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Resolution limit of the quadrant photodetector

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ABSTRACT

A theoretical analysis of the resolution limit of the light spot position measurement with the quadrant photodetectors has been presented in this paper. In order to reduce the interquadrant crosstalk each quadrant is separated from the adjacent quadrants with a narrow light-insensitive gap. However, it was found that these gaps limit the measurement resolution. Nevertheless, the estimated resolution is still just an order of magnitude lower than the resolution in position measurement with the standard quantum limited interferometer based on the He-Ne laser.

1. Introduction

Resolution in deep subnanometer realm, relatively simple signal processing circuitry, high speed measurements in a broad temperature range make the quadrant photodetector (QPD) one of the best choices for the position measurement in the nano world. Therefore, QPDs have been extensively used in the atomic force microscopes for microcantilever position sensing [1]. When the QPD is illuminated with a laser source a Gaussian irradiance distribution develops on the QPD surface. A simplified theoretical analysis in combination with an experimental verification of such a composed position measuring system is presented in Ref. [2]. The analysis shows that the smaller the light spot the higher the QPD sensitivity in light spot position measurement as well as the higher measurement resolution. However, the small gaps between the quadrants (photodetectors) significantly influence the measurement for a very small light spots. The gap typically represents the dead area of the QPD that has zero responsivity. The influence of these gaps on the light spot position measurement resolution with the help of the QPD will be investigated in this paper.

2. Theoretical analysis

In order to minimize the crosstalk between QPD elements and thus to reduce the measurement error, there is a narrow gap between each element as it is depicted in Fig. 1. However, although very narrow these gaps influence the QPD sensor sensitivity. The QPD sensor sensitivity will be found under the assumption of Gaussian irradiance distribution on the QPD surface. Therefore for the irradiance distribution $I(x,y)$, we have:

$$I(x,y) = \frac{P}{\pi\rho^2}\exp\left[-\frac{(x-\xi)^2+(y-\psi)^2}{\rho^2}\right], \tag{1}$$

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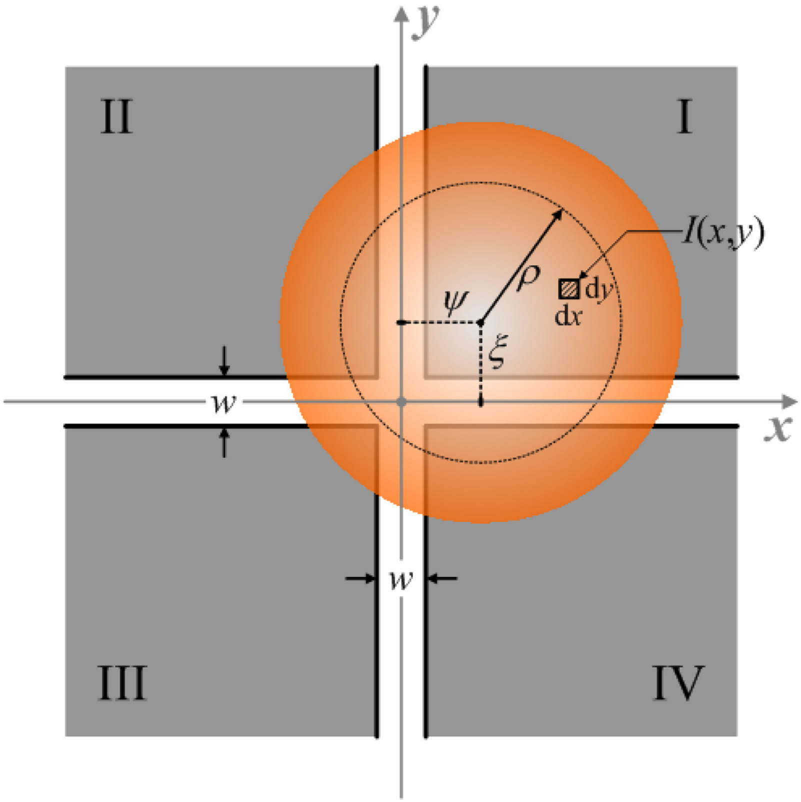

Fig. 1. Light spot geometry on the QPD surface.

where x and y are the coordinates in the coordinate system of the QPD, ξ and ψ are the coordinates of the light spot center, P is the optical power of the light source that arrive at the QPD surface, and ρ is the radius of the light spot for which the irradiance falls down to the $1/e$ value of its maximal value. According to Eq. (1) the corresponding optical powers P_K (K = I, II, III, and IV) that have been captured by the corresponding quadrants are given by:

$$\begin{gathered} P_{\mathrm{I}}\left(\xi,\psi\right)=\frac{P}{4}\mathrm{erfc}\left(\frac{\frac{w}{2}-\xi}{\rho}\right)\mathrm{erfc}\left(\frac{\frac{w}{2}-\psi}{\rho}\right),P_{\mathrm{II}}\left(\xi,\psi\right)=P_{\mathrm{I}}\left(-\xi,\psi\right), \\ P_{\mathrm{III}}\left(\xi,\psi\right)=P_{\mathrm{I}}\left(-\xi,-\psi\right),P_{\mathrm{IV}}\left(\xi,\psi\right)=P_{\mathrm{I}}\left(\xi,-\psi\right) \end{gathered} \tag{2}$$

where w is the interquadrant gap width. Due to the QPD geometry only indirect measurements of the light spot position with respect to the QPD center are possible. By simple processing of the QPD signals that are further proportional to the corresponding optical powers, it is only possible to determine the ratios of the light spot positions and the QPD's relevant geometrical parameters. The accurate measurements of these ratios are not possible but only their estimations can be made by using the following equations [3]:

$$\begin{aligned} \hat{\xi}_{\mathrm{R}}\left(\xi,\psi\right)&=\frac{P_{\mathrm{I}}\left(\xi,\psi\right)+P_{\mathrm{IV}}\left(\xi,\psi\right)-P_{\mathrm{II}}\left(\xi,\psi\right)-P_{\mathrm{III}}\left(\xi,\psi\right)}{P_{\mathrm{I}}\left(\xi,\psi\right)+P_{\mathrm{II}}\left(\xi,\psi\right)+P_{\mathrm{III}}\left(\xi,\psi\right)+P_{\mathrm{IV}}\left(\xi,\psi\right)} \\ \hat{\psi}_{\mathrm{R}}\left(\xi,\psi\right)&=\frac{P_{\mathrm{I}}\left(\xi,\psi\right)+P_{\mathrm{II}}\left(\xi,\psi\right)-P_{\mathrm{III}}\left(\xi,\psi\right)-P_{\mathrm{IV}}\left(\xi,\psi\right)}{P_{\mathrm{I}}\left(\xi,\psi\right)+P_{\mathrm{II}}\left(\xi,\psi\right)+P_{\mathrm{III}}\left(\xi,\psi\right)+P_{\mathrm{IV}}\left(\xi,\psi\right)} \end{aligned} \tag{3}$$

where $\hat{\xi}_{\mathrm{R}}\left(\xi,\psi\right)$ and $\hat{\psi}_{\mathrm{R}}\left(\xi,\psi\right)$ are the estimated values of the ratios along the x and y axes, respectively. Due to the QPD symmetry we will treat only one axis. Therefore, for the QPD sensitivity $S(w,\rho)$ we have:

$$S\left(w,\rho\right)=\frac{\partial\hat{\xi}_{\mathrm{R}}\left(\xi,\psi\right)}{\partial\xi}\bigg|_{\xi,\psi=0}=\frac{4}{\sqrt{\pi}w}\frac{\left(\frac{w}{2\rho}\right)\exp\left[-\left(\frac{w}{2\rho}\right)^{2}\right]}{\mathrm{erfc}\left(\frac{w}{2\rho}\right)}. \tag{4}$$