Photodiode amplifiers

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There are several important amplifier characteristics to consider when designing a fast photodiode circuit to work with low signal to noise, such as: gain bandwidth product (GBW), input offset voltage (V_{OS}), input noise voltage (e_{n}), input bias current (I_{b}), input offset current (I_{OS}), and input noise current (i_{n}). Also the thermal stability of the offsets, both voltage and current (known as offset drift) can become important if the amplifier changes temperature as this will affect the trimmed offset signal. The slew rate of the op-amp becomes important if large voltage changes will occur or if the response needs to be very fast for example in a linewidth narrowing fast feedback circuit.

The first choice to make for your photodiode amplifier is the gain bandwidth product. This is the maximum gain that can be achieved for a certain bandwidth response for the circuit. For example, if you are modulating your laser beam's frequency at 10 MHz for a Pound-Drever-Hall error signal then you could choose a maximum gain such that $G_{\mathrm{max}} = GBW/10$ MHz. This leads to the -3 dB point (the frequency at which three decibels of power is lost to be at 10 MHz). Gains higher than this would limit the frequency response, as shown in figure 1.

Now that the maximum signal at a given bandwidth is known the dominant source of noise for the circuit should be calculated for different circuit setups and amplifier choices. For photodiode circuits there are two general amplifier circuits used: a"normal" pre-amplifier setup, figure 2a; and a transimpedance setup, figure 2b. The pre-amp circuit is a simpler circuit to build as you don't have to worry about the impedance of the photodiode as the impedance is set by the resistor to ground (R_{S}, generally a 50 Ω termination). Due to the low input impedance, input current noise is less important than the input voltage noise as the voltage noise this becomes equivalent to is generally much smaller than the input voltage noise. For example a LT1226 in pre-amp configuration has an e_{n} of 2.6 nVHz$^{-1/2}$ and a i_{n} of 1.5 pAHz$^{-1/2}$, which is equivalent to 75 pVHz$^{-1/2}$, i.e. much smaller. In this setup generally a bipolar junction transistor (BJT) op-amp is a bet-

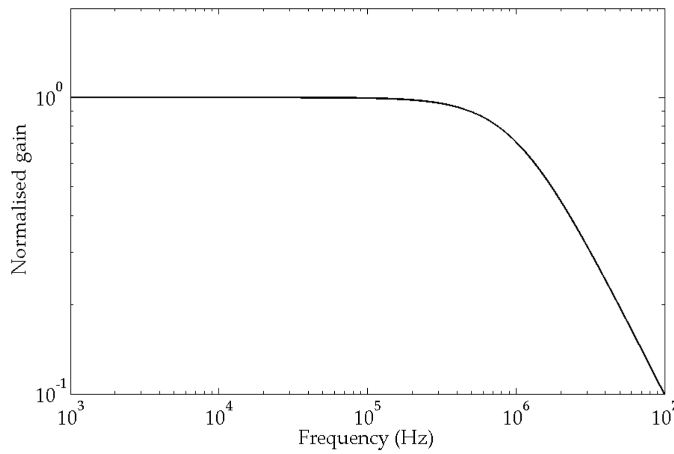


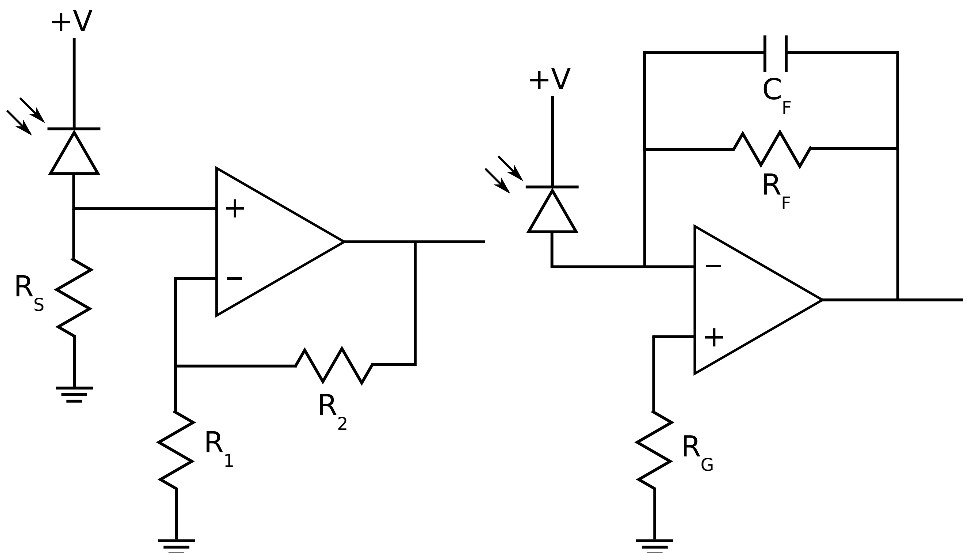
Figure 1: Typical frequency response of an op-amp where the -3 dB frequency is set to be 10 MHz. The gain has been normalized.

ter choice than a field effect transistor (FET) op-amp as it has a lower input voltage noise. In the transimpedance setup the gain of the circuit is set by the feedback resistor, R_{F}. To get gains equivalent to the pre-amp setup a large resistance is required which makes the input current noise the more relevant noise characteristic as the input voltage noise is not amplified. In the transimpedance case FET amplifiers are a better choice as they generally have much lower input current noise than BJTs.

All circuits which are designed to work at high frequencies should have their power lines decoupled. To do this ceramic capacitors of the correct capacitance should be used (don't use electrolytic or tantalum capacitors for the high frequency noise rejection on the power lines). The decoupling capacitor should be placed as close as possible to the component of interest, in this case the op-amp. For $\approx$10 MHz a capacitance of about 100 nF should be used. For low frequency drifts in power of the power supply a tantalum beam capacitor of about 10 μF should be used also. In addition the power lines should also go through voltage regulators before the decoupling capacitors to stabilize the power further.

1 Pre-amplifier

The current-to-voltage conversion in the pre-amp is set by the resistor to ground, R_{S}, this means the op-amp is amplifying the voltage and is often



(a) Pre-amplifier (b) Transimpedance

Figure 2: Two amplifier setups, not shown are the capacitively decoupled power lines which all high speed circuits should have.

called a voltage amplifier. The impedance of the photodiode is largely irrelevant as it is normally much larger than R_{S}. Increasing R_{S} increases the voltage generated by the photodiode, however this also increases the voltage noise generated by the input current noise of the op-amp and also decreases the bandwidth of the photodiode. The gain in non-inverting setup is set by one plus the ratio of the feedback resistor to the resistor to ground $G = 1 + R_2/R_1$. The bandwidth (cutoff frequency, $f_{-3\mathrm{dB}}$) of the circuit is normally set by the gain bandwidth product of the op-amp as the photodiode normally has a much larger bandwidth.

2 Transimpedance amplifier

In the transimpedance amplifier setup the amplifier itself is acting as the current-to-voltage convertor (this is often called a current amplifier), with the output voltage gain set by the feedback resistor. A feedback capacitor is also often needed control the frequency response of the circuit as at higher frequencies the signal increases with a gain of

$$Gain = 1 + \frac{Z_{\mathrm{F}}}{Z_{\mathrm{IN}}} = 1 + \frac{2\pi f R_{\mathrm{F}} C_{\mathrm{IN}}}{1 + 2\pi f R_{\mathrm{F}} C_{\mathrm{F}}} \ , \tag{1}$$

where Z_{F} is the impedance of the feedback part of the circuit, Z_{IN} is the impedance of the input of the circuit, and f is the frequency. The value for the feedback capacitor needed to roll off this gain can be calculated from

$$C_{\mathrm{F}} = \sqrt{\frac{C_{\mathrm{IN}}}{R_{\mathrm{F}} \pi f_{\mathrm{GBW}}}} \ , \tag{2}$$

where $C_{\mathrm{IN}} = C_{\mathrm{PD}} + C_{\mathrm{CMII}} + C_{\mathrm{DII}} + 0.2$ pF with C_{PD} being the photodiode capacitance, C_{CMII} the common mode input impedance of the op-amp, and C_{DII} the differential input impedance of the op-amp, the 0.2 pF is the parasitic capacitance of the circuit (varies from circuit to circuit). The capacitance of the photodiode can be changed by altering the bias voltage applied to it, this also changes the dark current and bandwidth of the photodiode. The C_{CMII} and C_{DII} are fundamental characteristics of the op-amp used. The feedback capacitance is often very small and can sometimes be neglected due to the parasitic capacitance caused by the surface mount nature of the op-amp. The smallest value C_{F} can take is this parasitic capacitance. The bandwidth of the circuit is set by

$$f_{-3\mathrm{dB}} = \sqrt{\frac{f_{\mathrm{GBW}}}{2\pi R_{\mathrm{F}} C_{\mathrm{IN}}}} \ . \tag{3}$$

With the roll-off (pole) of the high frequency gain set by

$$f_{\mathrm{pole}} = \frac{1}{2\pi R_{\mathrm{F}} C_{\mathrm{F}}} \ . \tag{4}$$

The resistor, R_{G}, is optional and is for reducing bias current offset errors. Figure 3 shows the affect of this high frequency gain and the feedback capacitor on the frequency response of the circuit.

3 Noise sources

Bias/offset noise will not be mentioned in this treatment of noise as for the application which this is to be used for the circuit will be AC-coupled and are therefore less important than random noise. This is true so long as the offset caused does not approach the voltage rails of the circuit. Shot noise and technical noise of the input signal, in this case photocurrent, are assumed to be smaller than other sources of noise in the circuit and cannot be reduced

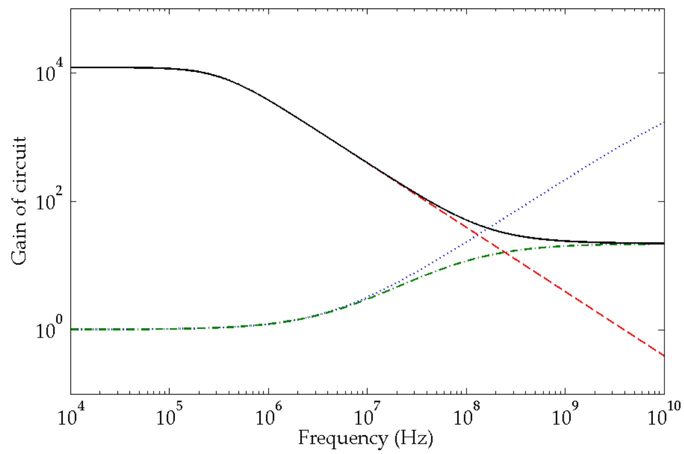


Figure 3: Frequency response of a transimpedance circuit. The red, long dashed line is of the same form as in figure 1. The blue, dotted line shows the increase in feedback with frequency for an uncompensated (no feedback capacitor) feedback resistor. The green, dot-dashed line has a feedback capacitor with a value which is calculated from equation 2. The black, solid line shows the overall response of the circuit with frequency, the frequency response is then flat at higher frequencies. Here the gain has not been normalized.

by the circuit anyway. The following sources of noise are all given in units of either amps or volts per root Hertz as it is then easier to calculate the noise in the relevant bandwidth at the end. The op-amp has two characteristic sources of noise, input voltage noise, e_{n}, and input current noise, i_{n}. The other major source of noise in low noise circuits is Johnson-Nyquist noise which is a fundamental source of noise caused by thermal fluctuations of the charge carriers in all resistors in the circuit and is given by

$$e_{\mathrm{JN}} = \sqrt{4k_{\mathrm{B}}TR} \tag{5}$$

$$i_{\mathrm{JN}} = \sqrt{4k_{\mathrm{B}}T/R} \tag{6}$$

where k_{B} is the Boltzmann constant, T is the temperature, R is the resistance of the resistor in question. Dark current from the photodiode leads to a DC offset noise, which is unimportant in this case but also has a shot noise associated with it given by

$$i_{\mathrm{DCSN}} = \sqrt{2qi_{\mathrm{D}}C} \tag{7}$$

where i_{DCSN} is the dark current shot noise, q is the charge on an electron, and i_{DC} is the dark current.

The input current noise of the op-amp is the lowest possible current noise in a circuit, it is only reached in certain circumstance and the total current noise in a given transimpedance circuit is given by

$$i_{\mathrm{TOT}} = \sqrt{i_{\mathrm{N}}^2 + \frac{4kT}{R_{\mathrm{F}}} + \left(\frac{e_{\mathrm{N}}}{R_{\mathrm{F}}}\right)^2 + \frac{(e_{\mathrm{N}}2\pi C_{\mathrm{IN}}B)^2}{3} + i_{\mathrm{DCSN}}^2}\,, \tag{8}$$

where i_{TOT} is the total input current noise of the circuit. This equation is only correct when the bandwidth of the noise/circuit is less than the frequency given in equation 4. The first term in this equation comes from the op-amp input current noise, the second term comes from the Johnson noise on the feedback resistor, the third term comes from the op-amp input voltage noise converted to current via the feedback resistor, the fourth term comes from the voltage noise being converted to current via the input impedance of the circuit which changes with frequency and hence why the relevant bandwidth is important and the last term comes from the shot noise of the dark current of the photodiode. To get the total output voltage noise the total input current noise should be multiplied by feedback resistor.

For the pre-amplifier case, it is easier to calculate the total input voltage noise instead of the total input current noise. This is given as

$$e_{\mathrm{TOT}} = \sqrt{e_{\mathrm{N}}^2 + (i_{\mathrm{N}}R_{\mathrm{S}})^2 + (i_{\mathrm{N}}R_{||})^2 + 4k_{\mathrm{B}}T(R_{\mathrm{S}} + R_{||}) + (i_{\mathrm{DCSN}}R_{\mathrm{S}})^2} \tag{9}$$

where e_{TOT} is the total input voltage noise, and $R_{||} = \frac{R_1R_2}{R_1+R_2}$ is the resistance of the feedback resistor network, this is acting as a potential divider which is why the resistance is reduced from R_2. The first term comes from the input voltage noise of the op-amp, the second and third terms come from current noise across the input resistor and the feedback resistors, the forth term comes from the Johnson noise of the resistors and the final term comes from the shot noise of the dark current of the photodiode over the source resistor.

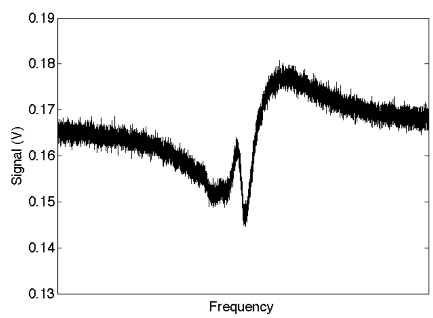
4 Calculations

It is now possible to calculate the total noise in a given bandwidth for various circuits to see which gives the best signal-to-noise ratio, SNR. For this *Matlab* programs are used to evaluate the signal, noise, and the SNR for various gains and bandwidths of the circuits, the optimal values for different setups/photodiodes for a given wavelength and light intensity is shown in table 1.

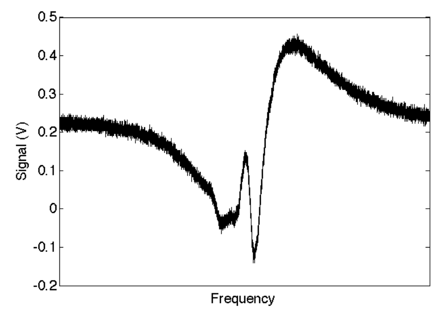
Op-amp	Photodiode	Signal	SNR
LT1226	S5972	0.7194	1.22E+06
LT1226	S5973-02	1.9862	2.95E+06
LT1226	OSD1-5T	0.6686	1.43E+06
LMH6624	S5972	0.6322	1.06E+06
LMH6624	S5973-02	1.6624	2.45E+06
LMH6624	OSD1-5T	0.6274	1.35E+06
OPA657	S5972	3.9273	5.56E+06
OPA657	S5973-02	7.1728	1.38E+07
OPA657	OSD1-5T	3.1309	5.94E+06
OPA847	S5972	6.6219	1.41E+07
OPA847	S5973-02	11.6984	3.09E+07
OPA847	OSD1-5T	14.0575	1.96E+07
Current	setup	0.0178	8.61E+04

Table 1: Optimal signal to noise and associated signal for a given wavelength and intensity for various photodiode amplifier setups.

Figure 4 shows the same spectrum for two different photodiode setups but otherwise identical conditions. The pre-amp setup has a S5972 photodiode, $R_S = 500\ \Omega$, an LT1226 op-amp in non-inverting configuration and a gain of 101 ($R_1 = 51\ \Omega, R_2 = 5.1\ \text{k}\Omega$). The transimpedance setup has a S5973-02 photodiode reverse biased with -5 V, an OPA847 op-amp, $R_F = 70\ \text{k}\Omega$, $R_G = 0\ \Omega$(no resistor - wire to ground), and no feedback capacitors (the parasitic capacitance of the surface mount components is adequate). It can be seen that the transimpedance setup has signal which is approximately ten times bigger and much better signal to noise.



(a) LT1226 & S5972



(b) OPA847 & S5973-02

Figure 4: Two different fast photodiode setups looking at sub-Doppler frequency modulation spectroscopy of the $5s^2\ {}^1S_0 \rightarrow 5s5p\ {}^1P_1$ transition (461 nm) in atomic strontium. (a) is in pre-amp setup with an LT1226 amplifier and a S5972 (red-sensitive) photodiode. (b) is in transimpedance setup with an OPA847 amplifier and a S5973-02 (blue-sensitive) photodiode.