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A small-angle self-mixing measurement system with improved detection resolution based on a rotatable pentagonal prism

Bo Yang [a,*], Chenchen Wang [b], Jun Zhang [a], Jiangli Ni [a]

[a] *Basic Experimental Teaching Center, Anhui Sanlian University, Hefei 230601, China*
[b] *Key laboratory of Opto-Electronic Information Acquisition and Manipulation of Ministry of Education, Anhui University, Hefei 230601, China*

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ABSTRACT

A modified small-angle measurement system is proposed to improve the angle measurement resolution by selecting a rotatable pentagonal prism to replace the right-angle prism based on the original small-angle measurement system. In our measurement system, the right-angle side length of pentagonal prism is crucial to the measurement resolution. For the pentagonal prism with 2 cm side length, the resolution can reach 64.68 urad, while the resolution is up to 30.48 urad for the pentagonal prism with 4 cm side length. Therefore, it is possible to obtain higher measurement resolution by choosing the pentagonal prism with a larger side length within a proper range as the key optical element in the modified small-angle measurement system, so as to achieve the purpose of system optimization. In addition, the small-angle measurement system with a rotatable pentagonal prism we have designed can be helpful and referential to the future study of self-mixing interference technology with high-resolution requirements on the basis of different prisms.

1. Introduction

With the development of nanofabrication and measuring technique, small-angle measurement technology is applied in various fields more and more widely, and the requirements of measurement accuracy and measurement resolution are becoming more and more highly in recent years. According to the different measurement methods, the small-angle measurement technology is mainly divided into mechanical angle measurement technology [1], electromagnetic angle measurement technology and optical angle measurement technology [2–8]. However, the mechanical and electromagnetic angle measurement technologies are not easy to be realized automation because of manual measurement, which can lead to the limitation of measurement accuracy and resolution. With the development of stable photoelectric technology, more and more attention has been paid to the optical angle measurement method with non-contact, high precision and high sensitivity. At present, the commonly used optical angle measurement technologies include total-internal-reflection method [2,3], auto-collimatic method [4] and laser interferometry method [5–8].

Among them, the traditional interferometry method based on Mich elson interference principle [8] is widely used because of its high measurement accuracy. The principle of the traditional laser interferometry method is to transform the angle change to the length change, and obtain the small-angle values by measuring the change of the interference fringes. Although the traditional interferometry measurement technique has high precision, the device is relatively complicated and the light path is not easy to be collimated. Compared to the traditional optical angle measurement technology, the laser self-mixing interference (SMI) measurement technology [9–11] has gradually been the important research direction of small-angle measurement technology due to the advantages of compactness, simple structure, low cost, robustness and easy implementation. The SMI measurement technology [12–20] refers to the light outputted from a laser is reflected or scattered by an external feedback object, then injected back into the laser cavity and interference with the light inside the cavity, causing the variability of the laser output, so as to realize the measurement of the external motion object.

At present, some researchers have proposed a small-angle measurement system by using a rotated plane mirror based on SMI measurement technology [10]. The measuring principle of the system is that through rotating a plane mirror causes the change in the optical path difference. And the output laser light power changes a fringe cycle when the optical path difference varies by one wavelength, then the measurement angle can be obtained according to the variations of the fringes. However, the measurement system has strict limits on the position of the incident light in the plane mirror and the light cannot trace the way back. If the plane mirror rotates slightly larger, the back-reflected beam re-enter the laser

* Corresponding author.
E-mail address: 530340749@qq.com (B. Yang).

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cavity will be greatly reduced or even completely unable to return to the laser cavity. Consequently, it is difficult to generate enough amplitude of self-mixing interference signal when the optical feedback is too weak. Thus, the small-angle measurement system with a rotated plane mirror will confront unavoidable problems on the aspects that the incidence point has an obvious impact on the measurement range and the detected resolution.

In order to overcome the above issues, we have proposed a method by adopting a right-angle prism instead of the plane mirror in the small-angle measurement system mentioned above [11]. The measurement system can ensure the beam re-enter the laser cavity along the way back and has no limitation on the location of the incident light within a certain measurement range, but there is a question still in low measurement resolution. In this paper, a novel modified small-angle measurement system proposed by replacing the right-angle to the pentagonal prism based on the original device, which can be further improved the detected resolution on the premise of ensuring the measurement structure is still simple. At the same time, the modified small-angle measurement system can also provide an effective research platform to study self-mixing interference technology with different prisms. In Section 2 the numerical simulations and the theoretical analysis of the small-angle measurement system are described, and the relevant experimental results are given in Section 3, which can be consistent with the theoretical analysis in Section 2. Finally, the conclusions we get in Section 4.

2. Theoretical analysis of small-angle measurement system

The biggest advantage is that no matter how big the incident angle from a right-angle plane of the pentagonal prism is, the emergent light and the incident light will always stay vertical after two reflections inside the pentagonal prism by using a pentagonal prism as the key optical part in the angle measurement system. As shown in Fig. 1(a), the laser is incident on the right-angle surface of the pentagonal prism from point A and shots out the other right-angle surface from point B after two reflections inside the pentagonal prism. The emergent light will be reflected back by the plane mirror and can be re-entered to the laser cavity, thus results the self-mixing interference. The Fig. 1(b) represents the laser light enters the right-angle surface of the pentagonal prism from point C and shots out the other right-angle surface from point D after two reflections inside the pentagonal prism when the angle is θ during the rotation process of the pentagonal prism. Due to the incident light and the emergent light from the pentagonal prism will always remain vertical within the measurable range, thus it can be greatly reduced the error from the laser light cannot return to the laser cavity along the original light path in the rotation process. According to the characteristics of the pentagonal prism, it can be simplified when calculating the internal optical path change by unfolding the pentagonal prism into three prisms. The laser light goes through the surface from point A and shots out another surface from point B in the actual optical path as shown in Fig. 1(a) by a solid line. In order to simplify the calculation, we can use the properties of the pentagonal prism reflect surface to straighten the deflection of the light path as shown in Fig. 1(a) by a dashed line, then the outgoing point will be changed from point B to point B'. Suppose the right-angle side length of the pentagonal prism is d and the total length from the right-angle side of the first pentagonal prism to the right-angle side of the third pentagonal prism is L, thus the actual optical path can be expressed by the formula:

$$L = \left(2 + \sqrt{2}\right) d. \quad (1)$$

The actual light path in Fig. 1(b) can also be seen as the optical path by a dashed line after unfolding the pentagonal prism into three prisms when the pentagonal prism rotated angle θ by using the same calculation method, then the outgoing point will be changed from point D to point D'. It can be concluded that the change of the optical path difference Δh is twice as long as the change of the external cavity when the pentagonal prism rotates angle θ and the internal refractive index of the pentagonal prism is known as n:

$$\begin{aligned} \Delta h &= 2L\left[1 - n - \cos\theta + \sqrt{n^2 - \sin^2\theta}\right] \\ &= \left(4 + 2\sqrt{2}\right) d \left[1 - n - \cos\theta + \sqrt{n^2 - \sin^2\theta}\right]. \end{aligned} \quad (2)$$

As we known the output signal waveform changes one fringe when the external cavity of the small-angle measurement system changes every half-wavelength, namely the optical path difference changes one wavelength in the signal diagram. Considering the initial location of the pentagonal prism in the process of actual measurement we can get the optical path difference further as follow:

$$\Delta h = \left(4 + 2\sqrt{2}\right) d \left[1 - n - \cos\left(\theta + \theta_0\right) + \sqrt{n^2 - \sin^2\left(\theta + \theta_0\right)}\right] = N\lambda \quad (3)$$

where θ_0 is the initial angle of the pentagonal prism, N is the fringe number, λ is the laser wavelength.

In the previous studies [11], we mainly chose the right-angle prism as the key optical element, and achieved the purpose of measuring the small-angle by rotating the right-angle prism. This article can not only provides the theoretical foundation for the research of the small-angle measurement system based on different optical components by change the right-angle prism into a pentagonal prism, at the same time can be further improved and optimized the small-angle measurement system, thus improve the system measurement resolution. The change of the optical path difference is proportional to the right-angle side length d of the pentagonal prism in the rotation process, which can be seen from Eq. (3). Next mainly analyzes the effect of the "side length d" on the resolution of the small-angle measurement system.

In order to concretely analyze the right-angle side length of pentagonal prism that influences on the measured results, we make a simulation analysis under the condition of the pentagonal prism with different right-angle side lengths, and then obtained the simulation output signal diagram, which is shown in Fig. 2. When the measured angle reaches 51.2 mrad, 4 fringes are obtained within the first 314 mrad and 5 fringes appear in the final 314 mrad by using the pentagonal prism with 2 cm side length as the key optical part of the small-angle measurement system shown in Fig. 2(a). Fig. 2(b) shows the result that 7 fringes and 10 fringes appear within the first 314 mrad and the last 314 mrad when choosing the pentagonal prism with 4 cm side length in the other condition same situation. It is indicated that the measurement resolution, namely the minimum step between the two measurement values, has a close relationship with the right-angle side length of pentagonal prism according to Fig. 2(a) and (b). As can be observed the longer the side length of the pentagonal prism is, the more the fringes appear, accordingly, the larger the optical path difference changes, which is consistence with Eq. (3). And as the measured angle increases, the space between the fringes becomes denser, which means the measurement resolution is higher and higher. As shown in Fig. 2(a) the interval between the peaks is about 80.15 urad within the first 314 mrad range, while the interval between the peaks of the fringes approximates 62.66 urad in the final 314 mrad range. The Fig. 2(b) shows that the gap between the fringe peaks is close to 45.23 urad within the first 314 mrad and the gap approaches 30.65 urad within the last 314 mrad respectively. Therefore, it can be further improved the measurement resolution when choosing a pentagonal prism with longer side length as the critical component in the small-angle measurement system under the appropriate conditions, thereby optimizing the small-angle measurement system.

3. Experimental setup and results of small-angle measurement system

The schematic diagram of the small-angle measurement system mentioned in this paper is shown in Fig. 3. We choose a He–Ne laser (CVI Melles Griot: 25-STP-912-230) with wavelength of 632.8 nm as