Position sensor based on slit imaging

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A position sensor based on slit imaging is proposed and its measurement principle is described. An imaging slit is illuminated by a collimated laser beam with square-wave modulation and imaged on a detection double slit through a $4f$ system. A magnified image of the detection double slit is formed on a bi-cell detector. The position of the imaging slit is obtained by detecting light intensity on two parts of the bi-cell detector. In experiments, the feasibility of the sensor was verified. The repeatability was less than 40 nm.

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Position sensor plays an important role in the microfabrication field. Optical methods such as image measurement[1], laser triangulation[2], and direct position detection using position-sensitive detector[3], have an advantage of noncontact measurement and have been applied to position measurements[4−6]. The measurement accuracy of above-mentioned methods is influenced by light intensity fluctuation or disturbance of ambient light on the measured object. In this paper, an optical position sensor based on slit imaging is presented. This sensor is independent of the incident intensity and ambient light on the measured object.

The position sensor is shown in Fig. 1. A laser beam emitted from a laser diode becomes parallel light through a collimating lens. The collimated laser beam illuminates an imaging slit to be positioned in the direction perpendicular to the slit. The imaging slit is located at the front focal plane of lens L_1 which forms a $4f$ system with lens L_2. At the back focal plane of lens L_2, a detection double slit is located. An inverted image of the imaging slit is formed on the detection double slit through the $4f$ system. The detection double slit is imaged on a bi-cell detector through lens L_3. The light intensity through the detection double slit that varies with the position of the imaging slit is detected by the bi-cell detector.

In Fig. 1, the laser diode is used as a light source and is modulated directly with square waves. The purpose of square-wave modulation is to improve signal-to-noise with a simple signal processing circuit. Therefore, the measurement system is independent of the ambient light. On the narrow imaging slit, uniform illumination is obtained using the laser spot larger than the slit width. The $4f$ system is a symmetrical optical system, hence its lateral aberration is eliminated. The modulation transfer function of the $4f$ system approaches the diffraction limit. The detection double slit is illustrated in Fig. 2(a), which is composed of two same rectangular slits whose length is greater than the width of the imaging slit. The detection double slit is formed by staggering the two slits, which are end to end in the groove direction, in the vertical direction of the groove. Lens L_3 has an appropriate magnification and greater numerical aperture than lenses L_1 and L_2 to transmit all rays through the detection double slit. The rays form two detection spots on the bi-cell detector. As shown in Fig. 2(b), the two detection spots are located on two parts of bi-cell detector, respectively. The bi-cell detector is composed of two same photodiodes separated by a channel. The bi-cell detector reduces the disparity error of the signal detection.

In Fig. 1, the intersection of x_1 axis with optical axis of the $4f$ system is defined as origin of x_1 axis. If the width of imaging slit is defined as p in x_1 axis, the light distribution on the imaging slit is expressed as

$$i(x_1) = I_0 \cdot \mathrm{rect}\left(\frac{x_1 - x}{p}\right), \tag{1}$$

where I_0 is the incident intensity on the imaging slit, and x is the distance between the center of the imaging slit and the origin of x_1 axis. In fact, diffraction occurs when the laser beam interacts with the imaging slit and the imaging slit is imaged by the diffracted rays. Because lenses L_1 and L_2 have large numerical aperture, the light distribution of the image of the slit in x_2 axis under the approximate condition can be written as

$$i(x_2) = I_0 \cdot \mathrm{rect}\left(\frac{x_2 - x}{p}\right), \tag{2}$$

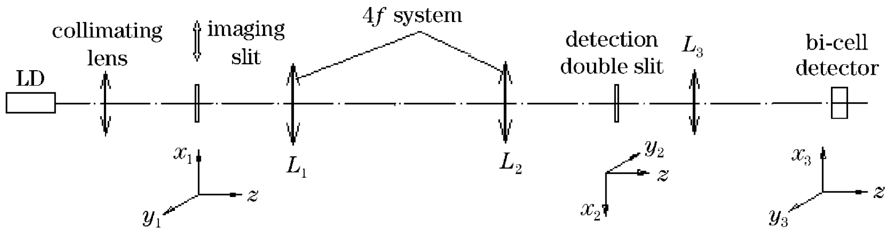

Fig. 1. Schematic diagram of the position sensor.

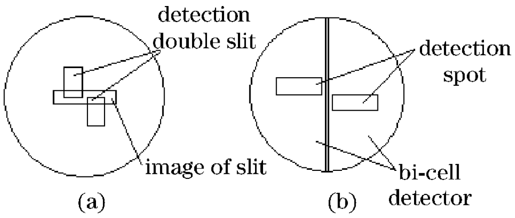

Fig. 2. Detection double slit and image of the imaging slit (a) and bi-cell detector and detection spot (b).

when the distance x satisfies the relation

$$-p < x < p, \tag{3}$$

the light intensities I_1andI_2 on two parts of the detector are expressed as

$$I_1 = \int_0^L i(x_2)\mathrm{d}x_2 = I_0(p/2 + x), \tag{4}$$

and $$I_2 = \int_{-L}^0 i(x_2)\mathrm{d}x_2 = I_0(p/2 - x), \tag{5}$$

respectively, where L is the slit length of the detection double slit. If the incident intensity I_0 were kept constant, x would be calculated just using the Eq. (4) or (5). In fact, the incident intensity on the imaging slit fluctuates due to the instability of the laser diode's output. We calculate the distance x using

$$x = \frac{p}{2} \cdot \frac{I_1 - I_2}{I_1 + I_2}, \tag{6}$$

thus x is insensitive to the light intensity fluctuation on the imaging slit.

In our experimental setup shown in Fig. 1, the wavelength of the laser diode was 650 nm. The imaging slit and the detection double slit were etched on optical flats. The imaging slit was located on a manual linear stage supplying up/down movement. The width and length of the imaging slit were 0.1 and 1 mm, respectively. The slit width and length of the detection double slit were 0.35 and 0.5 mm, respectively. The magnification of lens L_3 was 4×. The light path was adjusted using an internally focusing telescope.

In the experiment, the position of the imaging slit was changed by moving the manual linear stage, thus the height of the imaging slit to be measured using the position sensor was the displacement of the stage. First, the stage was moved down 70 μm from origin of x_1 axis. Then the stage was moved up step by step with 5-μm step within 140-μm range. At all measuring points, the measurement results are illustrated in Fig. 3. Figure 3(a) shows the relation between the measured height and the displacement of the stage. The measured height varies linearly with the displacement, therefore the measurement principle is verified. The measurement error in Fig. 3(a) is generated mostly due to manual adjustment of the stage. Figure 3(b) shows the repeatability at all measuring points, and the repeatability is less than 40 nm.

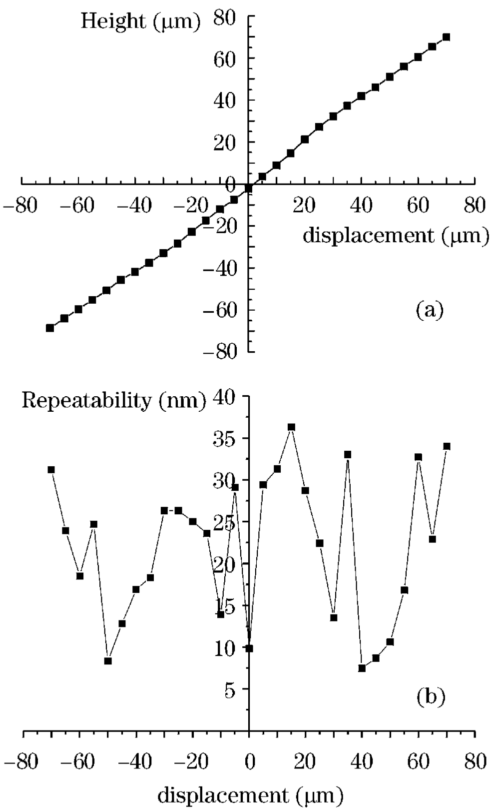

Fig. 3. Measurement results of height (a) and repeatability (b).

In conclusion, we have proposed a position sensor based on slit imaging. This method is independent of incident intensity and ambient light on the measured object. In experiments, the feasibility of the method was verified and high repeatability was obtained.

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References

1. X. D. Liu and Y. Z. Gu, Proc. SPIE **3897,** 214 (1999).
2. R. G. Dorsch, G. Hausler, and J. M. Herrmann, Appl. Opt. **33,** 1306 (1994).
3. X. F. Zhang, B. G. Wang, and C. Z. Jiang, Opt. Technique (in Chinese) **27,** 362 (2001).
4. Z. H. Huang, H. Y. Cai, H. Q. Li, and Y. M. Zhang, Opto-Electron. Eng. (in Chinese) **29,** 58 (2002).
5. H. X. Yuan, A. Z. He, Z. H. Li, and Z. X. Wang, Acta Opt. Sin. (in Chinese) **20,** 118 (2000).
6. A. M. Lu, H. X. Yuan, and A. Z. He, Acta Opt. Sin. (in Chinese) **18,** 762 (1998).