AN-1173

Low Voltage, Ultra-Low Power, Low-Noise Quadrant Photodiode Circuitry for High Precision Displacement Measurement

Author: Dr. Lazo M. Manojlović

Introduction

Quadrant photodiodes are critical components in optical tracking and displacement measurement systems. Typical applications include beam centering of the pick-up laser in optical data storage devices, bead position measurement and trap stiffness calibration in laser tweezers (optical trapping) systems, cantilever displacement measurement in scanning probe microscopy, and laser tracking in a variety of long distance applications such as free-space and satellite optical communications as well as alignment applications in civil engineering and mining industry. Moreover, quadrant photodiodes are among the most commonly used position sensitive detectors for two-dimensional beam centering and displacement measurement, due to their simple and robust design and high sensitivity. However, the circuitry, i.e. the analog signal processing chain that follows each quadrant photodiode, limits the characteristic of the overall sensing system. Therefore, special attention should be paid in the design of the accompanying circuitry. Typically, the quadrant photodiode-based displacement measurement system is used outdoors (such as in civil engineering and mining industry), where the measurement system must be battery powered. Keeping in mind that such a measurement system is typically extensively used, there is a constant need to lower the voltage of the power supply as well as the power consumption, so one must pay close attention to the circuit design.

In this app note we will present a low voltage, ultra-low power, low-noise quadrant photodiode circuit design for high precision displacement measurement based on the SLG88104V Rail to Rail I/O 375 nA Quad OpAmp.

Position Measurement with the Quadrant Photodiode

A measurement system's specific requirements are often dependent on: precision, accuracy, linearity, dynamic range, and frequency bandwidth. Between the object whose position is to be measured and the quadrant photodiode, an optical system consisting of a light source (typically a laser or LED is used) and typically very simple passive optical components are used to fulfill these appointed requirements. This specific and simple optical system has a role in determining the object position, and the position of the light spot on the quadrant photodiode's sensitive surface. The light spot irradiance distribution on the quadrant photodiode surface mostly depends on the light source used, but also on the object-coupling optics arrangement. Regardless of the light spot irradiance distribution on the quadrant photodiode surface, most algorithms for light spot position evaluation with respect to the quadrant photodiode center are based on the position measurement of the light spot's center of gravity. Such an algorithm enables high sensitivity, high speed, and high resolution position measurement. Each quadrant photodiode consists of four matched photodiodes deposited on a single chip as shown in Figure 1.

Depending on the light spot position and shape on the quadrant photodiode surface, each photodiode will generate the electric current that linearly depends on the amount of the captured optical power. Therefore, if the light spot is symmetric about both axes and centered in the quadrant photodiode center, the currents of all four photodiodes will be the same. If the light spot center is shifted from the quadrant photodiode center, the currents will differ.

© 2022 Renesas Electronics Corporation

Figure 1. Photo of a quadrant photodiode with four matched photodiodes deposited on a single chip

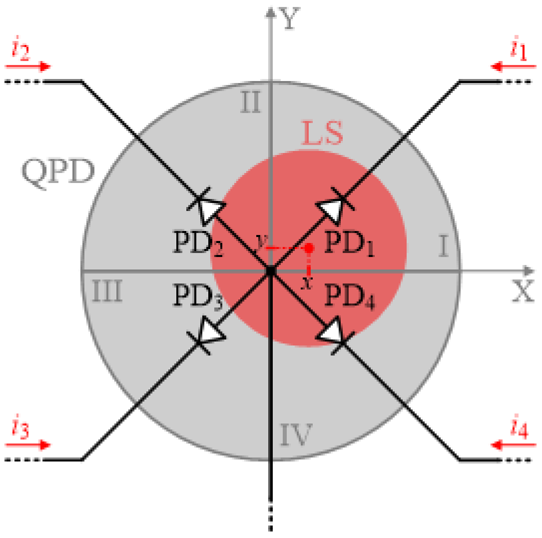


Figure 2. Quadrant photodiode (QPD) consisted of four photodiodes (PD1, PD2, PD3 and PD4) illuminated in a way to form the light spot (LS) on its surface

In order to determine the position of the light spot center regarding the center of the quadrant photodiode, the photodiode currents must be processed in such a way that at the circuitry outputs we have the voltage signals that are proportional to the light spot displacements along both axes. Moreover, as the overall optical power that is captured by the quadrant photodiode might vary, the circuitry at its output must provide the voltage signal, which carries the information about the overall optical power. This signal serves as the normalization signal. In order to fulfill all these requirements, the corresponding circuitry can be successfully produced based on the SLG88104V Rail to Rail I/O 375 nA Quad OpAmp operational amplifiers.

Direct measurement of the light spot center position with respect to the quadrant photodiode center by processing electrical current signals from the quadrant photodiode is not possible. However, by measuring these current signals, it would be possible to estimate only the ratios of positions of the light spot and the parameters of the irradiance distribution onto the quadrant photodiode surface. To determine these relations, it is essential to know the irradiance distribution on the quadrant photodiode surface. Due to the complex mathematical relations between the light spot center positions and the photodiodes generated electrical currents, the exact measurements of these ratios are not possible. Typically light spot movements onto the quadrant photodiode surface are small. Therefore, the light spot center positions are proportional to the photodiode currents in the following way:

$$x \propto \frac{(i_1+i_4)-(i_2+i_3)}{i_1+i_2+i_3+i_4}$$

$$y \propto \frac{(i_1+i_2)-(i_3+i_4)}{i_1+i_2+i_3+i_4}, \qquad (1)$$

where *x* and *y* are the positions of the light spot center along the X and Y axes, respectively, and i_j is the electrical current acquired by the quadrant photodiode *j*-th quadrant, where *j* = 1,2,3,4, as it is depicted in Fig. 2. In order to eliminate the influence of the possible variations of the light source emitted power on the measurement process, the normalization with the overall captured optical power must occur, i.e. the current difference signals ($(i_1+i_4)-(i_2+i_3)$ and $(i_1+i_2)-(i_3+i_4)$) must be divided by the corresponding signal proportional to the sum of the all four photodiode currents ($i_1+i_2+i_3+i_4$).

The Quadrant Photodiode Circuitry

In order to enable measurement of the light spot position, i.e. the position of the corresponding object, the circuitry that follows the quadrant photodiode must provide the currents difference signals as well as the signal proportional to the sum of all photodiode currents.

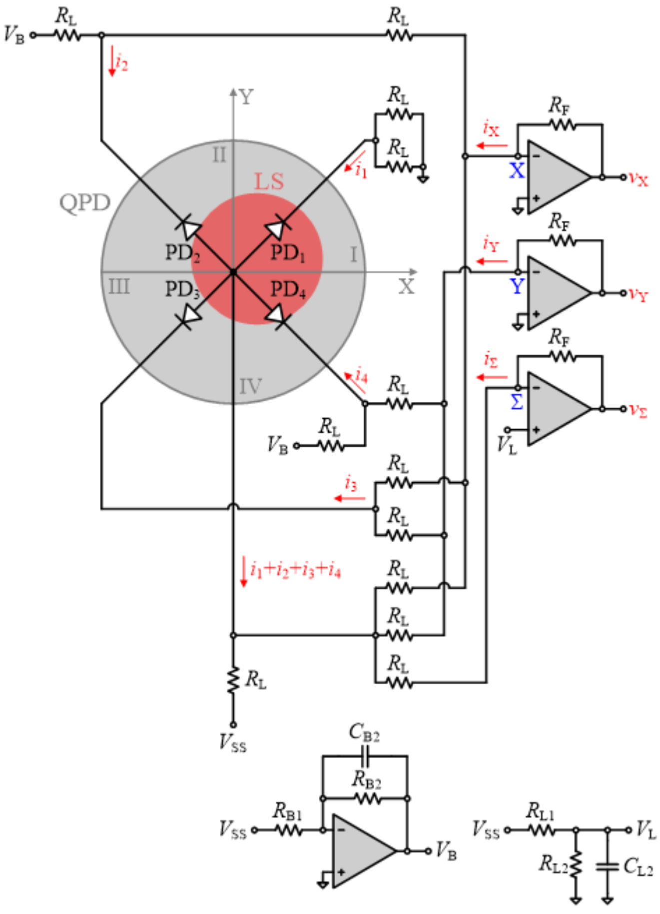


Figure 3. The suggested quadrant photodiode circuitry

Typical circuitry that fulfills this condition consists of at least seven operational amplifiers. A larger number of operational amplifiers can increase the overall power consumption as well as deteriorate the characteristics of the overall signal processing chain. In order to provide the low voltage, ultra-low power, low-noise quadrant photodiode circuitry, only three operational amplifiers can be employed for the analog signal processing of the photodiode currents, while the fourth operational amplifier is used only for the biasing purpose. This relatively simple circuit is presented in Figure. One can notice from Figure that all needed arithmetic has been performed by using the resistive network consisting of resistors with the same value R_L. By taking the advantage that quadrant photodiode anode current is equal to the sum of all four individual photodiode currents, the currents that come into three transimpedance amplifiers i_X, i_Y and i_Σ are given by:

$$i_X = \frac{1}{2}(i_2+i_3) - \frac{1}{4}(i_1+i_2+i_3+i_4) = -\frac{1}{4}[(i_1+i_4)-(i_2+i_3)]$$
$$i_Y = \frac{1}{2}(i_3+i_4) - \frac{1}{4}(i_1+i_2+i_3+i_4) = -\frac{1}{4}[(i_1+i_2)-(i_3+i_4)]$$
$$i_\Sigma = -\frac{1}{4}(i_1+i_2+i_3+i_4)$$

. (2)

The transimpedance amplifiers convert the current signals into the corresponding voltage signals v_X, v_Y and v_Σ given by:

$$v_X = R_F i_X = -\frac{1}{4} R_F [(i_1+i_4)-(i_2+i_3)]$$
$$v_Y = R_F i_Y = -\frac{1}{4} R_F [(i_1+i_2)-(i_3+i_4)]$$
$$v_\Sigma = R_F i_\Sigma = -\frac{1}{4} R_F (i_1+i_2+i_3+i_4)$$

, (3)

where R_F is the feedback resistor resistance and the transimpedance amplifier gain.

It is worth mentioning that the purpose of the two resistors R_L that are connected between the cathode of the photodiode PD_1 and ground is the symmetrization, i.e. all four photodiodes must be connected to the same resistance in order to match their frequency responses.

Biasing the Quadrant Photodiode Circuitry

The operational amplifiers have dual power supply, i.e. they are biased by two voltage sources V_{DD} ($V_{DD} > 0$) and V_{SS} ($V_{SS} < 0$). In order to provide photoconductive mode of the quadrant photodiode, the voltage source V_{SS} is connected to the common anode by the resistor R_L making the quadrant photodiode inversely polarized. However, this inverse polarization adds the DC voltage at the output of the transimpedance amplifiers even if the quadrant diode isn't illuminated, thus introducing the measurement error. Therefore, two constant voltages V_B and V_L are employed to compensate the influence of the quadrant photodiode inverse polarization and to eliminate measurement error. Neglecting the operational amplifiers' offset voltages and input currents and the dark currents of the quadrant photodiode, the outputs of all three transimpedance amplifiers must be equal to zero when the quadrant photodiode isn't illuminated. These conditions are fulfilled if the following two conditions are satisfied:

$$V_{\mathrm{B}} = -\frac{2(R_{\mathrm{F}} + R_{\mathrm{L}})}{3R_{\mathrm{F}} + 5R_{\mathrm{L}}} V_{\mathrm{SS}}$$
$$V_{\mathrm{L}} = \frac{R_{\mathrm{F}}}{3R_{\mathrm{F}} + 5R_{\mathrm{L}}} V_{\mathrm{SS}} \quad . \qquad (4)$$

The auxiliary circuits that provide these two constant voltages are presented at the bottom of Figure. In order to be able to simply set these two voltages at the desired levels without using the potentiometers one can simply choose $R_{\mathrm{F}} = R_{\mathrm{L}} = R$ where the following is obtained: $V_{\mathrm{B}} = -V_{\mathrm{SS}}/2$, $V_{\mathrm{L}} = V_{\mathrm{SS}}/8$, $R_{\mathrm{B1}}/R_{\mathrm{B2}} = 2$, and $R_{\mathrm{L1}}/R_{\mathrm{L2}} = 7$. It is important to point out that if the circuitry is battery powered, the drop of the battery voltage will not influence the voltage levels at the outputs of all three transimpedance amplifiers, irrespective of the voltage drop.

Small Signal Analysis of the Quadrant Photodiode Circuitry

When the quadrant photodiode is exposed to optical illumination, the photocurrents from the photodiodes will rush into the circuitry thus providing the information about the light spot position. The corresponding voltage signals are given by equation (3). However, these currents can influence the polarization of the quadrant photodiode. The inverse polarization voltages of the photodiodes are given by:

$$V_{\mathrm{PD1}} = \frac{V_{\mathrm{B}}}{2} - \frac{1}{4} R_{\mathrm{L}} (i_1 + i_2 + i_3 + i_4) - \frac{1}{2} R_{\mathrm{L}} i_1$$
$$V_{\mathrm{PD2}} = V_{\mathrm{B}} - \frac{1}{4} R_{\mathrm{L}} (i_1 + i_2 + i_3 + i_4) - \frac{1}{2} R_{\mathrm{L}} i_2$$
$$V_{\mathrm{PD3}} = \frac{V_{\mathrm{B}}}{2} - \frac{1}{4} R_{\mathrm{L}} (i_1 + i_2 + i_3 + i_4) - \frac{1}{2} R_{\mathrm{L}} i_3$$
$$V_{\mathrm{PD4}} = V_{\mathrm{B}} - \frac{1}{4} R_{\mathrm{L}} (i_1 + i_2 + i_3 + i_4) - \frac{1}{2} R_{\mathrm{L}} i_4 \quad . \qquad (5)$$

In order to keep the quadrant photodiode in the photoconductive mode, each of four photodiode corresponding inverse polarization voltages must be positive. Bearing in mind that for high linearity position measurement, $i_1 \approx i_2 \approx i_3 \approx i_4 \approx I/4$ must be satisfied, where $I = i_1 + i_2 + i_3 + i_4$, the condition for quadrant photodiode photoconductive mode is given by:

$$I < \frac{4V_{\mathrm{B}}}{3R_{\mathrm{L}}} = -\frac{2V_{\mathrm{SS}}}{3R} \quad , \qquad (6)$$

where $R_{\mathrm{F}} = R_{\mathrm{L}} = R$ and $V_{\mathrm{B}} = -V_{\mathrm{SS}}/2$ was assumed. This condition limits the maximal optical power of the light source that illuminates the quadrant photodiode keeping the overall quadrant photodiode current below the maximal value defined by inequality (6).

Noise Analysis of the Quadrant Photodiode Circuitry

Due to the large number of components, there are a large number of noise sources in the quadrant photodiode circuitry presented in Figure which makes the noise analysis rather complicated and time consuming. However, if we take $R_{\mathrm{F}} = R_{\mathrm{L}} = R$, the power spectral densities of the voltage noise signals $\left\langle v_{\mathrm{Xn}}^2 \right\rangle$ and $\left\langle v_{\mathrm{Yn}}^2 \right\rangle$ at the output of the transimpedance amplifiers get the simpler form given by:

$$\left\langle v_{\mathrm{Xn}}^2 \right\rangle \approx \left\langle v_{\mathrm{Yn}}^2 \right\rangle \approx R^2 \left\langle i_{\mathrm{n}}^2 \right\rangle + \frac{55}{16}\left\langle e_{\mathrm{n}}^2 \right\rangle + \frac{1}{8} R^2 qI + 9kTR \,, \tag{7}$$

where $\left\langle i_{\mathrm{n}}^2 \right\rangle$ and $\left\langle e_{\mathrm{n}}^2 \right\rangle$ are the power spectral densities of the operational amplifier input current and voltage noises, respectively, $q = 1.6\times10^{-19}$ C is the elementary positive charge, I is the overall quadrant photodiode current, $k = 1.38\times10^{-23}$ J/K is the Boltzmann constant, and T is the circuit absolute temperature. The power spectral density of the voltage noise signal at the output of the third transimpedance amplifier, where the voltage signal v_Σ, proportional to the sum of each photodiode currents is presented, isn't taken into consideration as this signal is much higher than other two, which are proportional to the difference in currents, and thus much less sensitive to the disturbances caused by the noise. Finally, the signal-to-noise ratios SNR_{X} and SNR_{Y} at the transimpedance amplifiers outputs are:

$$SNR_{\mathrm{X}} = \frac{R^2 i_{\mathrm{X}}^2}{\left\langle v_{\mathrm{Xn}}^2 \right\rangle B} \approx \frac{1}{16} \frac{\left[\left(i_1 + i_4\right) - \left(i_2 + i_3\right)\right]^2}{\left(\left\langle i_{\mathrm{n}}^2 \right\rangle + \dfrac{55\left\langle e_{\mathrm{n}}^2 \right\rangle}{16R^2} + \dfrac{1}{8}qI + \dfrac{9kT}{R}\right)B}$$

$$SNR_{\mathrm{Y}} = \frac{R^2 i_{\mathrm{Y}}^2}{\left\langle v_{\mathrm{Yn}}^2 \right\rangle B} \approx \frac{1}{16} \frac{\left[\left(i_1 + i_2\right) - \left(i_3 + i_4\right)\right]^2}{\left(\left\langle i_{\mathrm{n}}^2 \right\rangle + \dfrac{55\left\langle e_{\mathrm{n}}^2 \right\rangle}{16R^2} + \dfrac{1}{8}qI + \dfrac{9kT}{R}\right)B} \,, \tag{8}$$

where B is the bandwidth of interest.

Frequency Response of the Quadrant Photodiode Circuitry

Typically, photodiodes can be modeled in the photoconductive mode as a current source, which is connected in parallel with the photodiode parasitic capacitance. In order to eliminate crosstalk and measurement error at higher frequencies, there are some restrictions in resistor values.

Crosstalk and measurement error will be negligible if the photodiode impedance is much higher than the impedance connected to the photodiode. Therefore, the following conditions must be fulfilled:

$$\frac{1}{\omega C_{\mathrm{PD}}} >> \frac{3}{4} R \,, \tag{9}$$

where ω is the angular frequency and C_{PD} is the capacitance of each of four photodiodes. Bearing in mind that B is the bandwidth of interest, we have the following for the maximal value of the circuitry resistors:

$$R << \frac{2}{3\pi B C_{\mathrm{PD}}} \,. \tag{10}$$

Realization with SLG88104V Rail to Rail I/O 375 nA Quad OpAmp

The realization of the quadrant photodiode analog signal processing circuitry will be based on the unique characteristics of the SLG88104V Rail to Rail I/O 375 nA Quad OpAmp operational amplifiers. The use of these operational amplifiers will enable us to design low voltage, ultra-low power low-noise circuitry that at its outputs will provide the signals proportional to the displacements in two dimensions. Due to the high sensitivity of the sensor and low-noise design, these signals will provide very precise information about the displacements reaching the nanometer realm.

The complete circuitry is aimed to measure physical position of the object of interest. Typically, the frequency range of interest in the case of mechanical movement lies below 1 kHz ($B \leq 1$ kHz) where the typical value of photodiode parasitic capacitance is in the range of 10 pF ($C_{PD} \approx 10$ pF). According to the inequality (10) the resistance of the resistor must fulfill $R << 21$ MΩ. If we choose $R = 1$MΩ then the crosstalk is lower than 1.6%, which is, on the other side, significantly lower than the typical interquadrant crosstalk of the quadrant photodiode of 5%. The inequality (6) limits the maximal overall current of the quadrant photodiode. If we take a simple battery power supply having V_{SS}=-1.5V then according to inequality (6) the maximal sum of the photodiode currents must be lower than 1μA (I<1μA). According to equation (3) the maximal amplitude of the transimpedance amplifier output voltage signal, which is proportional to the sum of photodiode currents, must be lower than 250 mV. This data should be taken into consideration when choosing the adequate light source and its optical power for the quadrant photodiode illumination.

In order to test the circuit characteristics prior to the actual experimental verification, a simulation in LT Spice XVII software package has been performed based on the SLG88104V Rail to Rail I/O 375 nA Quad OpAmp operational amplifier **spice model**. The circuit model is presented in Figure. Besides the resistor's value of $\boldsymbol{R = 1}$**MΩ**, the following values of the components have been chosen: $\boldsymbol{V_{DD} = 1.5}$**V**, $\boldsymbol{V_{SS} = -1.5}$**V**, $\boldsymbol{R_{B1} = 2}$**MΩ**, $\boldsymbol{R_{B2} = 1}$**MΩ**, and $\boldsymbol{C_{B2} = 220}$**nF** (this capacitance value has been chosen in order to keep corner frequency below 1Hz).

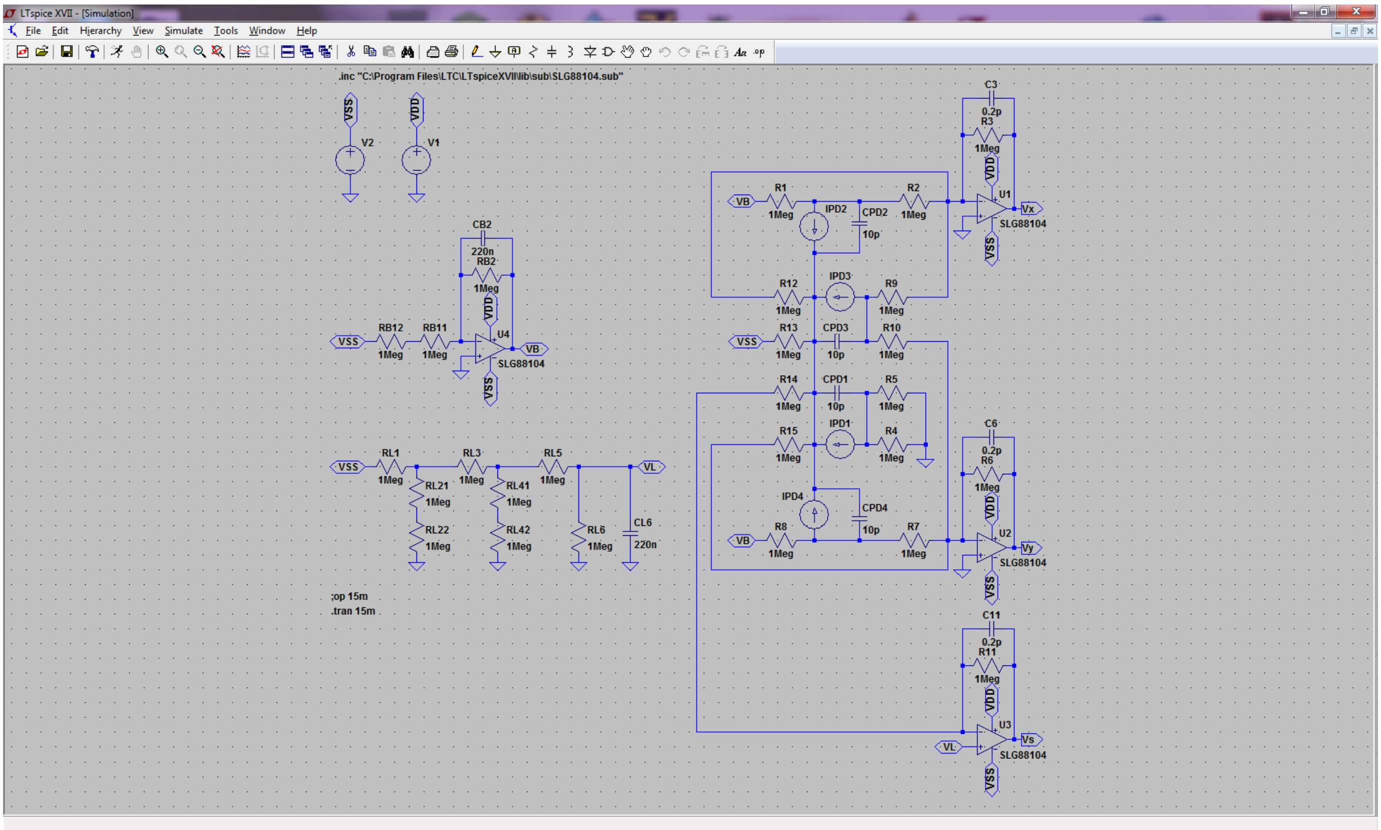
The auxiliary circuit (simple voltage divider) that should provide DC voltage V_L is realized as a simple R-2R voltage divider because the voltage V_L is $8 = 2^3$ times smaller than the power supply voltage V_{SS}. In order to suppress the noise signals, the same value for the capacitance $\boldsymbol{C_{L6} = 220}$**nF** has been used for the first auxiliary circuit. One can notice that the complete circuit can be arranged by using resistors having the same resistance value.

© 2022 Renesas Electronics Corporation

Transimpedance amplifiers feedback resistors have typically parasitic capacitance in the range of 0.2pF, which can deteriorate the amplifier characteristics. Therefore, each feedback resistor has in parallel capacitance with this value.

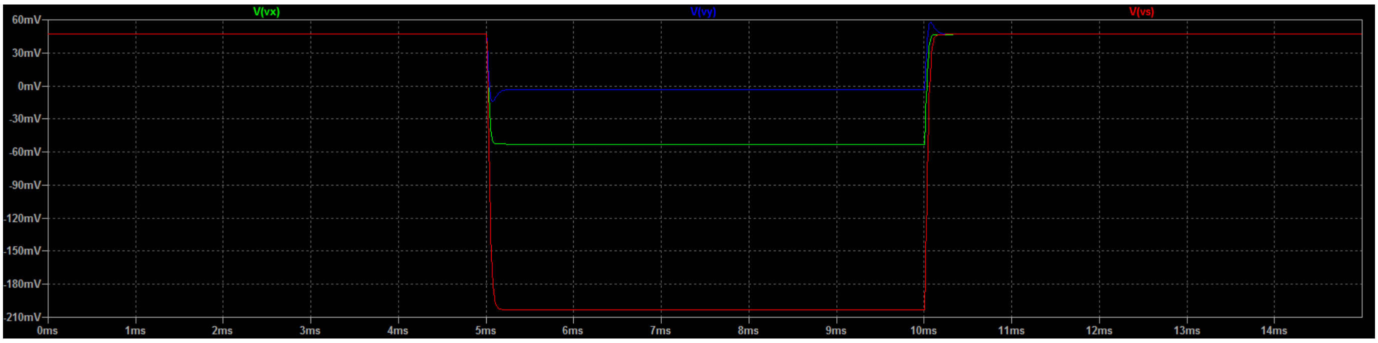
Finally, each photodiode has been modeled as the current source in parallel with the capacitance of 10pF, which represents the typical value of the photodiode parasitic capacitance.

The simulation results where it was assumed the pulsed illumination of the quadrant photodiode, i.e. the photodiode currents have been modeled as pulsed current sources is presented in Figure 5. Simulation results present the transient response of the circuit where (a) the light spot center is located in the first quadrant and (b) the light spot center is located in the second quadrant of the quadrant photodiode.

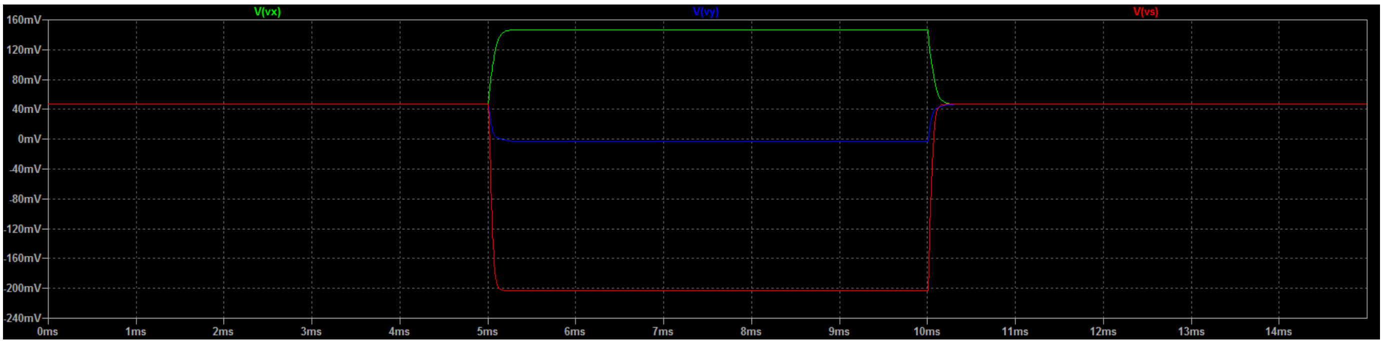


```
.inc "C:\Program Files\LTC\LTspiceXVII\lib\sub\SLG88104.sub"
;op 15m
.tran 15m
```

Figure 4. The Circuit Simulation Model



a)



b)

Figure 5. The simulation results where (a) the light spot center is located in the first quadrant and (b) the light spot center is located in the second quadrant

In order to find the frequency response of the complete circuitry an AC analysis was performed individually for each current source representing the corresponding photodiode, and for each output of the transimpedance amplifiers. Table 1 shows the simulation results where the numbers in the table represent the corresponding bandwidth. One can notice that each bandwidth is significantly larger than the typical 1 kHz bandwidth needed for capturing fast mechanical movement.

	VX	VY	VS
IPD1	6.7 kHz	6.7 kHz	6.8 kHz
IPD2	2.8 kHz	3.2 kHz	5.3 kHz
IPD3	4.8 kHz	4.7 kHz	4.5 kHz
IPD4	3.2 kHz	2.8 kHz	5.3 kHz

Table 1. AC analysis simulation results

Taking into consideration the bandwidth of interest of about $B \approx 1$ kHz and the power spectral densities of the transimpedance output voltage signals given by equations (7), one can obtain the 1σ noise floor of approximately 15 µV.

Finally, according to the simulation results the overall power consumption of the complete circuit when the quadrant photodiode isn’t illuminated is approximately 9 µW. Bear in mind that the overall quadrant photodiode current is smaller than 1 µA, so the power consumption wouldn’t be significantly larger if the quadrant photodiode is illuminated.

Example Implementation

Based on the provided evaluation board for the SLG88104V Rail to Rail I/O 375 nA Quad OpAmp and the quadrant PIN photodiode QDY80P (**http://nanosys.ihtm.bg.ac.rs/english/catalog/qdy80p.pdf**) with the active area of 80 mm^2 and the unit price of about 100 USD the test circuitry has been built. The photo of the proto-board realized circuitry is shown in Figure 6.

In order to test the circuit characteristics, the quadrant photodiode is exposed to the pulsed illumination with the help of an infrared LED that has a small radiation angle. One must pay special attention to the LED driving current as the LED emitted optical power must be in the range of a couple of µW.

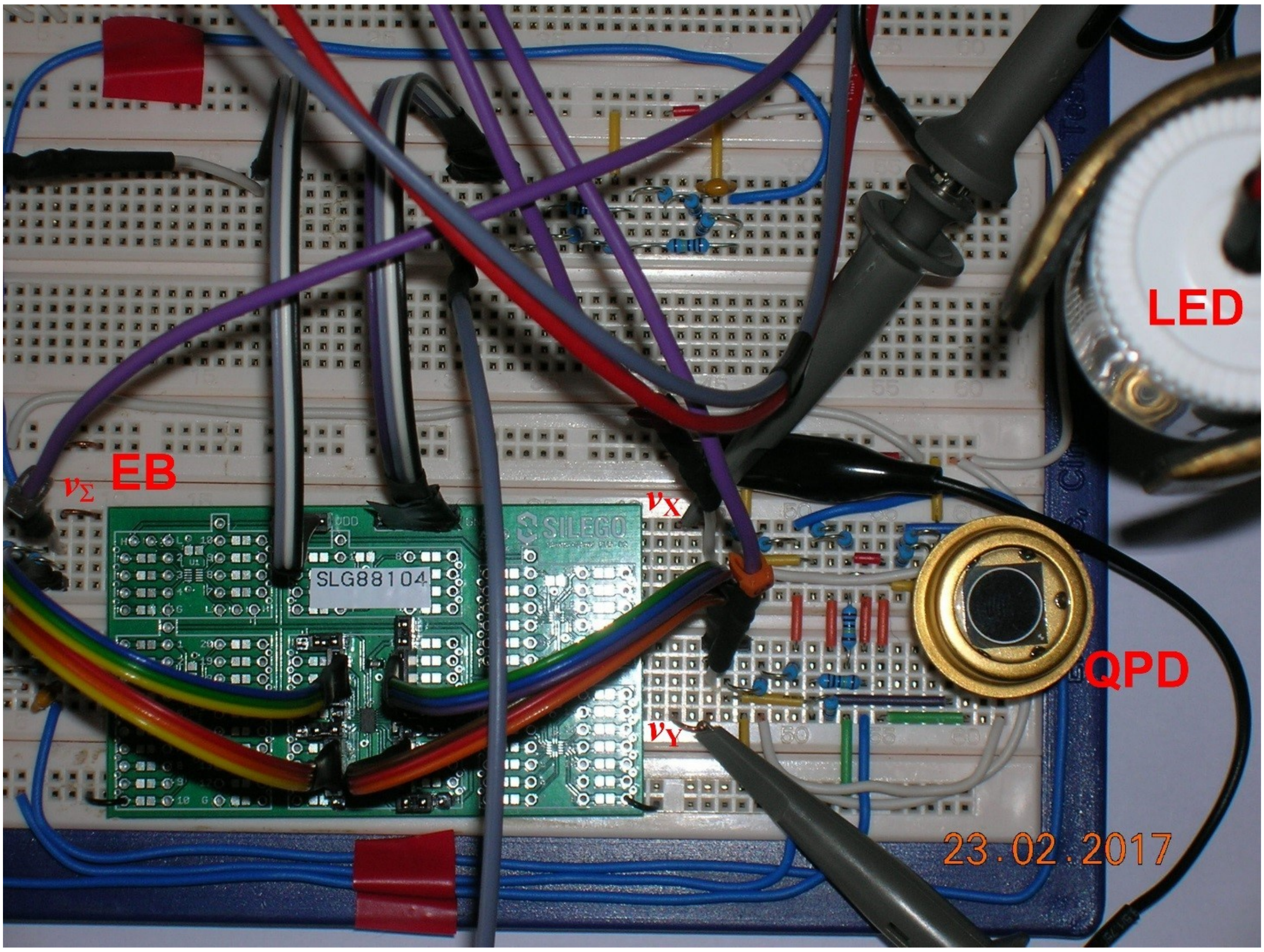
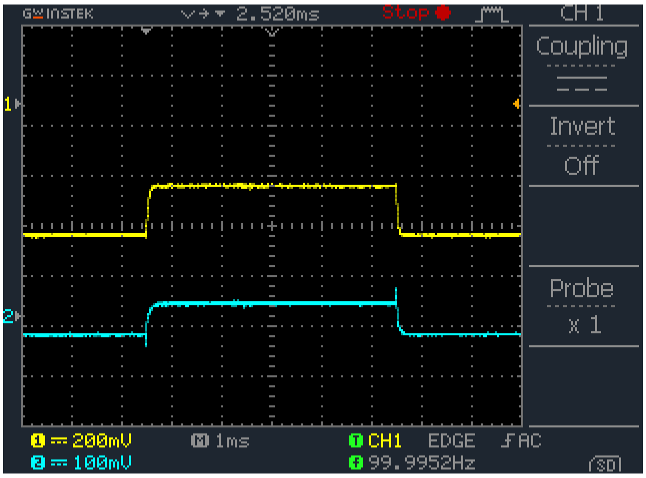
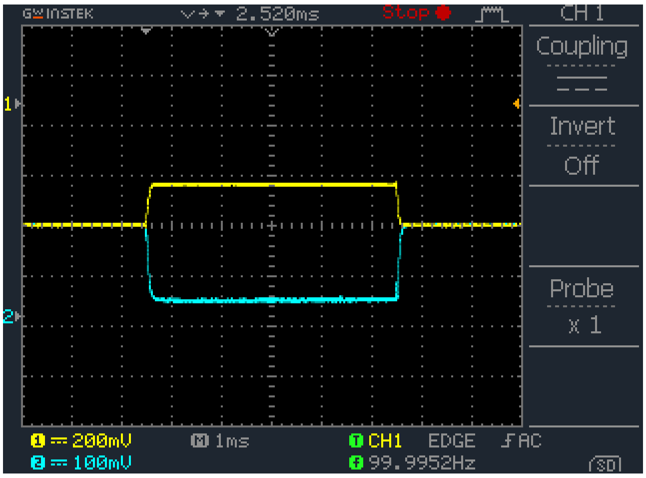


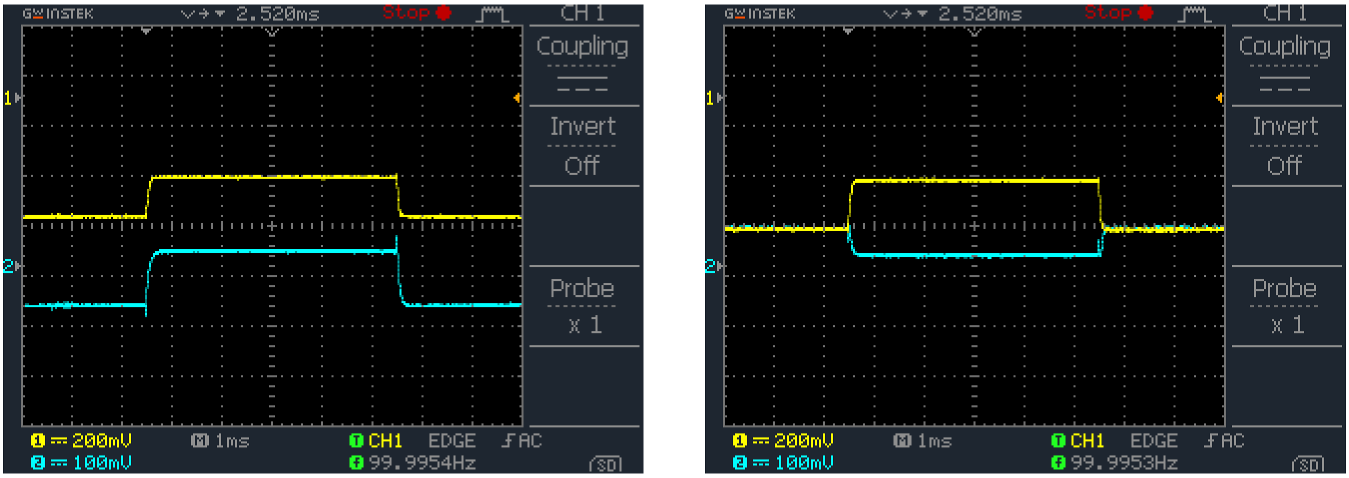
Figure 1. The photo of the circuitry where EB is the evaluation board, QPD is the quadrant photodiode and LED is the light emitting diode



(a) Channel 1 (yellow) – v_Σ and channel 2 (blue) – v_X.

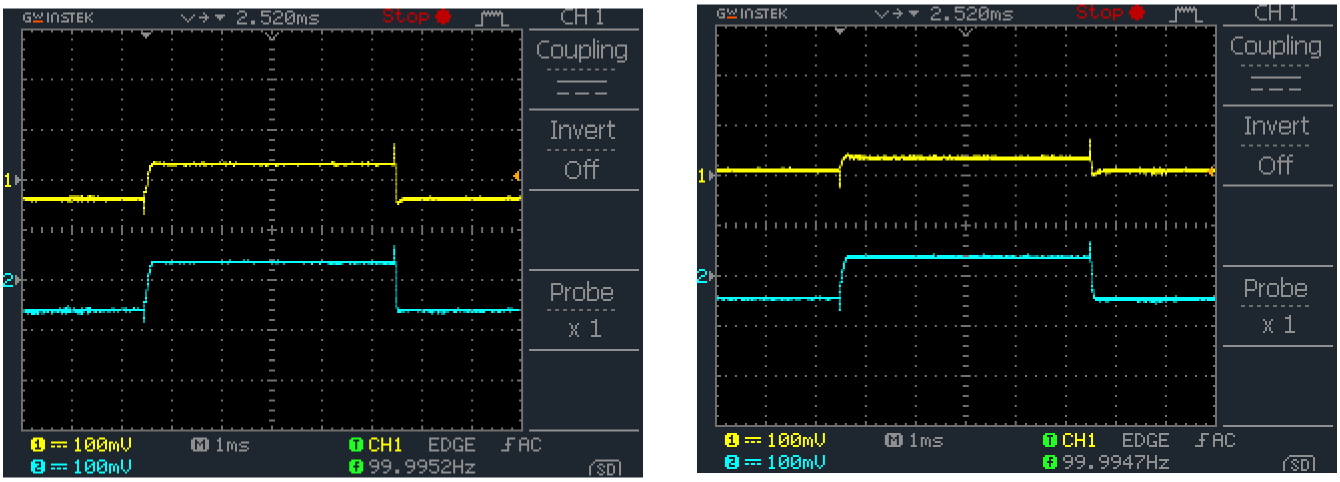


b) Channel 1 (yellow) – v_Σ and channel 2 (blue) – v_X.



(c) Channel 1 (yellow) – vΣ and channel 2 (blue) – vY

(d) Channel 1 (yellow) – vΣ and channel 2 (blue) – vY.



(e) Channel 1 (yellow) – vX and channel 2 (blue) – vY

(f) Channel 1 (yellow) – vX and channel 2 (blue) – vY.

Figure 7. Transimpedance amplifiers output voltage signals captured by the digital storage oscilloscope

This low power will keep the quadrant photodiode in the photoconductive mode thus providing high linearity of the overall circuit. Depending on the position of the light spot on the quadrant photodiode active surface we perform several measurements of the transimpedance output voltage signals. These measurements are captured by the digital storage oscilloscope and presented in Figure 7.

Figures (a), (c), and (e) represent the voltage signals v_Σ and v_X, v_Σ and v_Y, and v_X and v_Y, respectively when the center of the light spot is located in the first quadrant. Figures (b), (d), and (f) represent the voltage signals v_Σ and v_X, v_Σ and v_Y, and v_X and v_Y, respectively when center of the light spot is located in the third quadrant.

Conclusion

The high-precision displacement measurement based on the quadrant photodiode and corresponding circuitry has a very wide use in many fields of application. By introducing a low voltage, ultra-low power measurement system, which can be easily battery powered, the fields of application can be much broader. The circuitry has a very unique design that can be tested with different types of quadrant photodiodes, proving the concept of the circuit design. Moreover, the result of this test can be used in order to improve the design in a way to reach higher-precision and wider bandwidth.

IMPORTANT NOTICE AND DISCLAIMER

RENESAS ELECTRONICS CORPORATION AND ITS SUBSIDIARIES (“RENESAS”) PROVIDES TECHNICAL SPECIFICATIONS AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, OR NON-INFRINGEMENT OF THIRD-PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for developers who are designing with Renesas products. You are solely responsible for (1) selecting the appropriate products for your application, (2) designing, validating, and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. Renesas grants you permission to use these resources only to develop an application that uses Renesas products. Other reproduction or use of these resources is strictly prohibited. No license is granted to any other Renesas intellectual property or to any third-party intellectual property. Renesas disclaims responsibility for, and you will fully indemnify Renesas and its representatives against, any claims, damages, costs, losses, or liabilities arising from your use of these resources. Renesas' products are provided only subject to Renesas' Terms and Conditions of Sale or other applicable terms agreed to in writing. No use of any Renesas resources expands or otherwise alters any applicable warranties or warranty disclaimers for these products.

(Disclaimer Rev.1.01)

Corporate Headquarters

TOYOSU FORESIA, 3-2-24 Toyosu,
Koto-ku, Tokyo 135-0061, Japan
www.renesas.com

Contact Information

For further information on a product, technology, the most up-to-date version of a document, or your nearest sales office, please visit www.renesas.com/contact-us/.

Trademarks

Renesas and the Renesas logo are trademarks of Renesas Electronics Corporation. All trademarks and registered trademarks are the property of their respective owners.

© 2025 Renesas Electronics Corporation. All rights reserved.