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Small angle measurement method based on the total internal multi-reflection

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ABSTRACT

A small angle measurement method based on total internal multi-reflection (TIMR) effect has been presented. In the proposed configuration, the semiconductor laser with single-mode fiber affords the stable illumination beam, and the beam expander induces a gain factor enlarging the small angular displacement, thus improving the angle measurement sensitivity and stability simultaneously. The experimental results show that our method has better sensitivity and higher stability than the conventional method. These results in association with the theoretical analysis, demonstrates the potential applicability of the presented method in high precision on-line measurement of small angle.

1. Introduction

The measurement of small angle is very important in aerospace, military affairs, and precision instruments. Due to noncontact, high resolution, and high sensitivity, many optical methods have been presented, such as autocollimator, interferometer, differential detection based on internal-reflection effect. Interferometer [1,2] and autocollimator [3–7] can provide higher accuracy among these existing methods. However, it is often very difficult to integrate these methods with machines for on-line measurement because of their large size. In contrast, differential detection based on internal-reflection effect [8–10] can make devices very stable, compact, and flexible switchover from large measurement range to high resolution. Nevertheless, highly stable light source is essential. To address this issue, Chiu et al. [11,12] measured the phase difference between s- and p-polarization states instead of the reflectance difference. Considering the steep phase change around the resonant angle, surface plasma resonance (SPR) sensor [13] has been used instead of prisms. Although very high sensitivity has been reported, the heterodyne optical source and phase meter made the measurement system complex and expensive. It is, therefore, necessary to overcome these design limitations of the instrument.

For the angle measurement instrument based on internal-reflection effect, the sensitivity [8] is often improved by the initial angle of incidence on the prisms, the polarization state of the light beam, and the number of reflections in prisms. As the reflectance difference is used to obtain the angular displacement, implies the larger reflectance difference in response to small angular displacement implies to higher sensitivity. Based on the analysis of the reflectance versus the angle of incidence curves, it is clear that when the initial angle of incidence is near the vicinity of the critical angle, the sensitivity will be higher. Due to the reflectance is dependent on the polarization state, p-polarization light beam has higher sensitivity compared to the s-polarization case. When multiple reflections in critical-angle prisms or parallelogram prisms are introduced, the rate of reflectance change with respect to the incidence angle in the vicinity of the critical angle is increased exponentially with the number of reflections. Hence, the sensitivity increases with the number of reflections at the optimal angle of incidence. Of course, there is always a trade-off between large linear measurement range and high sensitivity. Nevertheless, in addition to the power jitter of laser source and the nonparallelism error of prism, the drift of the incoming datum ray induced by the mechanical structure, vibration, air turbulence, and environment temperature are considered to be the major noise source. During the small angle measurement with high resolution, the small drift of datum ray may induce large angular measurement error. Therefore, the stability of instruments is a prerequisite. In order to obtain high sensitivity and stability simultaneously, we improve the small angular measurement system based on total internal multi-reflection effect by adding a new sensor parameter, which is mainly dependent on the magnification of beam expander. In the proposed cost-effective system, the compact semiconductor laser with single-mode fiber is used to provide stable power. A beam expander is

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used to amplify the signal of the weak angular displacement, and to obtain higher sensitivity combined with multi-reflection in prisms. The experimental and analytical results are found to be in good agreement.

2. Theory analysis

When the measurement mirror has a small angular displacement with $\Delta\theta$ from the initial position, the angular displacement of the signal beam reflected by the mirror will be θ_1, provided that the illumination parallel light beam from the source has no drift. Based on the geometric optical theory, the relationship between the two parameters is shown in Fig. 1 that can be expressed as

$$\theta_1 = 2\Delta\theta. \tag{1}$$

After the above-mention parallel signal beam is directed to the beam expander, the change of angular displacements has been presented in Fig. 2. Because the beam expander is made up of two lenses with different focal length, under the paraxial approximation, we can obtain that

$$f_2 \tan(\theta_2) = f_1 \tan(\theta_1). \tag{2}$$

Considering that is a small angle, Eq. (2) can be expresses approximately as

$$\theta_2 = (f_1/f_2)\theta_1. \tag{3}$$

Substituting Eq. (1) into (3), we obtain another expression as

$$\theta_2 = 2(f_1/f_2)\Delta\theta, \tag{4}$$

where the focal length of L_2 and L_1 is f_2 and f_1, respectively. In our proposed configuration, the beam expander is located at the front of the measurement mirror. Then, the illumination light from the source and the signal light from the measurement mirror will go through it in opposite directions. Assuming that $f_1 > f_2$, the angular displacement of signal beam is magnified by $2(f_1/f_2)$ times.

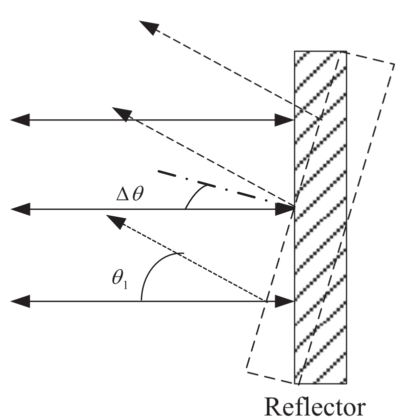

Fig. 1. Geometric relation between reflected light and reflector.

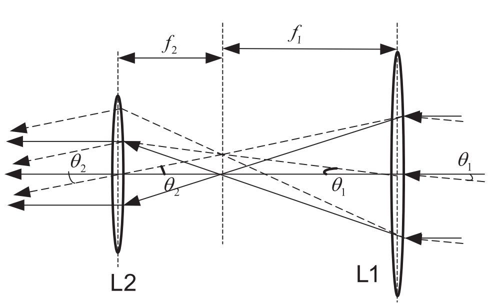

Fig. 2. Geometric relation of angular displacement between θ_1 and θ_2 induced by beam expander (L1/2: lens).

The s-polarization signal beam through the beam expander is directed to the setup shown in Fig. 3. Assuming that the initial incidence angle is θ_0 on the parallelogram prism, the incidence angle on the first parallelogram prism will become $\theta_0-\theta_2$, but $\theta_0+\theta_2$ on the second parallelogram prism. When θ_0 is a constant, the reflectances become the function of angular displacement θ_2 based on the Fresnel laws. Thus, the two reflectances through the pair of parallelogram prism are

$$R(\theta_0 \pm \theta_2) = \left(\frac{\sin(\theta_0 \pm \theta_2 - \arcsin(\sin(\theta_0 \pm \theta_2)/n)))}{\sin(\theta_0 \mp \theta_2 + \arcsin(\sin(\theta_0 \pm \theta_2)/n)))}\right)^m, \tag{5}$$

where n is the refractive index of prism, and m is the number of reflection in the parallelogram prisms. In our case, m is equal to 2. In order to compensate for the change of incident light power, the difference of the reflectances normalized by the sum of the reflectances is expressed as

$$\Delta R = \frac{R(\theta_0+\theta_2) - R(\theta_0-\theta_2)}{R(\theta_0+\theta_2) + R(\theta_0-\theta_2)}. \tag{6}$$

Substituting Eq. (5) into (6), another expression is obtained as

$$\Delta R \approx m(R'(\theta_0)/R(\theta_0))\theta_2. \tag{7}$$

When $\theta_2 \ll \theta_0$, the higher order terms about θ_2 has been ignored. Because the reflectances are received by the two detectors, the difference signal also can be expressed using the following equation with the assumption that the splitting ratio of the beam splitter is 1:1:

$$\Delta R = (I_1 - I_2)/(I_1 + I_2) = \Delta I, \tag{8}$$

where I_1 and I_2 are the optical intensity obtained by the detector PD1 and PD2, respectively.

Combining Eqs. (4), (7), and (8), we obtained that

$$\Delta I \approx m(R'(\theta_0)/R(\theta_0))2(f_1/f_2)\Delta\theta. \tag{9}$$

Thus, the measurement sensitivity coefficient of the system is

$$K = m(R'(\theta_0)/R(\theta_0))2(f_1/f_2). \tag{10}$$

Note that K depends on the number of reflections, the initial incidence angle, the polarization state of the incident light, and the magnification of the beam expander.

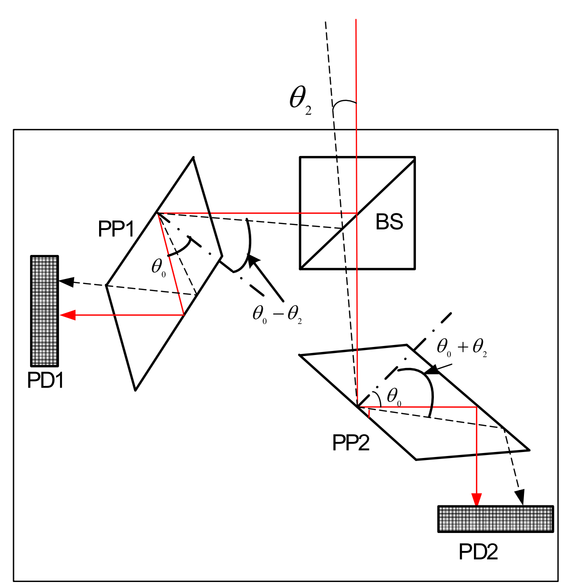

Fig. 3. Schematic of total internal multi-reflections in the prisms (PP1/PP2: parallelogram prism; PD1/PD2: photo diode; BS: beam splitter).