Application Report
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Transimpedance Amplifiers (TIA): Choosing the Best Amplifier for the Job

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ABSTRACT

This application note is intended as a guide for the designer looking to amplify the small signal from a photodiode or avalanche diode so that it would be large enough for further processing (e.g. data acquisition) or to trigger some other event in a system. The challenge in doing so, as always, is to not degrade the signal such that it becomes indistinguishable from random noise and to maintain enough signal bandwidth so that "information" is preserved. We will present some ideas on this and develop analysis and optimization techniques, as well as list the devices with the most desirable specifications for such applications.

Explore TI transconductance amplifiers

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1 General Considerations

As it turns out, selecting the best operational amplifier to interface to the photodiode is a juggling act between many parameters, some significant while others less so; for now, suffice to say that the lowest noise voltage device is *not always* the winner. We will discuss the tradeoffs further in this document.

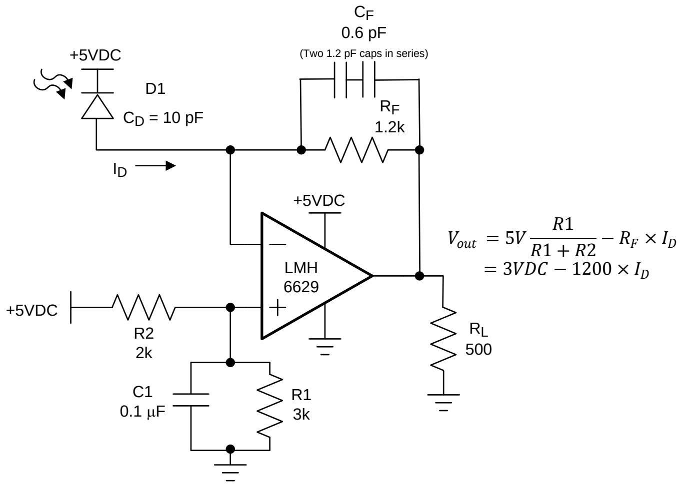

Figure 1. Basic TIA Configuration Using and Ultra-Low Noise Device (LMH6629)

Often times, the transducer (Photodiode) is chosen based on its form factor or electrical characteristics and the following need to be determined:

(a) How much gain is needed?

(b) What bandwidth has to be achieved?

(c) What is the highest noise than can be tolerated?

In most cases, since the photodiode signal is usually very small, the 1st TIA stage is followed by subsequent gain stage(s) to optimize the balance between noise and bandwidth. Photodiode manufacturers specify how much current can be generated for a certain incident light power. A large area photodiode produces more current in response to incident light, at the expense of higher capacitance (and hence lower speed).

So, knowing the final voltage level desired, based on the specifics of what needs to be driven (e.g. input of ADC, logic gate, etc.), the “total” signal path gain can be nailed down. Set the 1st Transimpedance stage gain too high, and you will limit the attainable bandwidth for the signal spectrum at hand. On the other hand, not enough gain degrades SNR and leaves you with too much gain to make up for and unnecessary cost, complexity, and possible signal degradation. Inherent in the question of the what gain to run the 1st stage, is the second order effect of the photodiode capacitance causing excessive noise gain increase at the higher frequencies (more on that later).

The equations in Figure 2 define the value of the compensation capacitor (C_F) as a function of the Operational Amplifier Gain Bandwidth Product (GBWP), Transimpedance gain (R_F), and the total input capacitance (C_{IN}) where:

$$C_{IN} = C_D + C_{CM} + C_{DIFF} \tag{1}$$

where:

C_D : Photodiode capacitance
C_{CM} : Amplifier common mode capacitance (each input to ground)
C_{DIFF} : Amplifier differential mode capacitance (across the inputs)

Optimum CF Value:

$$C_F = \sqrt{\frac{C_{IN}}{2\pi(GBWP)R_F}}$$

Resulting -3dB Bandwidth:

$$f_{-3\,dB} \cong \sqrt{\frac{GBWP}{2\pi R_F C_{IN}}}$$

Figure 2. TIA Compensation Capacitor (C_F) and Subsequent Bandwidth (f_{-3dB})

The attainable -3dB bandwidth (f_{-3dB}) can also be inferred from Figure 2.

2 Equivalent Input Noise Source Modeling

The highest noise that can be tolerated should be at least a few dB lower than the smallest signal present. It is a common technique to utilize noise analysis, using hand calculation or alternatively a simulation tool such as TINA-TI, on the entire signal path in order to make sure the noise level is below this limit. Often times, this is done with “input referred noise” modeled as a noise source next to the input such that it is possible to directly compare the signal and the noise level with each other. Refer to Figure 3 for the depiction of this input referred source “i_{ni}”.

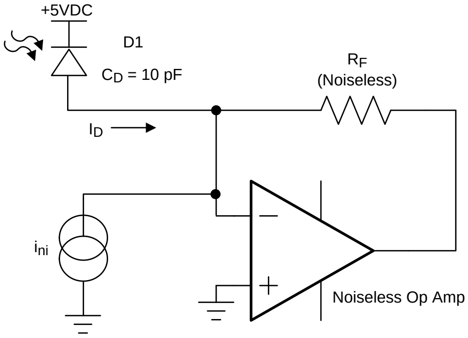

Figure 3. Transimpedance Amplifier Equivalent Input Source (i_{ni}) Model

Referring all noise sources to the input allows immediate SNR evaluation and highlights the “dominant noise” source, which can be an effective tool in any attempt at improving SNR by tackling the most offensive noise source(s).

The expression for i_{ni} is derived within the “*Transimpedance Considerations for High-Speed Amplifiers*” (shown as “i_{EQ}”) and copied below for reference:

$$i_{ni} = \sqrt{{i_n}^2 + \left(\frac{e_n}{R_F}\right)^2 + \frac{4kT}{R_F} + \frac{(e_n 2\pi f_{-3dB} C_{IN})^2}{3}} \quad (2)$$

Where:

- i_n = inverting input spot current noise
- 4kT = 16.4 × 10^{-21}J at room temperature
- R_F = feedback resistor
- e_n = non-inverting input spot voltage noise
- C_{IN} = Total inverting input total capacitance. See Equation 1
- f_{-3dB} = noise integration frequency limit

The contributing terms to input referred noise current (i_{ni}) in Equation 2 are:

a) Noise Current Term:

$$i_n \quad (3)$$

b) Noise Voltage Term:

$$e_n / R_F \quad (4)$$

c) Thermal Noise Term:

$$\sqrt{\frac{4kT}{R_F}} \quad (5)$$

where 4kT= 16.4E^{-21} J at room temperature

d) Input Capacitance Term:

$$\frac{e_n 2\pi f_{-3dB} C_{IN}}{\sqrt{3}} \tag{6}$$

While most of the terms shown may be self-explanatory, the last term needs to be described. This term is the result of the noise increase caused by the presence of the total inverting input capacitance (C_{IN}), which has the net effect of increasing Noise Gain beyond a certain frequency set by R_F and C_{IN}.

The overall SNR can be optimized by the proper choice of operational amplifier, selected gain, and the total signal path gain. With several cascaded stages, it is desirable to take the highest gain at the earliest stage and to minimize its noise contribution since it has the highest impact on SNR. So, for the 1st stage, choose the best operational amplifier (by using the analysis method developed here) while operating at the highest Transimpedance gain possible which still allows the entire spectrum of interest to pass.

3 Optimizing the Device Choice and Operation

For a given operational amplifier GBWP, use the expression in Figure 2 to pick the highest gain (R_F) that achieves the required bandwidth. If this R_F value causes excessive swing at maximum signal, set R_F to what the maximum signal and voltage swing dictates. A spreadsheet is a good tool to use so that you can evaluate many possible device options side-by-side, given their datasheet specifications and application operating conditions. Next, use the i_{ni} expression in Equation 2 to compute the equivalent input referred noise current and determine if the resulting SNR is adequate for the application at hand. To improve SNR, select a different operational amplifier to try and maximize SNR as much as possible. The individual noise sources in (Equation 3 through Equation 6) can point out which noise source is dominant and should therefore be targeted for reduction to have the maximum impact on SNR.

Let’s take an example photodiode and try to find the best amplifier to be used with it while considering all input referred noise sources described earlier:

Example:

- Total input capacitance C_{IN}: 10pF. Note: Device input capacitance not considered (assumed $C_{IN} = C_D$)
- Photodiode signal range: 10nA (Min) to 1uA (Max)
- Required Bandwidth: 80MHz
- Required swing with minimum signal: 1mV

Following the procedure above, and comparing some possible device candidates for the 1st stage amplification, here is what you get:

Table 1. Different Amplifier Candidates Optimized Setting Compared Side-by-Side

Device (1)	GBWP (MHz)(2)	i_n (pA / RtHz)(2)	e_n (nV / RtHz)(2)	R_F (Ohm) (3)	Noise Current Term (pA / RtHz) (4)	Noise Voltage Term (pA / RtHz) (4)	Thermal Noise Term (pA / RtHz) (4)	Input Capacitance Term (pA / RtHz) (4)	SNR (dB)(5)	Post Amp Gain (dB)(6)
THS4631	325	0.002	7	810	0.002	8.7	4.5	20.3(7)	53	42
LMH6629	4,000	2.6	0.69	10k	2.6(7)	0.07	1.3	2(7)	69	20
OPA657	1,600	0.0013	4.8	3.9k	0.0013	1	2	14(7)	57	28

(1) Device input capacitance not considered (assumed $C_{IN} = C_D$)
(2) Datasheet parameter
(3) Selected to meet bandwidth required using Figure 2
(4) Computed using Equation 2
(5) SNR computed as ratio of minimum signal (10nA) to input referred spot noise i_{ni} [= 20 * log(10nA / i_{ni})]
(6) For 1mV final signal with minimum signal
(7) Dominant term

Table 1 results show that the LMH6629 delivers the highest SNR for this application by virtue of its ultra-low input noise voltage (e_n) which is low enough to be a non-factor and also results in a minimal "input capacitance term" as well. In the end, which amplifier gives the best SNR is determined by the specifics of the application or operating conditions and the determining factor depends which of the noise terms dominates. Notice that one must weigh the benefit of the highest SNR against cost, and also the additional post amp gain needed. The small R_F value for THS4631, and the subsequent large post amp gain it needs, might prohibit this device's application in this particular example. A very important thing to note is that the FET input devices (e.g. THS4631, OPA657, etc.) not only have an inherent noise current advantage over BJT input devices (e.g. LMH6629, etc.), but they also reduce the output offset error that arises from their near zero input bias current working against the feedback resistor R_F. If the operating conditions of this example were different, one might very well end up with a situation where low noise current sets the attainable SNR and thus it would be more appropriate to select a FET input device instead.

4 Post Amplification Effect on SNR

To demonstrate how SNR is affected when the 1st TIA stage is followed by additional non-ideal (noisy) amplifiers to increase signal amplitude to what is needed, let's consider an example shown in Figure 4. In this example, the LMH6629 1st stage from Table 1 is chosen along with a cascade of 6dB voltage gain stages having a NF of 10dB each as post amp. To get 20dB total post amp voltage gain needed, we must use more than 3 cascaded stages. Four cascaded stages are shown in the example below:

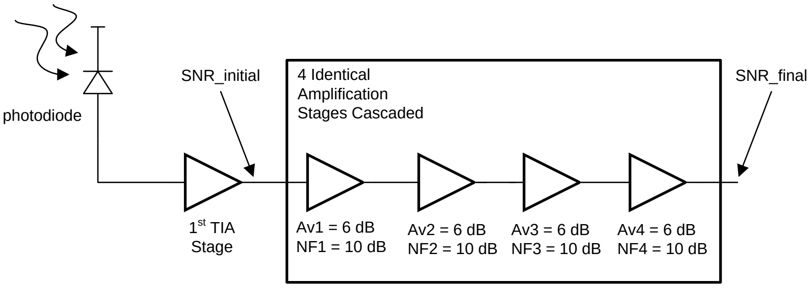

Figure 4. Block Diagram of Entire Signal Path to Compute Overall SNR

The post amp consists of a series of identical cascaded stages of voltage gain (A_v) and Noise figure (NF) each.

Here is the overall Noise Factor (F) expression (known as "Friis Formula") at the post amp output using Power Gain (G_n) and Noise Factor (F_n) of the n stages:

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \ldots + \frac{F_n - 1}{G_1 G_2 G_3 \ldots G_{n-1}} \tag{7}$$

Knowing the entire signal path Noise Figure (NF= 10*log(F)), one can compute the resulting SNR_final with SNR_initial known (69dB in this case from the Table 1 entry for the LMH6629):

$$\text{SNR\_final} = \text{SNR\_initial} - \text{NF} \tag{8}$$

Let's compute G and F from A_v and NF given:

$$G_1 = G_2 = G_3 = G_4 = [10\text{\^{}}(A_v / 20)\,]^2 = [10\text{\^{}}(6 / 20)\,]^2 = (2)^2 = 4\ (V^2/V^2) \tag{9}$$

$$F_1 = F_2 = F_3 = F_4 = 10\text{\^{}}(NF / 10) = 10\text{\^{}}(10 / 10) = 10\ (V^2/V^2) \tag{10}$$

From Equation 7:

$$F = 10 + (10-1) / 4 + (10-1) / 4^2 + (10-1) / 4^3 = 13 \tag{11}$$

Computing NF from knowing F:

$$NF = 10 * \log (13) = 11.1\text{dB} \tag{12}$$

From Equation 8:

$$\text{SNR\_final} = \text{SNR\_initial} - \text{NF} = 69\text{dB} - 11.1\text{dB} = 57.9\text{dB} \tag{13}$$

5 Summary

This application note developed some insight into the parameters that affect the TIA most in terms of bandwidth and noise and demonstrated with examples how to compute SNR, and optimize it which in turn allows one to find the most suitable amplifier to use for the 1st TIA stage. Furthermore, the impact of additional amplification on overall SNR was analyzed and evaluated numerically such that the user can keep track of the noise in order to successfully specify and build an optimized photodiode amplifier system.

Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (November 2015) to A Revision **Page**

- Added link for Explore TI transconductance amplifiers.. 1

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