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Using a Digital Potentiometer to Optimize a Precision Single-Supply Photo Detection Circuit

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INTRODUCTION

Photodiodes bridge the gap between light and electronics. Many times, precision applications (such as CT scanners, blood analyzers, smoke detectors, position sensors, IR pyrometers and chromatographs) utilize the basic transimpedance amplifier circuit that transforms light energy into a usable electrical voltage. In these circuits, photodiodes are used to capture the light energy and transform it into a small current. This current is proportional to the level of illumination from the light source. A preamplifier then converts the current (in amperes) from the photodiode sensor into a usable voltage level.

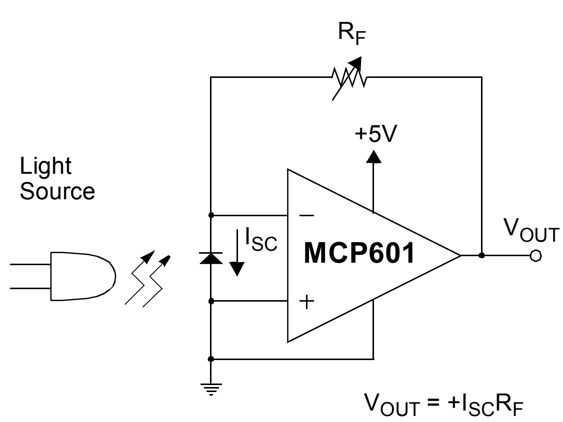


FIGURE 1: *In this precision photosensing configuration, a photodiode (in the Photovoltaic mode) is used to capture the luminance energy from a light source. The effects of the variability, due to alignment problems, is reduced by using a potentiometer for the resistive element in the feedback loop of the amplifier.*

This application note will show how the adjustability of the digital potentiometer can be used as an advantage in photosensing circuits. Initially, photodiode characteristics will be looked at, followed by various digital potentiometer circuits that use photodiodes in the Photoconductive and Photovoltaic modes.

Photodiode Characteristics

A photodiode can be operated in the Photovoltaic or Photoconductive mode, as shown in Figure 2.

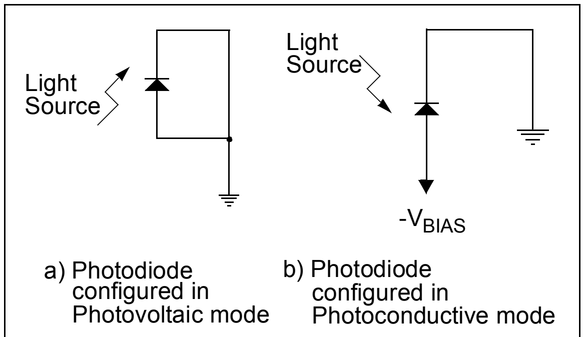


FIGURE 2: *The two modes that photodiodes can be used in are: (a) Photovoltaic and (b) Photoconductive. In the Photovoltaic mode, the photodiode is biased with zero volts which optimizes the sensor's accuracy. In the Photoconductive mode, the diode is reverse biased in order to optimize the responses to step functions.*

A photodiode configured in the Photovoltaic mode is zero biased. In this mode, the light-to-current response of the diode is maximized for light sensitivity and linearity, making it well suited for precision applications. A photodiode configured in the Photoconductive mode has a reverse voltage bias applied. In this mode, the photodiode is optimized for fast response to light sources. An ideal application for a diode configured in the Photoconductive mode is digital communication.

The key elements that influence the circuit performance of each mode are the photodiode capacitance (C_{PD}) and the photodiode leakage current (I_L), as shown in Figure 3. These parasitic elements can effect the precision and speed of photo detection circuits.

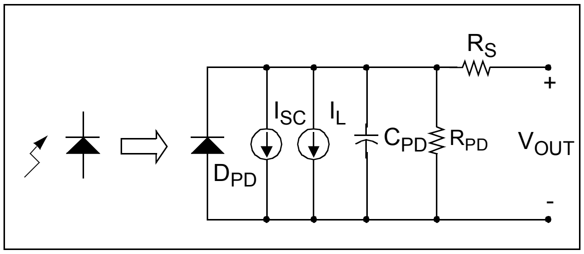


FIGURE 3: *The photodiode can be described with an ideal current source (I_{SC}) that is a result of radiant flux energy from light, an ideal diode (D_{PD}), a junction capacitance (C_{PD}), leakage current (I_L), a parasitic series resistor (R_S) and a shunt resistor (R_{PD}).*

The junction capacitance (C_{PD}) is determined by the width of the depletion region between the p-type and n-type material of the photodiode. The depletion region width of the photodiode is inversely proportional to the diode's reverse bias voltage. Wider depletion regions will increase the magnitude of the junction capacitance. Conversely, wider depletion regions (found with PIN photodiodes) have broader spectral responses.

Values of the junction capacitance of silicon photodiodes in the Photovoltaic mode (zero bias) range from approximately 20 pF to 25 pF, up to several thousand pico farads. Values of the junction capacitance of silicon photodiodes in the Photoconductive mode (with a reverse bias of -10V) are generally ten times lower. This reduced parasitic capacitance facilitates high-speed operation. However, the linearity and offset errors are not optimized.

A reverse bias voltage across the photodiode will cause an increase in leakage current, I_L. When the reverse bias voltage exceeds several millivolts, linearity starts to be compromised in precision circuits. With large voltages, this leakage current can be high enough to make the diode only useful in digital applications.

The shunt resistance (R_{PD}), also called "dark" resistance, is measured with zero volts across the element. At room temperature, the magnitude of this resistance typically exceeds 100 MΩ. In most circuits, this resistance is generally ignored.

The second parasitic diode resistance (R_S) is known as the series resistance of the diode. This parasitic resistance typically ranges from 10 to 1,000Ω. Due to the small size of this resistor, it only has an affect on the frequency response of the circuit well past the bandwidth of operation.

When light illuminates on the photodiode, current (I_{SC}) flows from the anode to the cathode of the device. The transfer function of light-to-photodiode current is equal to the following:

EQUATION

$$I_{SC} = \textit{Radiant Flux Energy/Flux Responsivity}$$

where:

I_{SC} = the current produced by the photodiode with units in amperes/cm^2.

Radiant Flux Energy = the light energy with units in watts/cm^2.

Flux Responsivity = the measure of the photodiode's sensitivity with units in watts/amperes.

Photovoltaic Mode Circuits

A practical way to design a precision photosensing circuit is to place a photodiode in a Photovoltaic mode. This can be done by placing the device across the inputs of a CMOS input amplifier and a resistor in the feedback loop. The single-supply circuit implementation of this circuit is shown in Figure 4.

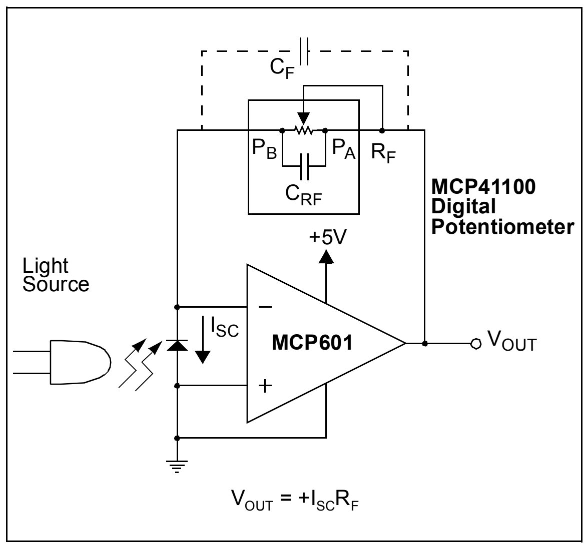


FIGURE 4: *This is a standard, single-supply, transimpedance amplifier circuit with the photodiode in the Photovoltaic (zero bias) mode.*

In this circuit, the light source illuminates the photodiode, causing diode current to flow from cathode to anode. Since the input impedance of the inverting input of the MCP601 CMOS amplifier is extremely high, the current generated by the photodiode flows through the feedback resistor (R_F). In this configuration, the feedback resistor is implemented with a digital potentiometer (MCP41100).

The current-to-voltage transfer function of this circuit is:

EQUATION

$$V_{OUT} = I_{SC} \times R_F$$

with a single pole at $1/(2pR_F(C_{RF} + C_F))$

where:

V_{OUT} = the voltage at the output of the operational amplifier in volts.

I_{SC} = the current produced by the photodiode with units in amperes.

R_F = a digital potentiometer that is serving as the feedback resistor with units in ohms.

C_{RF} = the parasitic capacitance of the digital potentiometer with units in farads. This parasitic capacitor can cause oscillation with some digital potentiometer settings. If this occurs, place a 100 pF to 500 pF in parallel (C_F) with the digital potentiometer, as shown in Figure 4.

The programmed value of the digital potentiometer (R_F) is equal to:

EQUATION

$$R_F = \frac{D_{CODE} \times R_{NOMINAL}}{2^n}$$

where:

D_{CODE} = the programmed code to the digital potentiometer.

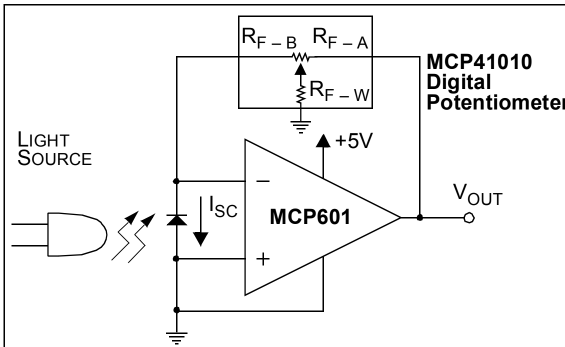
$R_{NOMINAL}$ = the nominal resistance of the digital pot from P_A to P_B.

n = the number of bits that the digital potentiometer has. In the case of Microchip digital potentiometers, the 'n' is equal to eight.

If the digital potentiometer is programmed to equal 50 kΩ (D_{CODE} = 128), the maximum current from the photodiode is 75 µA and the maximum output voltage (V_{OUT}) is 3.75V. With this configuration, the digital potentiometer capacitance (C_{RF}) is 75 pF. As a result, the frequency response of the circuit is equal to $1/2\pi R_F C_{RF}$ or 42.4 kHz.

Circuit flexibility is added with the inclusion of a digital potentiometer, as opposed to a standard resistor. By changing the value of the digital potentiometer, the maximum output voltage (V_{OUT}) can be adjusted. This kind of flexibility accommodates alignment problems between the light source and the photodiode.

Another circuit configuration that can be used for Photovoltaic mode circuits is shown in Figure 5.



$V_{OUT} = + I_{SC}\ (1+R_{F-A}/R_W)R_{F-B}$

$R_{F-B} >> R_{F-A}$

FIGURE 5: *In this precision light-sensing circuit, the potentiometer is to implement a T-network style feedback loop. This configuration provides higher gains while using a lower value potentiometer.*

In this circuit, the digital potentiometer is configured to form a T-network. The digital potentiometer is a good fit in this circuit because of its low wiper resistance and resistor adjustability. The potentiometer's A and B resistive elements are used in this circuit so that the gain versus the potentiometer digital code is linear.

The transfer function of this circuit is:

EQUATION

$$\frac{V_{OUT}}{I_{SC}} = R_{F-A} + \left(\frac{1 + R_{F-A}}{R_W}\right) R_{F-B}$$

where:

R_{F-A} = the A portion of the digital potentiometer resistor.

R_{F-B} = the A portion of the digital potentiometer resistor.

R_W = the parasitic resistance through the wiper.

This formula can be further worked by using the following substitutions:

EQUATION

$$R_{F-A} = R_{F-NOM} - R_{F-B}$$

$$R_{F-B} = \frac{R_{F-NOM} D_n}{2^n}$$

where:

R_{F-NOM} = the nominal resistance across the digital potentiometer. In Figure 5, this value is equal to 10 kΩ.

D_n = the programmed digital code of the potentiometer.

n = the number of bits of the digital potentiometer. In Figure 5, this value is equal to eight.

Given all of the above calculations, the graph in Figure 6 shows the gain of this T-network circuit for the entire digital code range of the MCP41010. The resistive values used in this graph are:

R_{F-NOM} = 10 kΩ (data sheet typical)

R_W = 25Ω (data sheet typical)

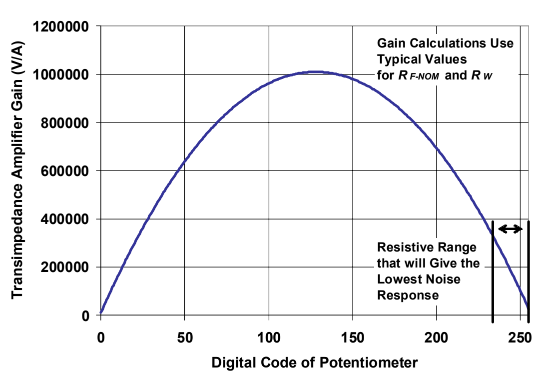


FIGURE 6: *This graph shows the gain versus digital code of the circuit shown in Figure 7.*

The primary sources of error that effect the performance of this circuit are amplifier offset voltage, amplifier noise and digital potentiometer noise.

The actual offset voltage of the amplifier will produce a gain error in the lower codes. For instance, an offset voltage of 0.35 mV will produce a 4.2% error when the digital potentiometer is set to code 50. When the offset of the amplifier is 0.1 mV, the gain error of the circuit is 1% with the same digital potentiometer code.

In cases where this circuit is used for precision sensing, the noise response of the circuit should be kept as low as possible. The two factors that effect the overall noise originate from the amplifier and the resistive network. In order to achieve the lowest possible noise in this circuit $R_{F-B} >> R_{F-A}$. The range of digital potentiometer codes that meet this criteria is from codes 233 to 255.

Photoconductive Mode Circuits

The response of a photodiode can be configured in the Photoconductive mode, as shown in Figure 7.

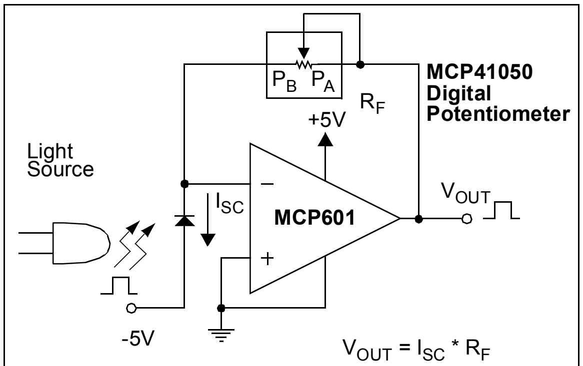


FIGURE 7: *When a photodiode is configured in the Photoconductive mode, the diode is reversed biased in order to reduce the diode parasitic capacitance.*

CONCLUSION

The two modes that a photosensing circuit can be configured are: Photovoltaic and Photoconductive. Photovoltaic configurations are best suited for precision circuits, while Photoconductive configurations are best suited for higher speed, digital circuits. If real-time adjustability of photodiode current to voltage gain is an issue in these photo detection circuits, a digital potentiometer can effectively be used to achieve this goal.

This application note presents three photosensing circuits configured with a digital potentiometer for real-time adjustments that can be used to calibrate LED/ photodiode alignment variability.

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