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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; δv is the laser spectral linewidth; L_{ext} is the external cavity length; v 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 δv 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:

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

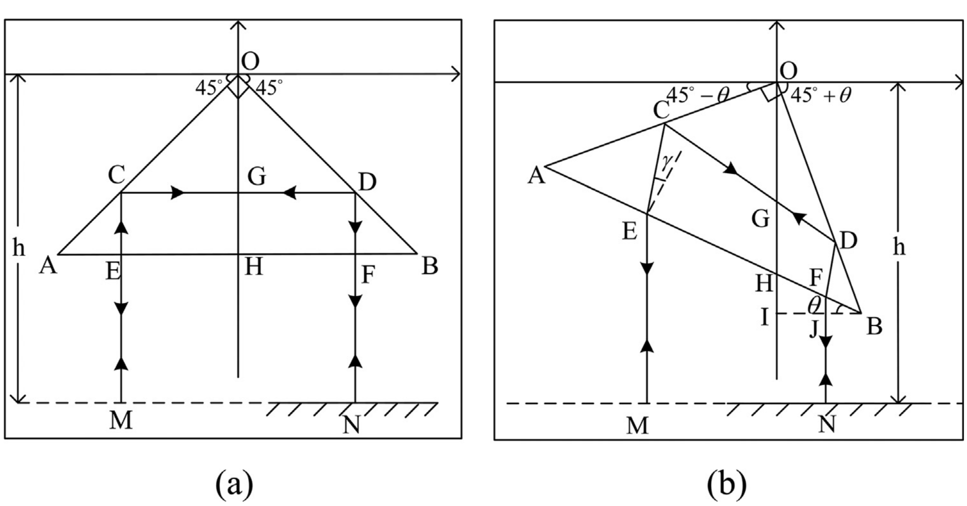

Fig. 1. Principle schematic of the modified SRM angle measurement system **(a)** the light path of the initial position of the prism; **(b)** the light path of the prism with angleθ($AC = q_1$,$OC = q_2$,$AO = BO = \rho$,$EM = h_1$,$FN = h_2$,$EC + CD + DF = h_3$).

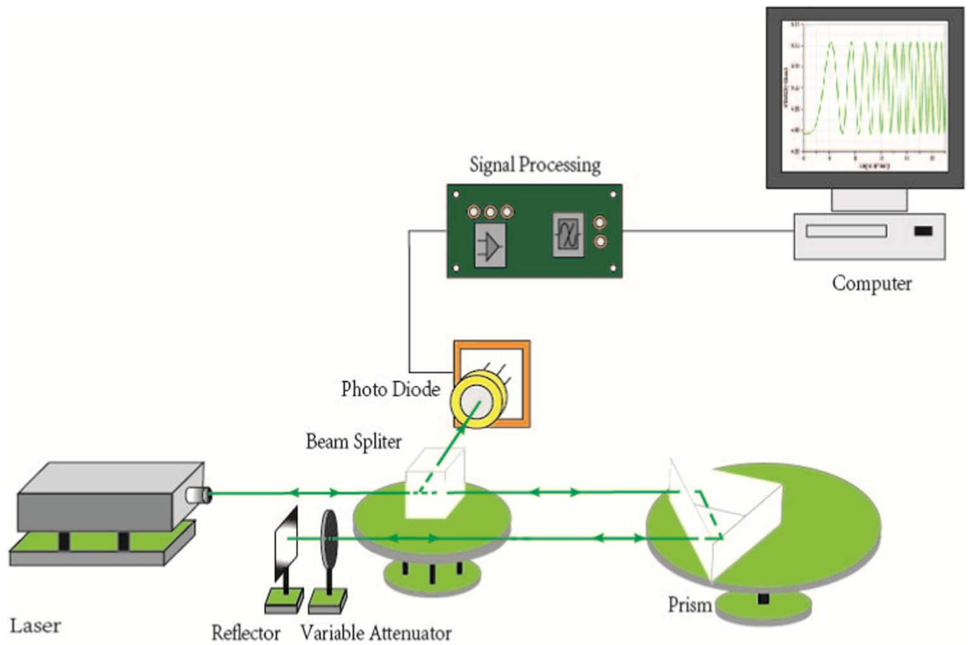

Fig. 2. Experimental setup for the modified SRM angle measurement system.

where θ_0 is the initial angle of prism in the process of actual measurement, N is the fringe number. At the same time, we will give the simulation results in Section 3.

We use the fringe counting method counted by a half-integer fringe of the self-mixing waveform to measure the angle in our measurement system. It can be observed that the resolution of MSL (532 nm) is higher than the He-Ne laser (632.8 nm) based on the Eq. (6). Through the above analysis, this is a solid evidence that shorter wavelength MSL will bring higher measurement resolution than the He-Ne laser as light source in our system.

In order to verify the feasibility of the modified SRM angle measurement system, we design and set up the experimental system to measure the angle with the fringe counting method in Section 3, and obtain the corresponding ultra-small-angle simulation and measurement results in this section.

3. Experimental setup and results of SRM angle measurement system

The experimental setup for the modified SRM angle measurement system is shown in Fig. 2. The configuration of our experiments consists of a single longitudinal mode MSL with wavelength of 532 nm (Impex High Tech Co) or the He-Ne laser with wavelength of 632.8 nm (Melles Griot), a Beam Splitter (BS), a photo diode, a rectangular prism fixed on a rotation stage and a reflector (a mirror). The reflector in our experiment is a square mirror which length of side is 3.6 cm. The material of prism we used is N-BK7. A variable attenuator ATT was inserted into the external cavity to modify the feedback level.

Our rotating device is composed of a rotary table, a conveyor belt and a Permanent magnet low speed synchronous motor (Suzhou Wilkie Telecom and Motor Manufacturing Company, Model 70TDY4). The rotary table is rotated by the conveyor belt which connected and driven by the motor. The beam from the MSL laser is divided into two beams by the BS. One of the beams passes through the prism and is reflected by the reflector. Actually, the laser beam incidents to the inclined plane of the right-angle prism, then shots from the same face after double-reflection, finally reenters the laser cavity along the original path. Therefore, the laser beam can trace along the way back with no change in the feedback intensity. The other beam is detected by a Photo Diode (Ruihai, Model RPD-P-3-A-85-FCAPC) followed by a signal processing circuit in order to test the SMI signal. In our experimental setup, the self-mixing signal processing circuit includes a amplifier, filters and further amplifier. Then the experimental signal is digitized with a 200-kHz, 16-bit analog-to-digital (A/D) board (National Instruments PCI6251) on a computer bus.

Here, we mainly analyze the simulation and experimental results of the angle measurement system. It can be seen that the self-mixing output laser waveform in Fig. 3(a),(b) changes a fringe cycle when feedback light path changes every half-wavelength of laser source. At the same time, the simulation results are in good agreement with the experimental results in Fig. 3(c),(d).

Fig. 3(a) shows the simulated self-mixing output signal of MSL with 532 nm. 13 fringes appeared when the measured angle of prism is close to 22 mrad. The self-mixing fringes become denser while the measured angles become larger. In order to compare the influence of different wavelengths of lasers as light source in the SRM angle measurement system, we also simulate the signal of He-Ne laser with 632.8 nm shown in Fig. 3(b). The results show that appearance of He-Ne laser appear 10 fringes when the measured angle of prism is 22 mrad with the same condition. According to Fig. 3(a),(b), self-mixing signal fringe number only depends on the laser wavelength under the same condition. It is indicated that the angle measurement resolution, namely the minimum step between two measurements, has a close relationship with the wavelength of laser source. Fig. 3(c),(d) compares waveforms of the modified SRM angle measurement system by different type of laser source with MSL and He-Ne laser. As can be observed the larger angle is, the bigger the optical path difference changes, accordingly, the self-mixing fringes become denser with the increased angle, which is in well agreement with the theoretical analysis as shown in Fig. 3(a), (b). We can count the fringe number to measure angle of different laser as light source from Fig. 3(c), (d). It can be measured in a wider range in the experiment, but we only select the clear part of fringes. When the measured angle of prism is closed to 22 mrad, the fringe number of MSL is 13 while the He-Ne laser is 11, which shows a consistent trend with the simulation result. It is indicated that this modified SRM measurement system has a close relationship with wavelength greatly.

After the comparative study of waveforms of MSL and He-Ne laser as the light source in the modified SRM angle measurement system, we

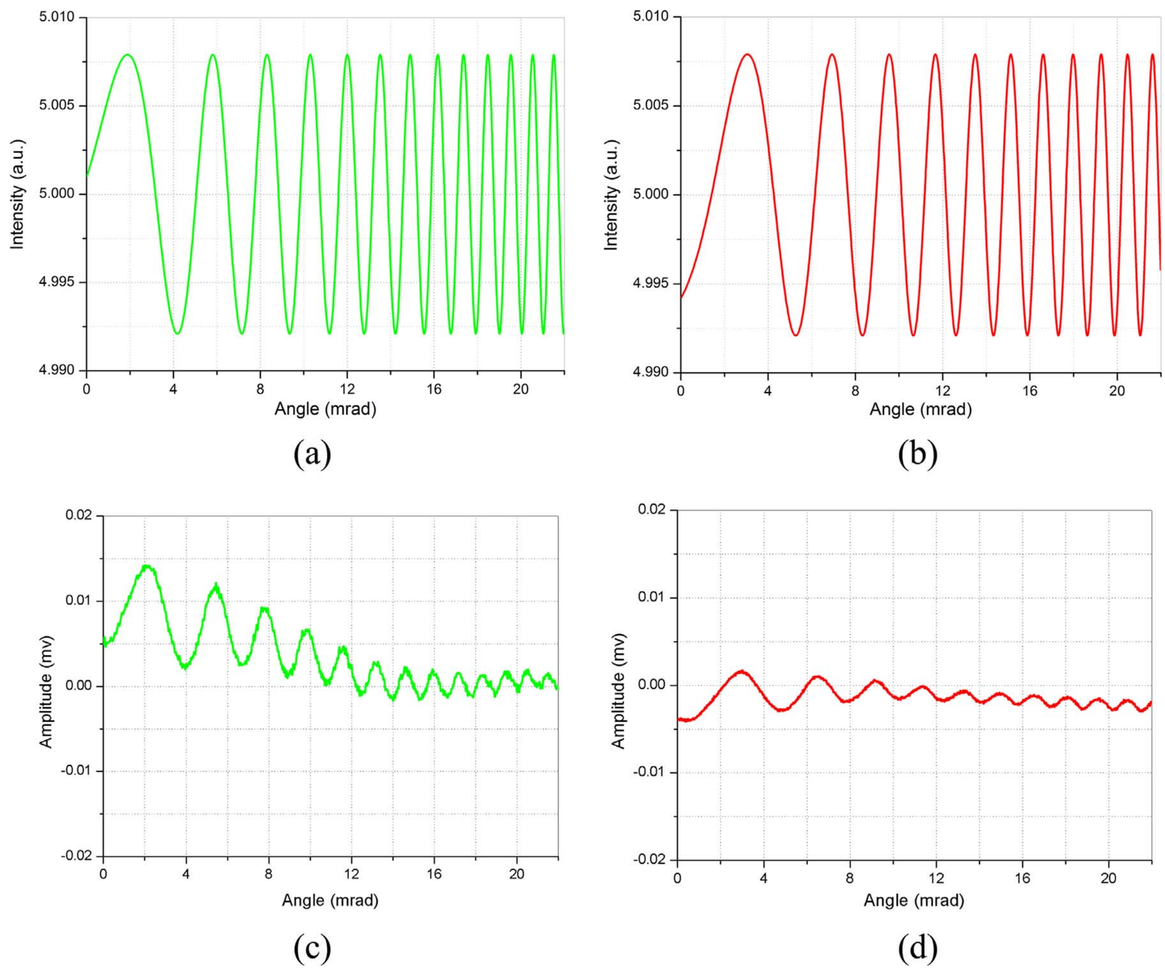

Fig. 3. The simulation and experimental results of the angle measurement system **(a)** the simulation results of MSL; **(b)** the simulation results of He-Ne laser; **(c)** the experimental results of MSL; **(d)** the experimental results of He-Ne laser.

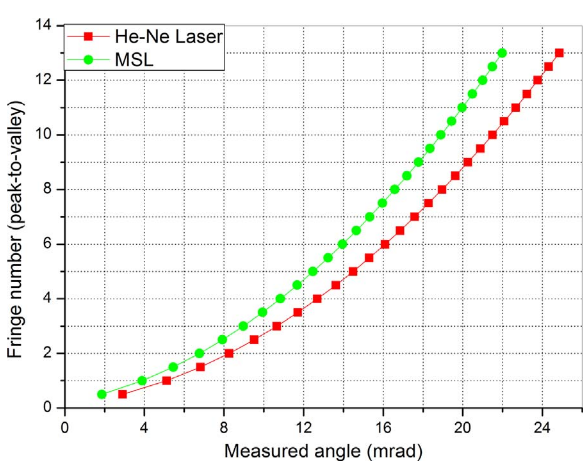

Fig. 4. The relationship of the fringe number and the measured angle.

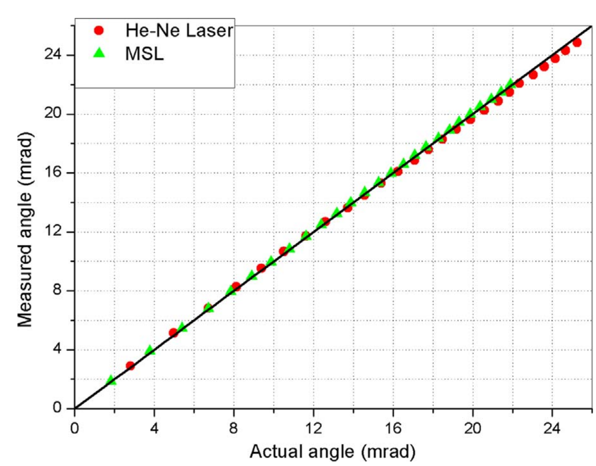

Fig. 5. The relationship of the actual angle and the measured angle.

analyze the relationship between the fringe number and the measured angle after modification of the initial location of the prism, which is shown in Fig. 4. The data points of both lines represent the appeared fringe number at various measured angles, respectively. The red points represent the results of the He-Ne laser as light source, while the green points represent the MSL as light source. Based on the experimental results, it is observed that the slope of the green line is higher than the red line, namely the fringe number of MSL is more than the He-Ne laser under the same change of the external cavity. When using the MSL as the light source the sensitivity of the system is higher than the He-Ne laser in the angle measurement system. Then Fig. 5 is led to further comparison and analysis about the influence on measurement results of lasers with different wavelengths by carefully adjusting our modified SRM angle measurement system in order to keep the initial angle of prism close to zero.

In the theoretical analysis section the measured angle values in the modified SRM angle measurement system are obtained from the fringe number fed into the formula Eq. (6). The comparison schematic shown in Fig. 5 is drawn by using the data which are obtained from the theory and the experimental measurement. As shown in Fig. 5, the black line

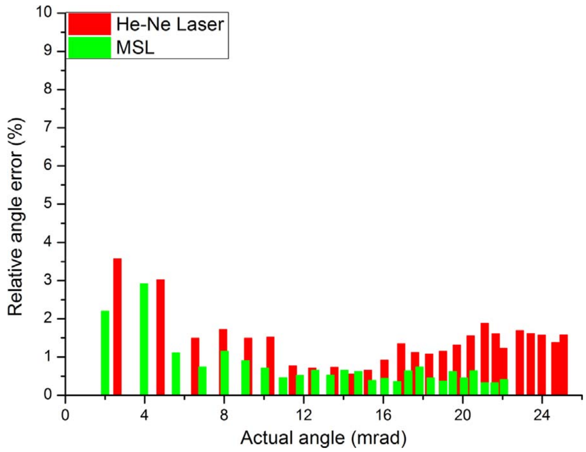

Fig. 6. The relationship of the relative angle error and the actual angle.

means the actual angle values. We measured the angular velocity of the turntable by recording the rotating radian in a certain time. The angular velocity of turntable in our experiment is 1.257 rad/s. Thus we can get the accurate angle value according to the angular velocity and measurement time. The red circle dots represent the angle measured by He-Ne laser as light source in the modified SRM angle measurement system, while the green triangle dots represent the angle measured by MSL as light source. In the experiment, the measured angle values of MSL coincidences with the actual angle values in the measured angle range, which can reach 22 mrad, but the measured angle range of He-Ne laser is up to 24.9 mrad. And the measured angle range of our modified SRM angle measurement system could be enlarged by increasing the bandwidth of circuit and optimization of the modified SRM angle measurement setup. In contrast, the measured angle range of the traditional method with a reflecting mirror is no more than 1.4 mrad [26], which shows that, regarding the measurement range, the modified SRM angle measurement system presents a superior performance.

Furthermore, the differences between the corresponding values of the first four half-integer of MSL are 2.03 mrad, 1.56 mrad and 1.32 mrad using the fringe counting method respectively. Correspondingly, the values of He-Ne laser are 2.22 mrad, 1.7 mrad, and 1.44 mrad, respectively. As can be observed from the above values, the corresponding values between every two half-integer are gradually reducing with the increasing of the measured angles, resulting in the increase of the resolution. It can also be seen that the measurement resolution of MSL can reach 0.49 mrad, while the He-Ne laser is 0.53 mrad, which is in accordance with the theoretical simulation results. In the actual measurement, we can use the phase measurement method to further improve the accuracy and resolution in the SRM angle measurement system.

A column chart is plotted in order to further analyze the relative angle error of the modified SRM angle measurement system by different type lasers shown in Fig. 6. These columns in the graph represent the half-integer fringe number counted from peak to valley. From the Fig. 6, we can see that the relative error is less than 5% in the whole measurement range, which is satisfied with the requirement of high-accuracy measurement, besides that the error is quite large when measurement angle less than 5 mrad. In our experiment, the measurement error is mainly arose from the position of the prism, the stability of turntable, the collimation of the optical path, the thermal expansion, and the material dispersion, which could be decreased by optimization of phase measurement method. Simultaneously, other sources of measurement error, like the temperature, pressure and the surface flatness specifications of the mirror would influence on experiment results by changing the external cavity length in some ways. The temperature and pressure can affect the air refractive index, on top of affect the external cavity length. So, we try to keep our experiment environment of constant temperature and pressure, for reducing the experimental error caused by the air refractive index. For the surface flatness specifications of the mirror factor, the error can be controlled less than 1% when the external cavity length change only half wavelength caused by the angle. With the increase of the external cavity length, the error caused by the surface roughness of the plane mirror will be smaller. In addition, the error values of He-Ne laser as light source are mostly higher than MSL as light source, which means the measurement accuracy and resolution of MSL is higher than that of He-Ne laser due to the shorter wavelength of MSL. Consequently, it can be concluded that the experimental phenomena show a good agreement with the theoretical simulation results from this relative error map very well.

4. Conclusions

In this paper, we have presented a modified SRM angle measurement system, which can be used to measure a wider angle range with higher resolution compared to the traditional method based on a reflecting mirror self-mixing angle measurement system. As a consequence, the measurement range and the resolution of MSL as light source in the modified SRM angle measurement system can reach 22 mrad and 0.49 mrad, while the range and the resolution of He-Ne laser is up to 24.9 mrad and 0.53 mrad. From the theoretical simulation and the experiment results, the measurement resolution of MSL is higher than that of He-Ne laser, which is due to the shorter wavelength of MSL. Furthermore, we could increase the measurement precision and resolution by using the phase measurement method during the actual measurement in the modified SRM angle measurement system in our future works.

Author Contributions

Y.B. conceived, designed, performed the experiments and wrote the paper; W.D.H, Z.L. and W.S. analyzed the data; X.R. and Z.W.H contributed analysis tools; G.H.Q, L.J.G, W.H.Q discussed the experimental results. L.L developed the concept, revised the manuscript for content. Y.B.L supervised the entire project. All authors reviewed the manuscript.

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