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A novel method to improve detecting sensitivity of quadrant detector

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ABSTRACT

This paper presents a set of formulae for estimating the light spot position projected on a quadrant detector (QD). A novel method of annular segmentation calculus (ASC) is designed to analyze the detecting light spot of QD. The influences of the spot movement mode, spot energy distribution, and dead area to the dynamic range and the detection sensitivity are analyzed. It is shown in simulations that our new formulae have achieved a much better results to increase measurement accuracy. It is also shown that on the condition of the same spot size, the detection sensitivity of Gaussian distribution is prior to uniform distribution. The detection sensitivity of diagonal mode is better than cross mode. The detection sensitivity increases with increase in the size ratio of dead area to spot. The simulating and experimental results show that the measuring range of QD is 400 μm, and the resolution is 50 μm. The study presented here will be beneficial in developing the nanomechanical displacement detection techniques.

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1. Introduction

The quadrant detector (QD) is a position detector based on the photovoltaic effect to determine the relative position of the light spot projected on its surface [1]. It is made of four identical p–n junction photodiodes and the photodiodes are separated by small gaps called the dead area [2]. Compared to other position sensitive detectors such as the lateral effect PSD [3] and the charged coupled device [4], QD has the advantage of fast response frequency, wide response wavelength, high response sensitivity and wide operating temperature range [5]. Due to these advantages, QD has been widely used to measure the beam displacement [6]. Recently, the QD is becoming more and more important in the area of nanotechnology [7,8]. However, when QD is used for high-precision measurements, some factors will influence QD measurement accuracy, dynamic range and sensitivity. The nonlinear relationship between the light spot position and its estimate is reported in some literatures [9,10]. The spot movement mode, spot energy distribution, and dead area will influence the dynamic range and the detection sensitivity. Thus, these factors analysis is highly desirable to improve the measurement accuracy of QD and enhance QD applications.

The objective of the paper is to analyze the influences of the spot movement mode, spot energy distribution, and dead area to the dynamic range and the detection sensitivity to improve the measurement accuracy of QD. The remainder of this paper is organized as follows: in Section 2, the novel method of annular segmentation calculus (ASC) is presented to analyze and compare the different light spot. The spot movement mode and spot energy distribution are analyzed and simulated. The influence of the dead area is described. Experiments and discussions are done in Section 3 and conclusions are drawn in Section 4. The study presented here will be beneficial in developing the nanomechanical displacement detection techniques.

2. Theoretical model

2.1. Theoretical model

QD consists of four junctions placed symmetrically with respect to the center shown in Fig. 1. The photocurrents will be generated when a light beam is projected. The conventional formulas to estimate the beam position are expressed as follows [11]:

$$X = k\frac{I_A + I_D - I_B - I_C}{I_A + I_B + I_C + I_D}, \quad Y = k\frac{I_A + I_B - I_C - I_D}{I_A + I_B + I_C + I_D} \tag{1}$$

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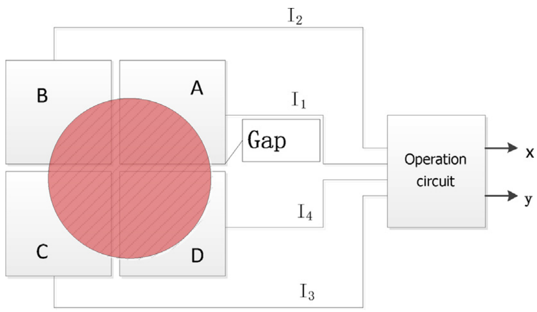

Fig. 1. Schematic diagram of the quadrant detector.

where X and Y are the estimate of the beam position in the x and y directions, k is the slope constant whose value is dependent on the beam profile, and I_A, I_B, I_C, and I_D are the photocurrents measured at each quadrant. For a single wavelength laser beam, the strength of the photocurrent is proportional to the light beam intensity on the quadrant which could be expressed by the following [12]:

$$I_i = \frac{\eta q}{h\upsilon}\iint_{S_i} D(x_0, y_0)dx_0 y_0, \quad (i = A, B, C, D) \tag{2}$$

where S_i denotes to the area of each quadrant, $D(x_0, y_0)$ is the power density of the beam at the location (x_0, y_0), η is the quantum efficiency, q is the electronic charge, h is the Planck constant, and ν is the light frequency.

In most applications where a single mode laser is employed as the light source, the beam density profile is Gaussian distributed and it is often regarded as the uniform intensity profile. However, for different beam intensity profiles, the sensitivity of the position estimates will be different.

Annular segmentation calculus is often used to calculate the dimension of annulus. We assume that the optical spot detected by QD consists of some annulus shown in Fig. 2. When the spot center deviates Δx away from the center of QD, the differentiated dimension from each pair of the four segments due to the displacement along the x-axis can be expressed as Eq (3):

$$S_x = \int_0^X 2\pi r dr + \int_X^R 4r \arcsin\left(\frac{X}{r}\right) dr \tag{3}$$

where r denotes the radius of annulus, dr is the width of annulus, and R is the radius of the spot.

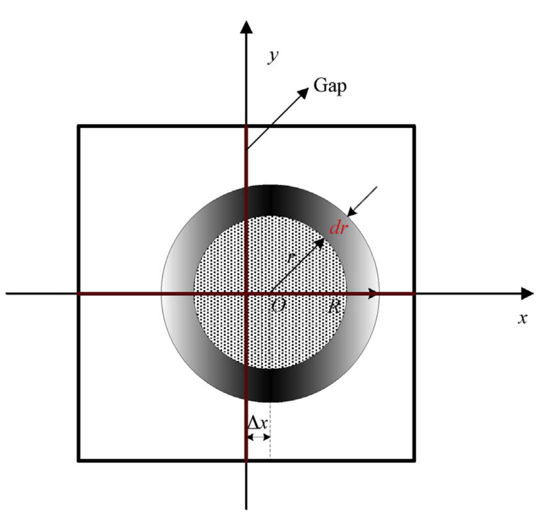

Fig. 2. Annular segmentation calculus theory schematic diagram

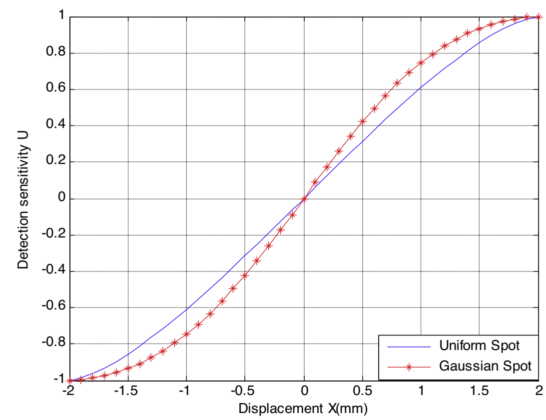

Fig. 3. Normalized differentiated output signal with the optical spot moves across QD.

The output signal power ($E_{\Delta X1}$) will be:

$$E_{\Delta X1} = \int_0^X 2\pi E_0 r dr + \int_X^R 4E_0 r \arcsin\left(\frac{X}{r}\right) dr \tag{4}$$

The detection sensitivity can be expressed as Eq (5):

$$U_1 = \frac{E_{\Delta X1}}{E_1} = \frac{\int_0^X 2\pi r dr + \int_X^R 4r \ \arcsin\left(\frac{X}{r}\right) dr}{\pi R^2} \tag{5}$$

When the beam density profile is Gaussian distributed:

$$I = I_0 \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(r-\mu)^2}{2\sigma^2}} \tag{6}$$

where r is the radial distance from the center of spot, σ and μ are constants that related to the laser.

The total incident power will be changed to:

$$E_{\Delta X2} = \frac{1}{\sqrt{2\pi}\sigma} I_0 \left[\int_0^X 2\pi r e^{\frac{-(r-\mu)^2}{2\sigma^2}} dr + \int_X^R 4r \ \arcsin\left(\frac{X}{r}\right) e^{\frac{-(r-\mu)^2}{2\sigma^2}} dr\right] \tag{7}$$

The detection sensitivity will be changed to:

$$U_2 = \frac{\int_0^X 2\pi r e^{\frac{-(r-\mu)^2}{2\sigma^2}} dr + \int_X^R 4r \arcsin\left(\frac{X}{r}\right) e^{\frac{-(r-\mu)^2}{2\sigma^2}} dr}{\int_0^R 2\pi r e^{\frac{-(r-\mu)^2}{2\sigma^2}} dr} \tag{8}$$

Fig. 3 shows the simulation results of uniform spot and Gaussian spot with MATLAB software (MATLAB R2011b). The radius of the spot (R) is 2 mm. The measuring linear range of the uniform spot is wider and measuring sensitivity of the Gaussian spot is higher.

2.2. Cross mode and diagonal mode

Traditional light spot movement mode is move along with the gap of QD called Cross mode. The other moving mode of light spot to QD is diagonal mode shown in Fig. 4.

The spot center deviates Δx away from the center of QD along the x-axis can be obtained from Eq (9):

$$\Delta x' = k_{x'} \frac{S_D - S_B}{S_D + S_B} = k_{x'} \frac{I_D - S_B}{S_D + S_B} \tag{9}$$

where $k_{x'}$ is a constant factor, they are related to the QD parameters.

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