 cm, 1.52 respectively. In our simulation, the modulation coefficient of the interference m is −0.022; the initial output power of laser P_0 is 5 mW; the feedback coefficient C under the initial external cavity length is 0.3; the laser spectral linewidth $\delta\nu$ is 100 MHz; the linewidth enhancement factor α used a typical value 3.

Considering the initial location of the prism, and letting the minimum measurable angle is equal to the corresponding value of the half fringe, we can enhance the measurement resolution of Eq. (4) further in the SRM angle measurement system while$\Delta h$is equal to a quarter wavelength:

$$\Delta h = 2\sqrt{2}\rho\left[1 - n - \cos(\theta + \theta_0) + \sqrt{n^2 - \sin^2(\theta + \theta_0)}\right] = \frac{1}{2}N\lambda \tag{6}$$

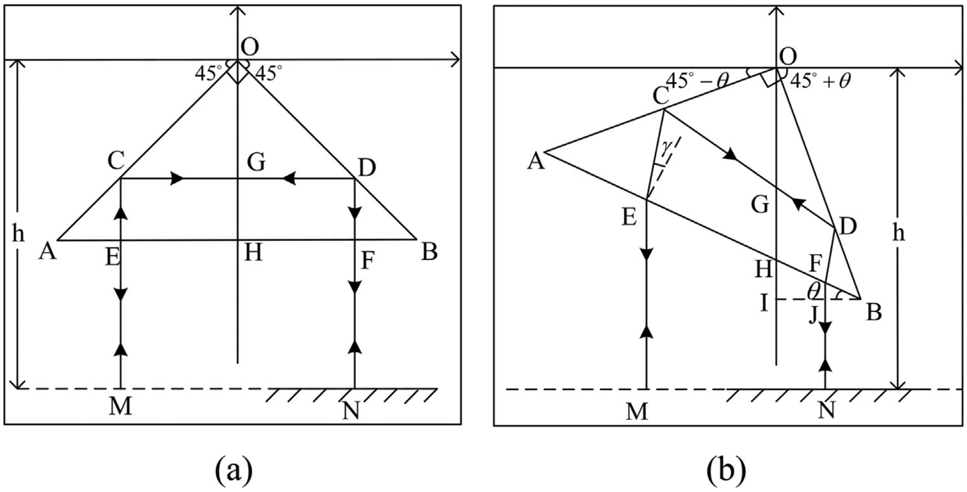

Fig. 1. Principle schematic of the modified SRM angle measurement system **(a)** the light path of the initial position of the prism; **(b)** the light path of the prism with angleθ($AC = q_1$,$OC = q_2$,$AO = BO = \rho$,$EM = h_1$,$FN = h_2$,$EC + CD + DF = h_3$).