Position-sensitive device

Bodo Kaiser

Ludwig-Maximilians-Universität München

bodo.kaiser@physik.uni-muenchen.de

March 3, 2019

Contents

1 Introduction

The performance of high-precision optical setups is determined by the magnitude of the variations of some critical parameters. One of these critical parameters is the beam alignment. The initial beam alignment is crucial in order to reduce optical aberrations by i.e. diffraction. Once performed temperature fluctuations, mechanical strain or human interaction can alter the beam alignment or render the initial beam alignment obsolete.

Given these circumstances it is therefore an obvious step to integrate a control loop into the optical setup that corrects for errors in the beam alignment. The control loop comprises a position-sensitive device to gather the current state of the beam alignment as well as a mechanical mirror to compensate for errors.

In the present document we want to summarise the design process of such a position-sensitive device.

1.1 Requirements

Parameter	Symbol	Values			Unit
		Min	Typical	Max	
Spatial resolution	Δx	0.7			µm
Photocurrent	I_{ph}	1	10	100	µA

Table 1: Technical requirements of the position-sensitive device.

1. Dual power supply $V_{\pm} = \pm 15\,\mathrm{V}$
2. Ethernet network interface
3. Analogue interface

1.2 Overview

Components of the device.

2 Position-sensitive detector

The position-sensitive detector (PSD) constitutes the heart of the position-sensitive device. Its characteristics give the upper bound of the performance of our device. In the following section we will give an overview of the available methods for optical position measurement in order to motivate the selection of a tetra-lateral PSD photodiode. The arguments given are an excerpt of Ref. [1]. To the end of this section we describe how the PSD can be integrated into the framework of electrical circuit analysis.

2.1 Optical position sensors

Position measurement can be encoded by frequency, amplitude, pulse and spatial modulation of an optical signal. However, only spatial modulation of an optical signal encodes the position information of the plane transverse to the signal. We can distinguish between three types of two-dimensional position sensors:

1. Image detectors
2. Quadrant detectors
3. Position-sensitive detectors

Image detectors typically consists of an array of a photo-sensitive detectors, therefore they are able to image precise spatial distribution of a signal. However, because of their discrete nature they only have a low resolution with respect to the center-of-mass of the signal. Quadrant detectors consist of four photodiodes in close proximity. From the photocurrent of every respective photodiode one can calculate the center-of-mass of the signal. With the quadrant detectors there is always a loss of signal in the spacing region between the photodiodes. In comparison to the quadrant detectors the PSD consists of a single (lateral) photodiode. Therefore we expect the PSD to provide the highest resolution with respect to the center-of-mass of the incident signal.

2.2 Operating principle

The operating principle of the PSD can be though as follows: Photons of the optical signal excite electrons to the surface of the PSD. These electrons will divide across the four PSD anodes according to the resistance. For an ideal PSD the surface resistance is homogeneous such that the effective resistance from the center-of-mass of the optical signal to the respective PSD anodes is determined by the respective linear distance. More precise the anode currents in one dimension I_1, I_2 are given by,

$$I_1 = \left(\frac{1}{2} - \frac{x}{L}\right)(I_1 + I_2), \qquad I_2 = \left(\frac{1}{2} + \frac{x}{L}\right)(I_1 + I_2), \tag{1}$$

wherein x is the distance of the center-of-mass of the signal from the center of the PSD. We can use Equation (1) to find the position x,

$$x = \frac{L}{2}\frac{I_2 - I_1}{I_1 + I_2}. \tag{2}$$

Analogue one obtains the positions in the two dimensional case from,

$$x = \frac{L}{2}\frac{(I_{X2} + I_{Y1}) - (I_{X1} + I_{Y2})}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}}, \tag{3}$$

$$y = \frac{L}{2}\frac{(I_{X2} + I_{Y2}) - (I_{X1} + I_{Y1})}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}}. \tag{4}$$

Fundamental to the derivation was the assumption that the surface resistance is homogeneous over the PSD. In case of the older tetra-lateral PSD design this assumption is not really justified and the surface resistance shows a linear distortion. Fortunately the modern design improved tetra-lateral (pin-cushion) PSD chooses an arrangement of the anodes to compensate for these non-linearities.

2.3 Detector selection

Given the previous information the obvious choice for our use case is a tetra-lateral PSD of the improved (pin-cushion) type. At the time of writing there are two major manufactures of such PSD — First Sensor and Hamamatsu. Having said that only Hamamatsu sells its PSD in small quantities. In Table 2 we present the PSD portfolio of Hamamatsu.

Item designation	S1880	S2044	S5990	S5991	Unit
Photosensitive area	12.0×12.0	4.7×4.7	4.0×4.0	9.0×9.0	mm^2

Table 2: PSD portfolio of Hamamatsu.

The S1880 and S2044 use a multi-zone design whereas the S5990 and S5991 use the preferable improved tetra-lateral (pin-cushion) design. The S5990 and S5991 share the same design but differ in size and specifications. The increase in size of the S5991 compared to the S5990 yields some more undesired electrical properties. In general we can use an additional lens in front of the PSD in order to project arbitrary optical signals onto the PSD surface, therefore the benefits of a better electronic characteristic outweigh the smaller photosensitive area and we select the S5990 as our preferred PSD.

2.4 Equivalent circuit

Figure 1 shows the abstract schematic symbol for a two-dimensional PSD with the four anode terminals on the right hand side and a common cathode terminal on the left hand side. We can apply a reverse bias voltage to the common cathode terminal in order to reduce the response time of the PSD. According to Ref. [1, 2] highest spatial resolution is achieved with no reverse bias — the common cathode terminal connected to ground — as the reverse bias voltage increases the dark current of the PSD.

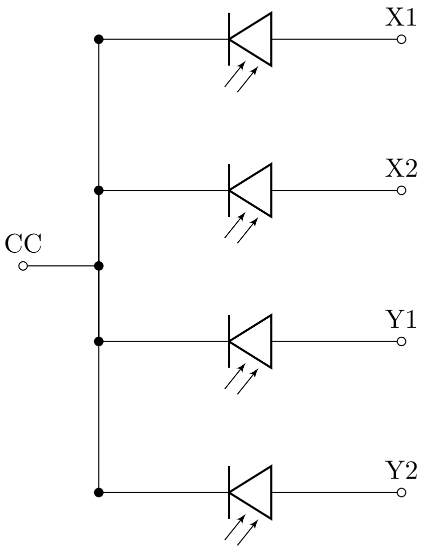

Figure 1: Equivalent circuit of one of the PSD output terminals according to [2].

That said, the representation of Figure 1 is not very useful for practical calculations. Instead we will model the output terminals of the PSD as a two current sources with internal resistance R_i and capacitance C_t [2]. Such an equivalent circuit is presented in Figure 2. The first current source represents the photo current I_p which is created from photons that excite electrons. The second current source represents the dark current I_d which is created from thermal excitation of electrons.

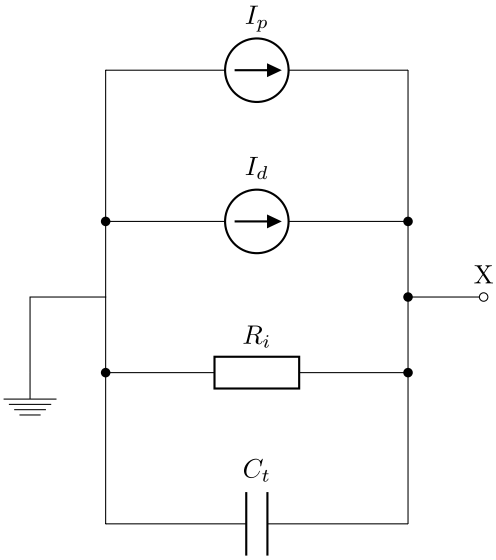

Figure 2: Equivalent circuit of one of the PSD output terminals according to [2].

The parameters for the equivalent circuit of the S5990 are summarized in Table 3. If not stated otherwise we will use the maximum values from the datasheet.

Parameter	Symbol	Values		Unit
		Typical	Maximum	
Dark current	I_d	0.5	10	nA
Interelectrode resistance	R_e	7	15	kΩ
Terminal capacitance	C_t	150	300	pF

Table 3: Important parameters of the S5990 extracted from the datasheet [2].

3 Analogue signal processing

3.1 Preamplifier

Glossary

PSD position-sensitive detector. 3–6

S5990 Hamamatsu two-dimensional PSD. 4, 6

References

[1] Date Noorlag. "Lateral-photoeffect position-sensitive detectors". PhD thesis. Delft University of Technology, 1974.

[2] *PSD*. Hamamatsu.