# Position-sensitive device

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# 1 Introduction

# 2 Requirements

## 2.1 Precision and accuracy

## 2.2 Technical specifications

| Parameter | Symbol | Values | | | Unit |
|---|---|---|---|---|---|
| | | Min | Typical | Max | |
| Spatial resolution | $\Delta x$ | 0.7 | | | µm |
| Photocurrent | $I_{\mathrm{ph}}$ | 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

# 3 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.

## 3.1 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.

## 3.2 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.

### 3.3 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 | $12.0 \times 12.0$ | $4.7 \times 4.7$ | $4.0 \times 4.0$ | $9.0 \times 9.0$ | $mm^2$ |

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.

### 3.4 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.

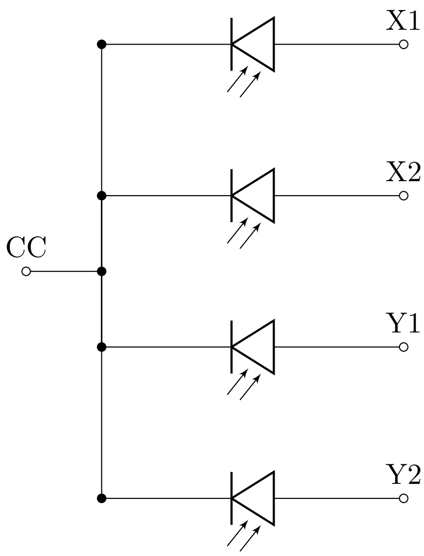



Figure 1: Equivalent circuit of one of the PSD output terminals according to [2].

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.

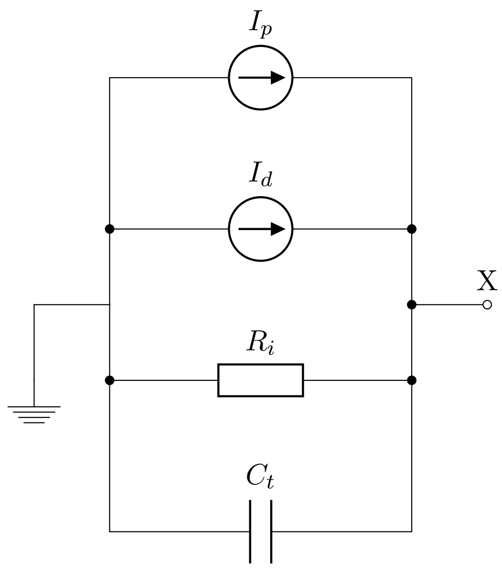



Figure 2: Equivalent circuit of one of the PSD output terminals according to [2].

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 [3].

# 4 Transimpedance amplifier

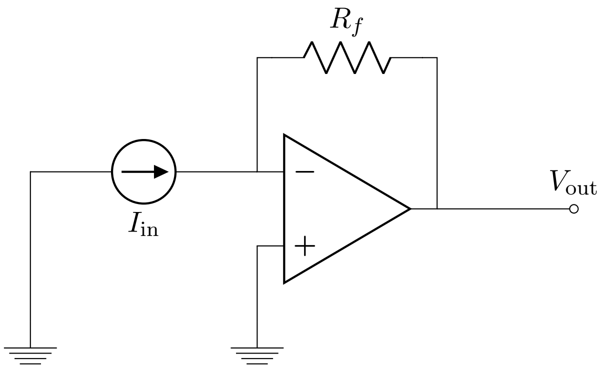
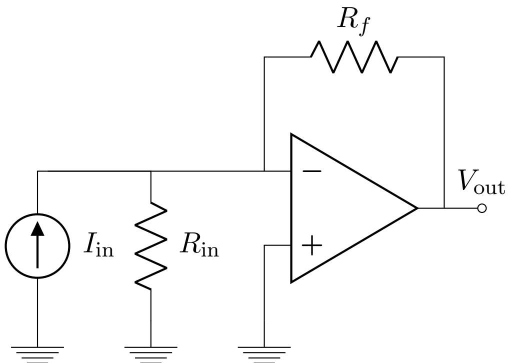
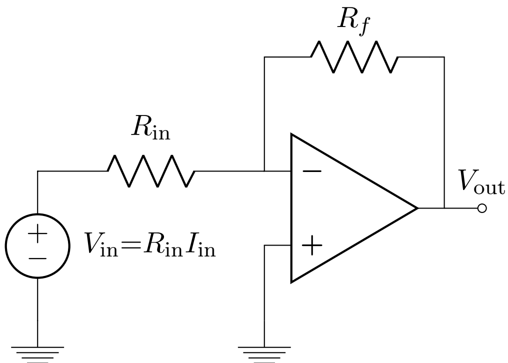



Figure 3: Simple transimpedance amplifier circuit.

$$V_{\text{out}} = R_f I_{\text{in}} \tag{5}$$




(a) Transimpedance amplifier.




(b) Inverting amplifier.

Figure 4: Equivalence between transimpedance and inverting amplifier using source transformation.

## 4.1 Offset

### 4.1.1 Input offset voltage

[4, p. 54]

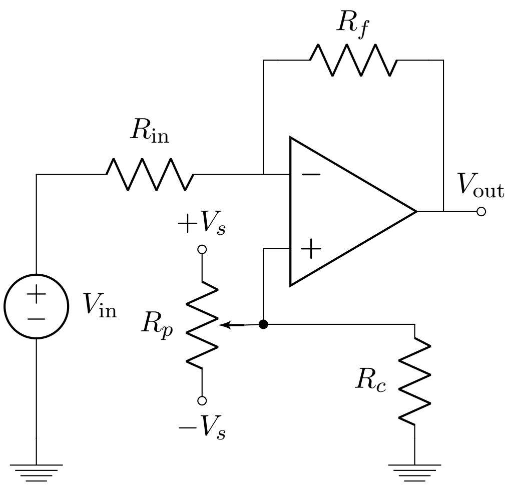
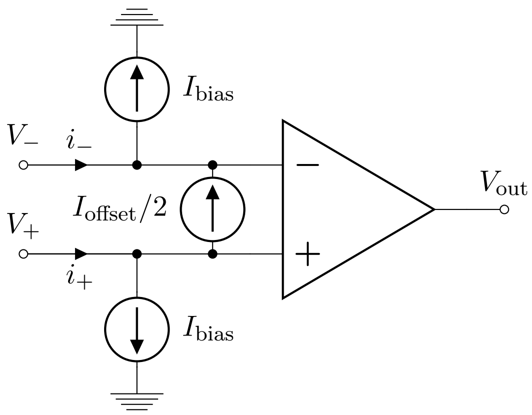
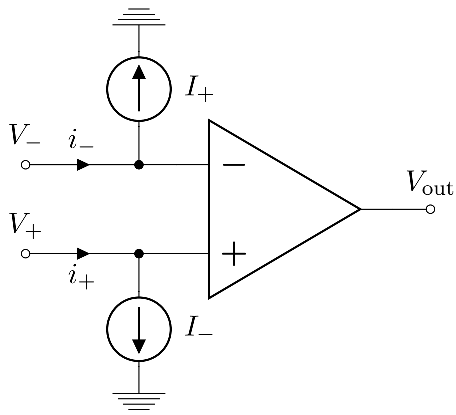



Figure 5: Input current offset compensation.

### 4.1.2 Input current




(a) Equivalent current sources as reported in the datasheet.




(b) Alternative equivalent current sources.

Figure 6: Non-zero input current from the operational amplifier.

$$I_+ = I_{\text{bias}} + \frac{1}{2} I_{\text{offset}} \qquad I_{\text{offset}} = I_+ - I_- \tag{6}$$

$$I_- = I_{\text{bias}} - \frac{1}{2} I_{\text{offset}} \qquad I_{\text{bias}} = \frac{I_+ + I_-}{2} \tag{7}$$

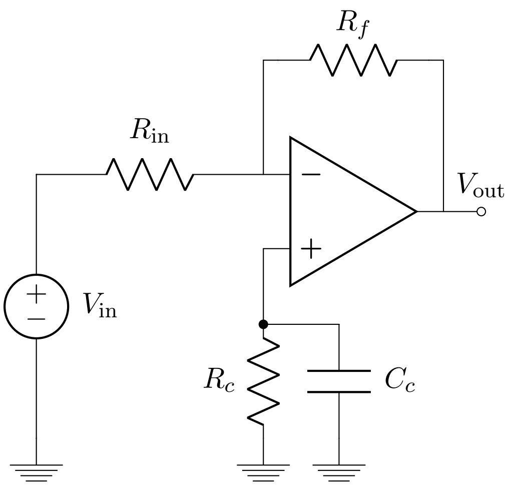


Figure 7: Input current offset compensation.

[4, p. 57] [5, p. 25]

$$R_c = \frac{R_{\text{in}} R_f}{R_{\text{in}} + R_f} \tag{8}$$

## 4.2 Bandwidth

# 5 Power management

## 5.1 Input voltage

### 5.1.1 Reverse polarity protection

### 5.1.2 Capacitance multiplier

## 5.2 Internal power supply

### 5.2.1 Dual supply voltage regulator

### 5.2.2 High-precision voltage reference

# 6 Printed circuit board

## 6.1 Layout and stackup

## Glossary

**PSD** position-sensitive detector. 4–7

**S5990** Hamamatsu two-dimensional PSD. 5, 7

## References


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

[2] *PSD*. Hamamatsu. URL: `https://www.hamamatsu.com/resources/pdf/ssd/psd_techinfo_e.pdf` (visited on 03/03/2019).

[3] *S5990 2D PSD*. Hamamatsu. URL: `https://www.hamamatsu.com/resources/pdf/ssd/s5990-01_etc_kpsd1010e.pdf` (visited on 03/03/2019).

[4] Walt Jung. *Op Amp Applications Handbook*. Elsevier, 2005. ISBN: 9780750678445.

[5] Jerald Graeme. *Photodiode Amplifiers. Op Amp Solutions*. McGraw Hill Professional, 1996. ISBN: 9780070242470.