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Design Considerations for a Transimpedance Amplifier

Application Note AN-1803

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It's challenging to design a good current-to-voltage (transimpedance) converter using a Voltage-Feedback Amplifier (VFA). By definition, a photodiode produces either a current or voltage output from exposure to light. The Transimpedance Amplifier (TIA) is utilized to convert this low-level current to a usable voltage signal and the TIA often needs to be compensated for proper operation. This article explores a simple TIA design using a 345 MHz rail-to-rail output VFA, such as National's LMH6611. The main goal of this article is to offer necessary information for TIA design, discuss TIA compensation and performance results and analyze the noise at the output of the TIA.

A voltage feedback amplifier modeled as a TIA with photodiode and the internal op amp capacitances is illustrated in ***Figure 1***.

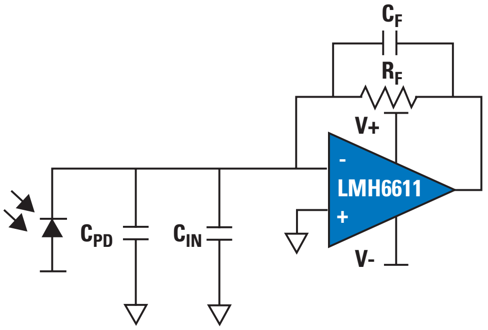

Figure 1. Photodiode Modeled with Capacitive Elements

The LMH6611 allows circuit operation of a low light intensity due to its low-input bias current by using larger values of gain (R_F). The total capacitance (C_T) on the inverting terminal of the op amp includes the photodiode capacitance (C_{PD}) and the input capacitance (C_{IN}). The C_T plays an important role in the stability of the circuit. The Noise Gain (NG) of this circuit determines the stability, and is defined by:

$$NG = \frac{1 + sR_F(C_T + C_F)}{1 + sC_FR_F} \qquad \textit{Equation 1}$$

Where $$f_Z \cong \frac{1}{2\pi R_F C_T} \qquad \textit{Equation 2}$$

Figure 2 shows the bode plot of the noise gain intersecting the op amp open-loop gain (A_{OL}). With larger values of gain (R_F), C_T and R_F create a zero in the transfer function. At higher frequencies, transimpedance amplifiers could become inherently unstable as there will be excess phase shift around the loop.

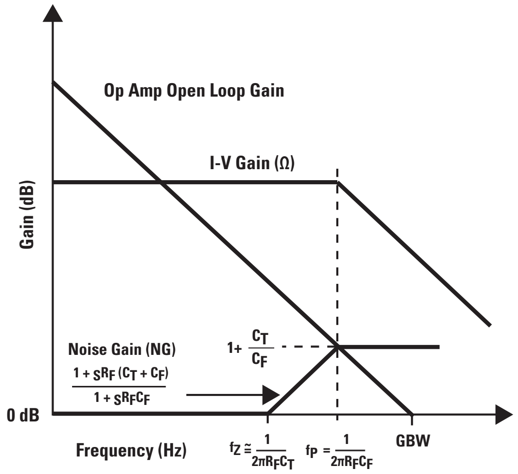

Figure 2. Bode Plot of Noise Gain Intersecting with Op Amp Open-Loop Gain

In order to maintain the stability, a feedback capacitor (C_F) across R_F is placed to create a pole at f_P in the noise gain function. The noise gain slope will be flattened by choosing an appropriate value of C_F for the optimum performance, such that noise gain is equal to the open loop gain of the op amp at f_P. This "flattening" of the noise gain slope beyond the point of intercept of A_{OL} and noise gain will result in a Phase Margin (PM) of 45°. Because at the point of intercept, the noise gain pole at f_P will have a 45° phase lead contribution that gives PM of 45° (assuming f_P and f_Z are at least a decade apart).

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Equations 3 and *4* theoretically calculate the optimum value of C_F and the expected -3 dB bandwidth:

$$C_F = \sqrt{\frac{C_T}{2\pi R_F(GBW)}} \qquad \textit{Equation 3}$$

$$f_{-3dB} = \sqrt{\frac{GBW}{2\pi C_T R_F}} \qquad \textit{Equation 4}$$

Equation 4 indicates that the -3 dB bandwidth of the TIA is inversely proportional to the feedback resistor. Therefore, if the bandwidth is important, then the best approach would be to have a moderate transimpedance gain stage followed by a broadband voltage gain stage.

Table 1 shows the measurement results of the LMH6611 with different photodiodes having various capacitances (C_{PD}) at a transimpedance gain (R_F) of 1 kΩ. The C_F and f_{-3dB} values are calculated from the *Equations 3* and *4* respectively.

Table 1. TIA (Figure 1) Compensation and Performance Results

C_{PD} (pf)	C_T (pf)	C_F CAL (pf)	C_F USED (pf)	$f_{-3\,dB}$ CAL (MHz)	$f_{-3\,dB}$ Meas (MHz)	Peaking (dB)
22	24	5.42	5.6	29.3	27.1	0.5
47	49	7.75	8	20.5	21	0.5
100	102	11.15	12	14.2	15.2	0.5
222	224	20.39	18	9.6	10.7	0.5
330	332	20.2	22	7.9	9	0.8

Note:
Vs= +/-2.5V
GBW = 130 MHz
$C_T = C_{PD} + C_{IN}$
C_{IN} = 2 pf

Figure 3 shows the frequency response for the various photodiodes used in *Table 1*. The signal-to-noise ratio is improved when all the required gain is placed in the TIA stage, because the noise spectral density produced by R_F increases with the square-root of R_F and the signal increases linearly.

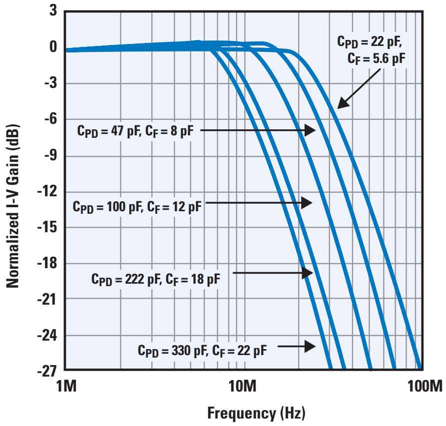

Figure 3. Frequency Response of the LMH6611 for the Various Photodiodes

It is essential to take into account various noise sources. Op amp noise voltage, feedback resistor thermal noise, input noise current, and photodiode noise current do not all operate over the same frequency range while analyzing the noise at the output of the TIA. The op amp noise voltage will be gained up in the region between the noise gain's zero and its pole. The higher the values of R_F and C_T, the sooner the noise gain peaking starts, and therefore its contribution to the total output noise will be larger. An equivalent total-noise voltage is computed by taking the square root of the sum of squared contributing noise voltages at the output of TIA.

To summarize, the total capacitance (C_T) plays an important role in the stability of the TIA and hence it is advantageous to minimize C_T by proper op amp choice, or by applying a reverse bias across the diode at the expense of excess current and noise. This article has also shown that various photodiodes and the compensation method used in the lab confirm a good match between the theory and the bench measurements.

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