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EVALUATION OF A FOCUSED LASER SPOT DIAMETER FOR AN OPTICAL ANGLE SENSOR

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ABSTRACT

This paper presents a new method for measurement of a focused laser beam diameter by using a single cell photodiode (PD) for achievement of further higher measurement sensitivity of an optical angle sensor based on laser autocollimation. The proposed method referred to as the PD edge method utilizes an edge of the PD active cell in the same manner as the conventional knife-edge method, which is often employed for the evaluation of light spot diameter. The proposed PD edge method is expected to evaluate the focused laser beam diameter without the influence of light diffraction, which is often observed in the case of knife-edge method. After a description of the proposed PD edge method, its feasibility is demonstrated throughout the experiments by using a developed prototype optical setup.

Index Terms - *Optical angle sensor*, *Laser autocollimation*, *Abbe principle*.

1. INTRODUCTION

Strong demands on the fabrication of highly-precise free form optics can be found in the field of production engineering. Fabrication accuracy of such precision products is determined by the positioning accuracy of positioning systems to be used in ultra precision machine tools [1]. For feedback control of a positioning system, high precision displacement sensors such as linear encoders or laser interferometers are often employed [2]. Meanwhile, most of the positioning systems such as linear stages have an offset between its measurement axis and the motion axis, resulting in a positioning error [3] which is often referred to as the Abbe error. Some novel positioning systems [4-8] are designed to comply with the Abbe principle. In the case of employing laser interferometers [4-6], the measurement axes of the interferometers are aligned to intersect at the tip of the measurement probe so that angular error motions of the positioning table will not affect the measurement accuracy. Such a configuration can also be realized while using linear encoders as the displacement sensors for feedback control of a positioning table [7, 8]. Meanwhile, such configurations of the displacement sensors with respect to the positioning table will severely restrict the mechanical design of a precision positioning system. Therefore, in most of the cases, it is difficult to design positioning systems in machine tools or measuring instruments complying with the Abbe principle. To achieve further higher positioning accuracy in such machine tools or measuring instruments, the angular error motions of a positioning table are required to be measured by using appropriate angle sensors so that feedback control of a stage table can be carried out with the output signals from the angle sensors.

For measurement of angular error motions of a stage table, autocollimators are often employed. Some of the commercially available autocollimators have achieved a high measurement resolution of up to 0.005 arc-second [9]. Meanwhile, most of the autocollimators have employed a CCD (Charge Coupled Device), whose cutoff frequency is not high enough to be applied for closed-loop control of the stage table, as its position detector. It has therefore been difficult to apply the commercially available autocollimators to the feedback control of a stage system. This drawback can be addressed by applying photodiodes (PDs), whose cutoff frequency is much higher than that of the CCD, to the optical angle sensors [10-12] based on laser autocollimation [13] for the dynamic measurement of the angular error motions of stage systems. By using a quadrant photodiode (QPD), two-degree-of-freedom tilt can be measured simultaneously. Furthermore, with the employment of a diffraction grating as a measurement target, three-dimensional angular motion of a stage table can be measured simultaneously [14]. Meanwhile, the sensitivity of angle sensor can be improved by reducing the diameter of focused laser beam on the PDs [12]. The employment of single cell photodiodes (SPDs) can accept further smaller focused laser beam to achieve further higher sensitivity [15]. In this case, the evaluation of the diameter of focused laser beam becomes an important task to assure the high measurement resolution of the optical angle sensor.

In responding to the background described above, in this paper, a new method for the measurement of the diameter of focused laser beam is proposed. Some experiments by using the developed optical setup are carried out to demonstrate the feasibility of the proposed method.

2. PRINCIPLE OF THE PROPOSED METHOD

2.1 Laser Autocollimation

Figure 1 shows a schematic of the optical configuration for an optical angle sensor based on laser autocollimation [7]. In the optical angle sensor, angular displacement of a measurement target (a plane mirror) is detected as the translational displacement of the laser beam, which is reflected by the mirror and is made incident to a collimator objective, on the detector plane. The relationship between the angular displacement about the $X(Y)$-axis $\Delta\theta_{X(Y)}$ and the translational displacement of the focused laser beam along the $X(Y)$-axis $\delta_{X(Y)}$ can be expressed as follows [10]:

$$\Delta\theta_{X(Y)} = \arctan\left(\frac{\Delta\delta_{X(Y)}}{2f}\right) \approx \frac{\Delta\delta_{X(Y)}}{2f} \tag{1}$$

where f is the focal length of the collimator objective. By detecting $\delta_{X(Y)}$ from the output signals of a PD, $\Delta\theta_{X(Y)}$ can be detected. Now the focused laser beam diameter w on the PD plane can be expressed as follows [16]:

$$w = \frac{1.22 f\lambda}{D} \tag{2}$$

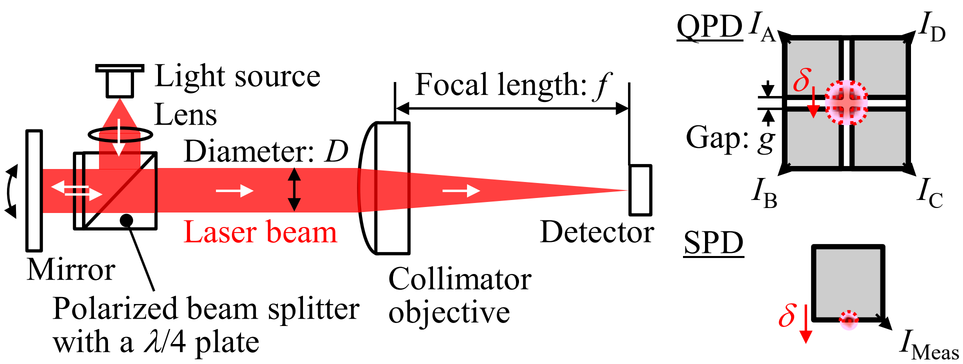


Fig. 1 A schematic of the optical configuration for two-axis laser autocollimator

where D and λ are the diameter and the light wavelength of the laser beam made incident to the collimator objective, respectively. From Eqs. (1) and (2), the following equation can be obtained:

$$\Delta\theta_{X(Y)} \approx \frac{0.61\lambda}{wD}\Delta\delta_{X(Y)} \tag{3}$$

Equation (3) means that the smaller focused laser beam diameter w contributes to improve the sensor sensitivity. However, in the case of employing quadrant-cell photodiode (QPD) as the position sensing detector, too small focused laser beam cannot be detected due to the existences of insensitive area with the gap of g among the active cells. This drawback can be overcome by employing a single cell photodiode as the position sensing detector and align the focused laser beam on the edge of the single cell. This optical configuration can accept further smaller focused laser beam and thus improve the measurement resolution of the optical angle sensor [15].

2.2 Evaluation of a focused laser beam diameter by using an edge of an active cell in photodiode

For the evaluation of laser beam diameter, the knife edge method [17], a schematic of which is shown in Fig. 2(a), has often been employed due to its simple principle and easy setup. In the method, the knife edge will be moved to cut across the laser beam, while monitoring the light intensity of the laser beam passed around the knife edge. However, in the case of measuring the focused laser beam diameter, this method is not suitable since the influence of diffraction at the knife edge becomes significant.

To address the drawback of knife-edge method described above, in this paper, a new method referred to as the PD-edge method, a schematic of which is shown in Fig. 2(b), is therefore proposed. In the proposed method, a detector plane will be placed at the focal plane of the objective lens. The focused laser beam will be placed around the edge of the active cell of PD. After that, a relative motion will be given in-between the laser beam and the PD, while monitoring variation of the light intensity of the laser beam made incident to the active cell of PD (Fig. 3). Since there are not any influences of the light diffraction at the edge, which becomes significant especially in the case of measuring focused laser beam diameter by the conventional knife edge method, the proposed method is expected to achieve precise measurement of the focused laser beam diameter.

3. EXPERIMENTS FOR EVALUATION OF THE FOCUSED LASER BEAM DIAMETER

To verify the feasibility of the proposed PD-edge method, experiments were carried out.

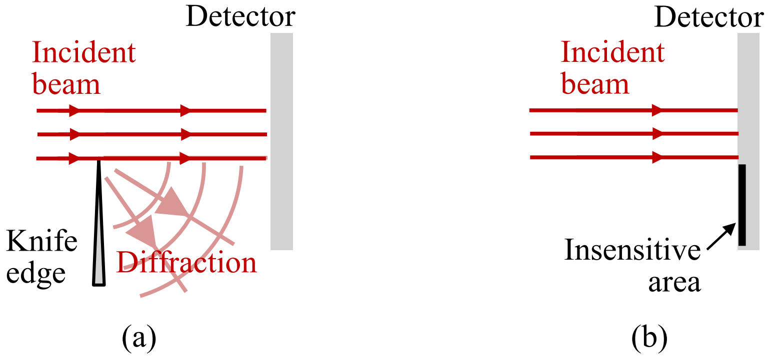


Fig. 2 (a) The conventional knife-edge method and (b) the proposed PD-edge method

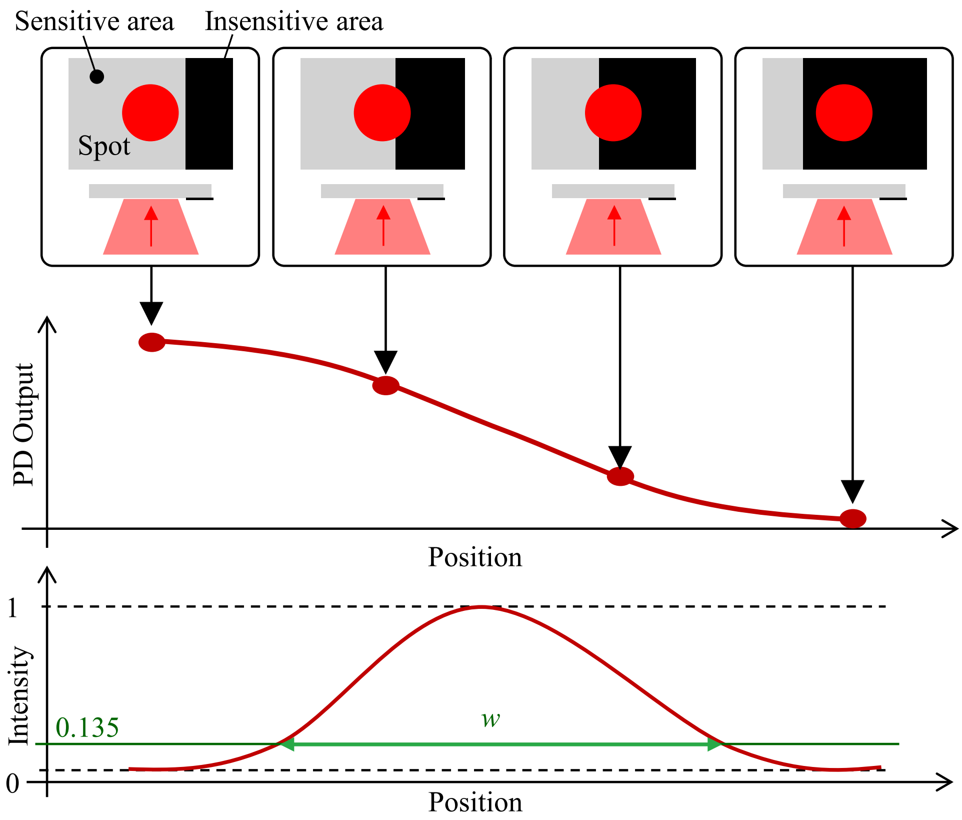
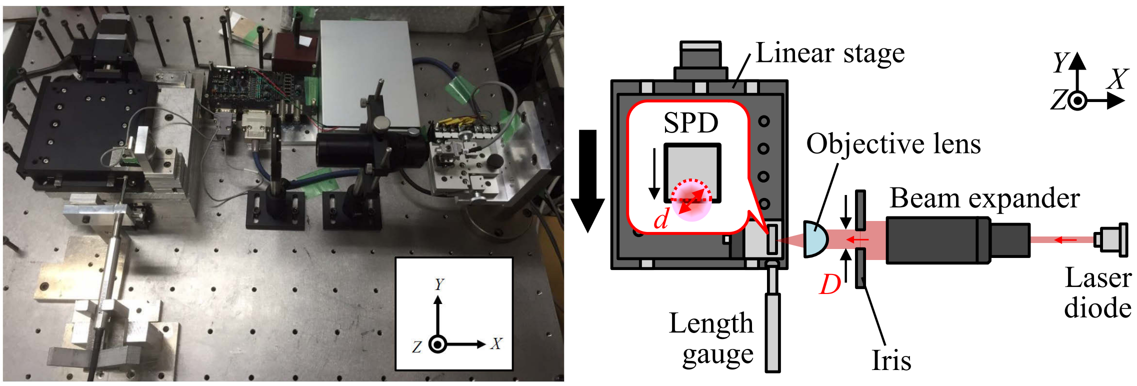


Fig. 3 Relationship among the position of the focused laser beam on the photodiode, photodiode output and the intensity distribution of the focused laser beam

Figure 4 shows a schematic of the experimental setup constructed in this paper. A laser beam from the laser diode was collimated, and was expanded by a beam expander. A diameter of the expanded laser beam *D* was adjusted by an iris, and was focused on a SPD by using a collimator objective. The SPD was mounted on a linear stage so that it could be scanned in the *Y*-direction for the measurement of the focused laser beam diameter *d*. The displacement of the linear stage was measured by a length gauge, whose measurement axis was aligned to be coincide with the motion axis of the SPD. Experiments were repeated while increasing the



(a) A photograph of the setup (b) A schematic of the setup

Fig. 4 Experimental setup for the PD-edge method

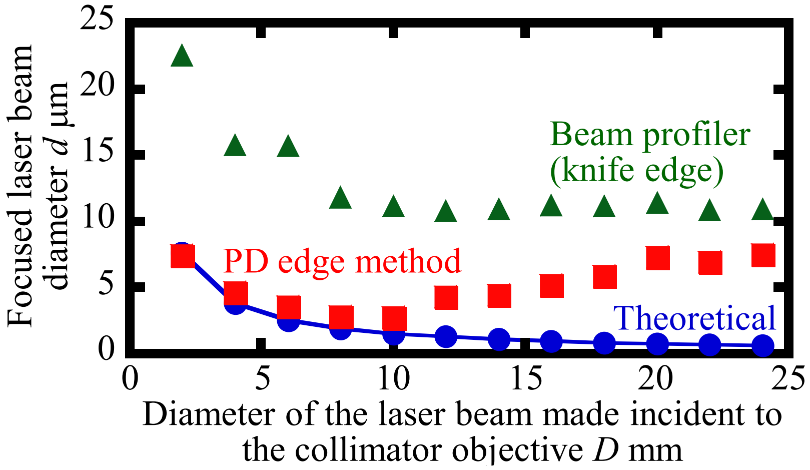


Fig. 5 Focused laser beam diameter measured by the conventional method (knife-edge method) and the proposed PD edge method

incident beam diameter D from 2 mm to 24 mm by adjusting the iris. For comparison, the focused laser beam diameter d was also measured by a commercial beam profiler (BeamScan, Photon Inc.), whose measurement principle was based on the knife edge method.

Figure 5 shows the measured focused laser beam diameter d with each incident beam diameter D. In the figure, theoretical value of the focused laser beam diameter calculated from a thin-lens equation without aberrations is also plotted. As can be seen in the figure, the commercial beam profiler showed relatively larger focused laser beam diameter than that acquired by the PD-edge method. Meanwhile, on the other hand, the result of the PD-edge method showed a good agreement with the theoretical value in the region where the incident beam diameter D was smaller than 10 mm. From these results, it has been verified that the proposed PD-edge method can measure the micrometric diameter of a focused laser beam. It should be noted that the measured focused laser beam diameter d was found to increase when the incident beam diameter D was set to be larger than 12 mm. A spherical aberration of the objective lens is considered as a root cause of the increase of the focused laser beam diameter [15].

4. CONCLUSIONS

A new method for measurement of a focused laser beam diameter, which is referred to as the PD edge method, is proposed for achieving further higher measurement sensitivity of an optical angle sensor based on the laser autocollimation. Experimental results by the developed prototype optical setup for the PD edge method have demonstrated that the proposed method can measure the diameter of focused laser beam, which cannot have been measured by the commercial beam profiler based on the knife-edge method. It should be noted that attentions have been paid in this paper to verify the feasibility of the proposed PD edge method. A verification test of the improvement of angle sensor sensitivity by optimizing the focused laser beam diameter, as well as the uncertainty analysis of the beam diameter measurement will be carried out in future work.

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