

Design Considerations for a Transimpedance Amplifier

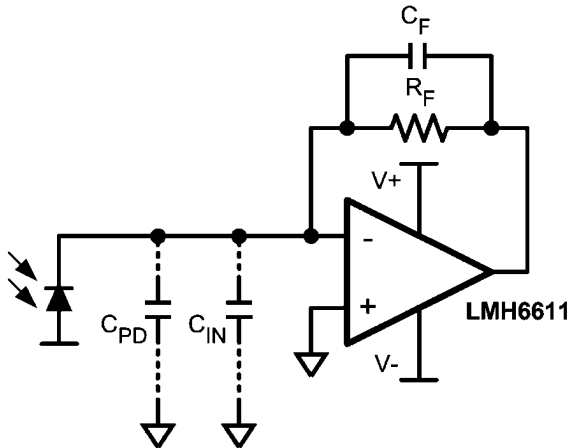
National Semiconductor
Application Note 1803
Maithil Pachchigar
February 28, 2008



Abstract

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*.



30055201

FIGURE 1. Photodiode Modeled with Capacitive Elements

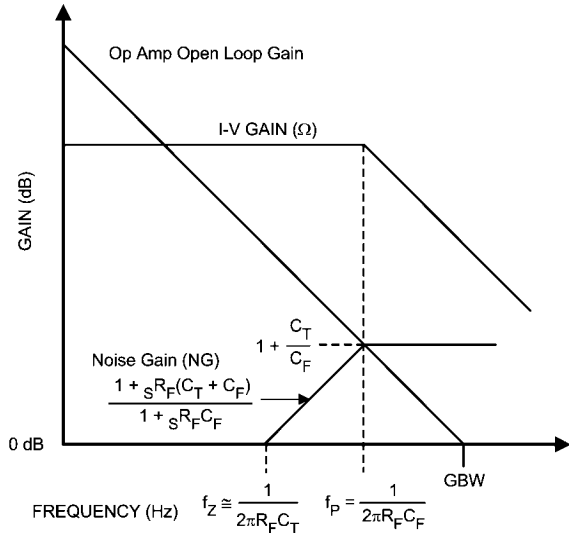
The LMH6611 allows circuit operation of a low light intensity due to its low-input bias current by using larger values of gain (R_F). The total capacitance (C_T) on the inverting terminal of the op amp includes the photodiode capacitance (C_{PD}) and the input capacitance (C_{IN}). The C_T plays an important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

$$NG = \frac{1 + sR_F(C_T + C_F)}{1 + sC_F R_F} \quad (1)$$

$$\text{Where } f_z \cong \frac{1}{2\pi R_F C_T} \quad (2)$$

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 inher-

ently unstable as there will be excess phase shift around the loop.



30055204

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).

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

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

$$f_{-3dB} = \sqrt{\frac{GBW}{2\pi C_T R_F}} \quad (4)$$

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 *Equation 3* and *Equation 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_{-3dB} CAL (MHz) | f_{-3dB} 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:

$V_s = \pm 2.5V$

GBW = 130 MHz

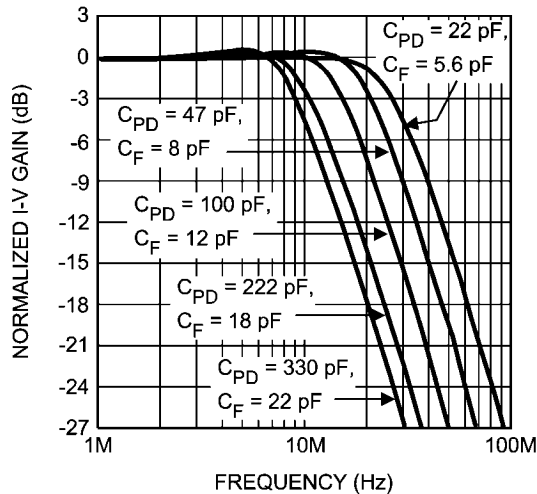
$C_T = C_{PD} + C_{IN}$

$C_{IN} = 2pf$

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.

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.



30055207

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

Notes

For more National Semiconductor product information and proven design tools, visit the following Web sites at:

| Products | | Design Support | |
|--------------------------------|--|-------------------------|--|
| Amplifiers | www.national.com/amplifiers | WEBENCH | www.national.com/webench |
| Audio | www.national.com/audio | Analog University | www.national.com/AU |
| Clock Conditioners | www.national.com/timing | App Notes | www.national.com/appnotes |
| Data Converters | www.national.com/adc | Distributors | www.national.com/contacts |
| Displays | www.national.com/displays | Green Compliance | www.national.com/quality/green |
| Ethernet | www.national.com/ethernet | Packaging | www.national.com/packaging |
| Interface | www.national.com/interface | Quality and Reliability | www.national.com/quality |
| LVDS | www.national.com/lvds | Reference Designs | www.national.com/refdesigns |
| Power Management | www.national.com/power | Feedback | www.national.com/feedback |
| Switching Regulators | www.national.com/switchers | | |
| LDOs | www.national.com/lido | | |
| LED Lighting | www.national.com/led | | |
| PowerWise | www.national.com/powerwise | | |
| Serial Digital Interface (SDI) | www.national.com/sdi | | |
| Temperature Sensors | www.national.com/tempsensors | | |
| Wireless (PLL/VCO) | www.national.com/wireless | | |

THE CONTENTS OF THIS DOCUMENT ARE PROVIDED IN CONNECTION WITH NATIONAL SEMICONDUCTOR CORPORATION ("NATIONAL") PRODUCTS. NATIONAL MAKES NO REPRESENTATIONS OR WARRANTIES WITH RESPECT TO THE ACCURACY OR COMPLETENESS OF THE CONTENTS OF THIS PUBLICATION AND RESERVES THE RIGHT TO MAKE CHANGES TO SPECIFICATIONS AND PRODUCT DESCRIPTIONS AT ANY TIME WITHOUT NOTICE. NO LICENSE, WHETHER EXPRESS, IMPLIED, ARISING BY ESTOPPEL OR OTHERWISE, TO ANY INTELLECTUAL PROPERTY RIGHTS IS GRANTED BY THIS DOCUMENT.

TESTING AND OTHER QUALITY CONTROLS ARE USED TO THE EXTENT NATIONAL DEEMS NECESSARY TO SUPPORT NATIONAL'S PRODUCT WARRANTY. EXCEPT WHERE MANDATED BY GOVERNMENT REQUIREMENTS, TESTING OF ALL PARAMETERS OF EACH PRODUCT IS NOT NECESSARILY PERFORMED. NATIONAL ASSUMES NO LIABILITY FOR APPLICATIONS ASSISTANCE OR BUYER PRODUCT DESIGN. BUYERS ARE RESPONSIBLE FOR THEIR PRODUCTS AND APPLICATIONS USING NATIONAL COMPONENTS. PRIOR TO USING OR DISTRIBUTING ANY PRODUCTS THAT INCLUDE NATIONAL COMPONENTS, BUYERS SHOULD PROVIDE ADEQUATE DESIGN, TESTING AND OPERATING SAFEGUARDS.

EXCEPT AS PROVIDED IN NATIONAL'S TERMS AND CONDITIONS OF SALE FOR SUCH PRODUCTS, NATIONAL ASSUMES NO LIABILITY WHATSOEVER, AND NATIONAL DISCLAIMS ANY EXPRESS OR IMPLIED WARRANTY RELATING TO THE SALE AND/OR USE OF NATIONAL PRODUCTS INCLUDING LIABILITY OR WARRANTIES RELATING TO FITNESS FOR A PARTICULAR PURPOSE, MERCHANTABILITY, OR INFRINGEMENT OF ANY PATENT, COPYRIGHT OR OTHER INTELLECTUAL PROPERTY RIGHT.

LIFE SUPPORT POLICY

NATIONAL'S PRODUCTS ARE NOT AUTHORIZED FOR USE AS CRITICAL COMPONENTS IN LIFE SUPPORT DEVICES OR SYSTEMS WITHOUT THE EXPRESS PRIOR WRITTEN APPROVAL OF THE CHIEF EXECUTIVE OFFICER AND GENERAL COUNSEL OF NATIONAL SEMICONDUCTOR CORPORATION. As used herein:

Life support devices or systems are devices which (a) are intended for surgical implant into the body, or (b) support or sustain life and whose failure to perform when properly used in accordance with instructions for use provided in the labeling can be reasonably expected to result in a significant injury to the user. A critical component is any component in a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system or to affect its safety or effectiveness.

National Semiconductor and the National Semiconductor logo are registered trademarks of National Semiconductor Corporation. All other brand or product names may be trademarks or registered trademarks of their respective holders.

Copyright© 2008 National Semiconductor Corporation

For the most current product information visit us at www.national.com



**National Semiconductor
Americas Technical
Support Center**
Email:
new.feedback@nsc.com
Tel: 1-800-272-9959

**National Semiconductor Europe
Technical Support Center**
Email: europe.support@nsc.com
German Tel: +49 (0) 180 5010 771
English Tel: +44 (0) 870 850 4288

**National Semiconductor Asia
Pacific Technical Support Center**
Email: ap.support@nsc.com

**National Semiconductor Japan
Technical Support Center**
Email: jpn.feedback@nsc.com