Technical Article

What You Need to Know about Transimpedance Amplifiers – Part 1

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Transimpedance amplifiers (TIAs) act as front-end amplifiers for optical sensors such as photodiodes, converting the sensor's output current to a voltage. TIAs are conceptually simple: a feedback resistor (R_F) across an operational amplifier (op amp) converts the current (I) to a voltage (V_{OUT}) using Ohm's law, $V_{OUT} = I \times R_F$. In this series of blog posts, I will show you how to compensate a TIA and optimize its noise performance. For a quantitative analysis of a TIA's key parameters, such as bandwidth, stability and noise, please see the application note, ""Transimpedance Considerations for High-Speed Amplifiers."

In a physical circuit, parasitic capacitances interact with the feedback resistor to create unwanted poles and zeros in the amplifier's loop-gain response. The most common sources of parasitic input and feedback capacitances are the photodiode capacitance (C_D), the op amp's common-mode (C_{CM}) and differential input capacitance (C_{DIFF}), and the circuit-board capacitance (C_{PCB}). The feedback resistor, R_F is not ideal and has a parasitic shunt capacitance that may be as large as 0.2pF. In high-speed TIA applications, these parasitic capacitances interact with each other and R_F to create a response that is not ideal. In this blog post, I will illustrate how to compensate a TIA.

Figure 1 shows a complete TIA circuit with parasitic-input and feedback-capacitance sources.

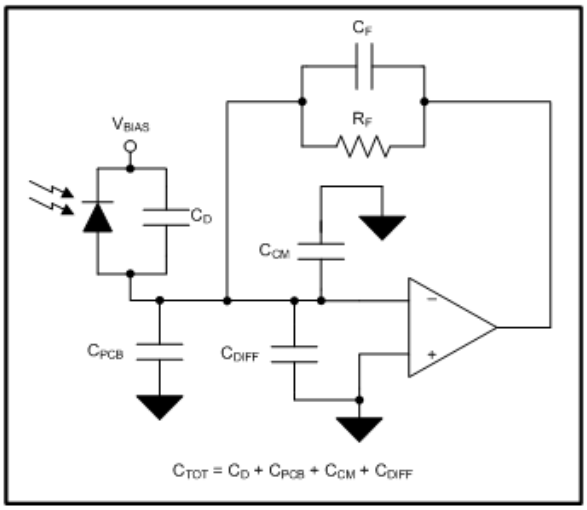

Figure 1. TIA Circuit Including Parasitic Capacitances

Three key factors determine the bandwidth of a TIA:

- Total input capacitance (C_{TOT}).
- Desired transimpedance gain set by R_F.
- The op amp's gain-bandwidth product (GBP): the higher the gain bandwidth, the higher the resulting closed-loop transimpedance bandwidth.

These three factors are interrelated: for a particular op amp, targeting the gain will set the maximum bandwidth; conversely, targeting the bandwidth will set the maximum gain.

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Single-pole Amplifier with No Parasitics

The first step of this analysis assumes an op amp with a single pole in the A_{OL} response and the specifications shown in Table 1.

Table 1. TIA Specifications

Op amp open-loop gain at DC, $A_{OL}(DC)$	120dB
Op amp GBP	1GHz
Feedback resistor R_F	159.15kΩ

An amplifier's closed-loop stability is related to its phase margin, Φ_M, which is determined by the loop-gain response defined as $A_{OL} \times \beta$, where β is the inverse of the noise gain. Figure 2 and Figure 3 show the TINA-TI™ circuits to determine the op amp's A_{OL} and noise gain, respectively. Figure 2 configures the device under test (DUT) in an open-loop configuration to derive its A_{OL}. Figure 3 uses an ideal op amp with the desired R_F, C_F and C_{TOT} around it to extract the noise gain, 1/β. Figure 3 excludes parasitic elements C_F and C_{TOT} – for now.

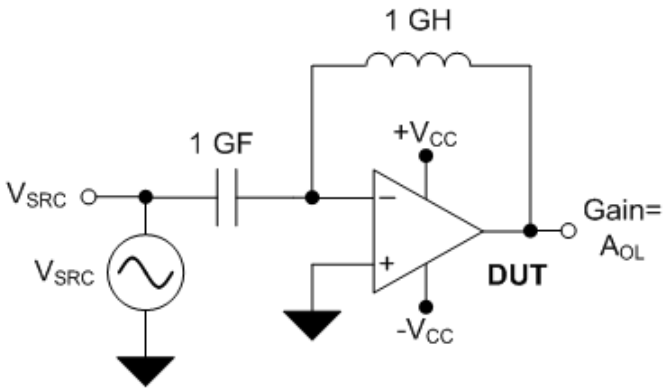

Figure 2. DUT Configuration to Determine a_{OL}

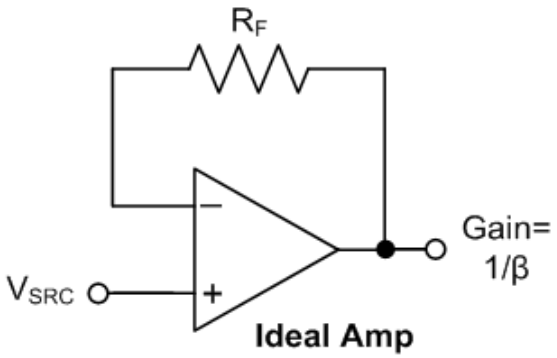

Figure 3. Ideal Amplifier Configuration to Determine Noise Gain (1/B)

Figure 4 shows the simulated magnitude and phase of loop gain, A_{OL} and 1/β. Since 1/β is purely resistive, its response is flat across frequency. The loop gain is $A_{OL}(dB) + \beta(dB) = A_{OL}(dB)$, since the amplifier is in a unity-gain configuration as shown in Figure 3. The A_{OL} and loop-gain curves thus lie on top of each other, as shown in Figure 4. Since this is a single-pole system, the total phase shift due to the A_{OL} pole at f_d is 90°. The resulting Φ_M is thus 180°-90° = 90°, and the TIA is unconditionally stable.

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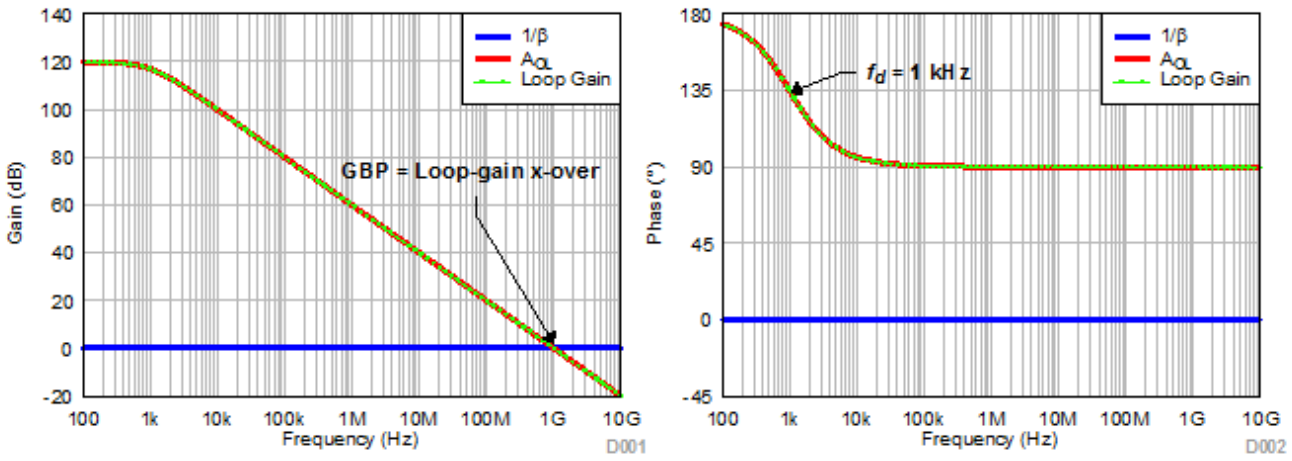

Figure 4. Simulated Loop Gain, a_{OL} And 1/B for an Ideal Case

Effect of Input Capacitance (C_{TOT})

Let's analyze the effect of capacitance at the amplifier's inputs on loop-gain response. I'll assume a total effective input capacitance, C_{TOT}, of 10pF. The combination of C_{TOT} and R_F will create a zero in the 1/β curve at a frequency of $f_z = 1/(2\pi R_F C_{TOT})$ = 100kHz. Figure 5 and Figure 6 show the circuit and resulting frequency response. The A_{OL} and 1/β curves intersect at 10MHz – the geometric mean of f_z (100kHz) and the GBP (1GHz). A zero in the 1/β curve becomes a pole in the β curve. The resulting loop gain will have a two-pole response, as shown in Figure 6.

The zero causes the magnitude of 1/β to increase at 20dB/decade and intersect the A_{OL} curve at a 40dB/decade rate of closure (ROC), resulting in potential instability. The dominant A_{OL} pole at 1kHz results in a 90° phase shift in the loop gain. The zero frequency, f_z, at 100kHz adds another 90° phase shift. Its effect is complete by 1MHz. Since the loop-gain crossover occurs at only 10MHz, the total phase shift from f_d and f_z will be 180°, resulting in Φ_M = 0° and indicating that the TIA circuit is unstable.

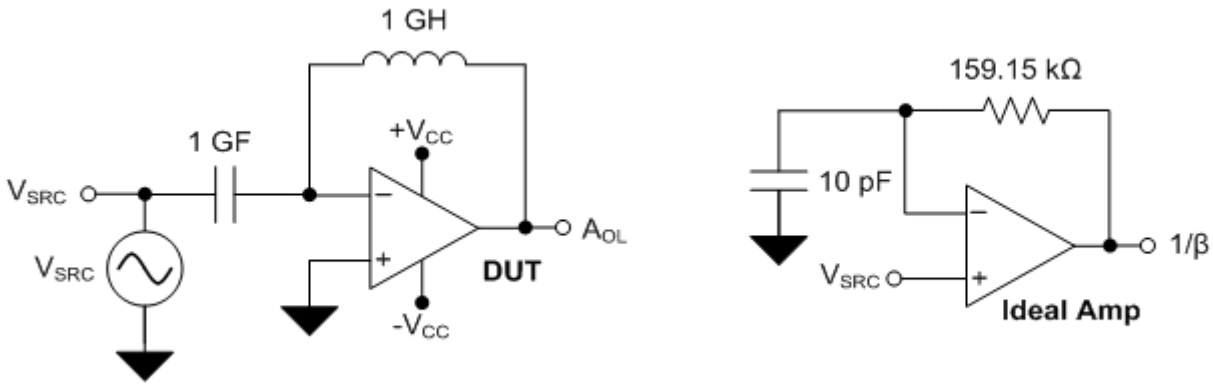

Figure 5. Simulation Circuit Including a 10pF Input Capacitor

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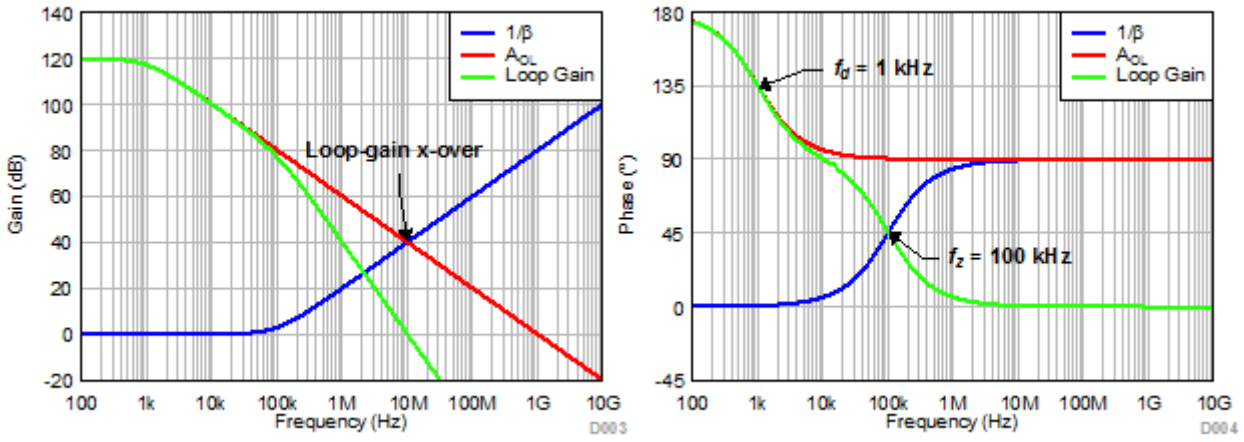

Figure 6. Simulated Loop Gain, a_{OL} And (1/B) When Including the Effects of Input Capacitance

Effect of Feedback Capacitance (C_F)

To recover the phase loss due to f_z, insert a pole, f_{p1}, into the 1/β response by adding capacitor C_F in parallel with R_F. f_{p1} is located at $1/(2\pi R_F C_F)$. To get a maximally flat, closed-loop Butterworth response (Φ_M = 64°), calculate C_F using Equation Figure 7:

$$C_F = \frac{1}{2\pi(0.707)R_F f_{-3dB}} \qquad (1)$$

Figure 7. (1)

where f_{-3dB} is the closed-loop bandwidth shown in Equation Figure 8:

$$f_{-3dB} = \sqrt{\frac{GBP}{2\pi R_F C_{TOT}}} \qquad (2)$$

Figure 7. (2)

The calculated C_F = 0.14pF and f_{-3dB} = 10MHz. f_z is located at ≈7MHz. The feedback capacitor includes the parasitic capacitances from the printed circuit board and R_F. In order to minimize C_{PCB}, remove the ground and power planes beneath the feedback trace between the amplifier's inverting input and output pin. Using resistors with small form factors, such as 0201 and 0402 reduces parasitic capacitance caused by the feedback components. Figure 9 and Figure 10 show the circuit and resulting frequency response.

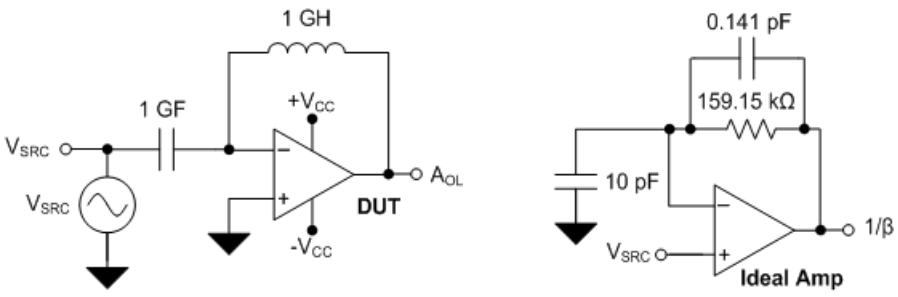

Figure 7. Simulation Circuit, Including a 0.14pF Feedback Capacitor

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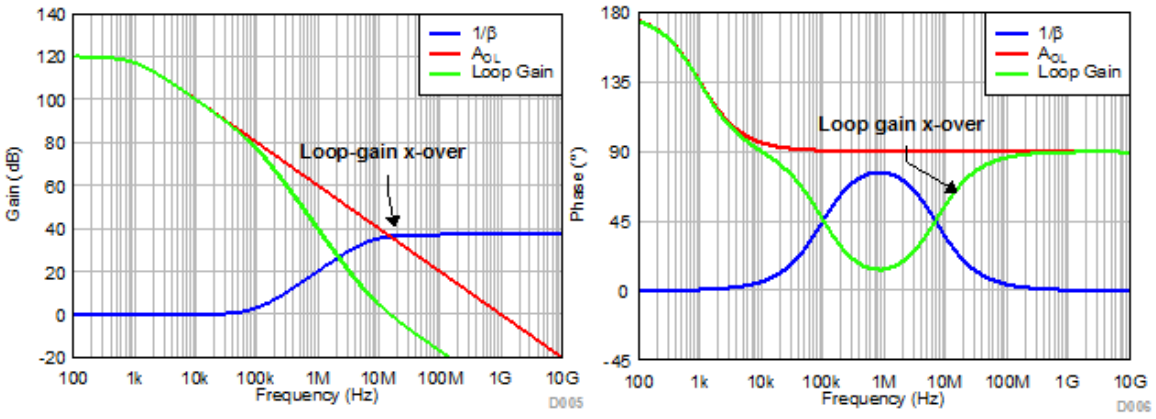

Figure 8. Simulated Loop Gain, a_{OL} And 1/B When Including the Effects of Input and Feedback Capacitance

Using Bode-plot theory, Table 2 summarizes the points of inflection in the loop-gain response.

Table 2. Effect of Poles and Zeros on the Loop-gain Magnitude and Phase

Cause	Effect on magnitude	Effect on phase
A_{OL} dominant pole, f_d = 1kHz	The magnitude decreases at -20dB/dec starting at 1kHz	Starting at 180°, the phase decreases at -45°/dec from 100Hz-10kHz
1/β zero at f_z = 100kHz	Combined with the effect of f_d, the magnitude decreases at -40dB/dec starting at 100kHz	Starting at 90°, the phase decreases at -45°/dec from 10kHz-1MHz
1/β pole at f_{p1} = 7MHz	Combined with the previous two effects, the slope of the loop-gain magnitude reduces from -40dB/dec to -20dB/dec	Starting at 700kHz, the phase increases at 45°/dec and starts to recover the Φ_M. Its effect continues till 70MHz.

The 1/β curve reaches a maximum value of $20\log_{10}(1+\frac{10pF}{0.14pF}) \approx 37dB$. For a Butterworth response, 1/β intersects A_{OL} near its maximum value at a frequency $\frac{GBP}{(C_{TOT}/C_F)} \approx 14MHz$. f_d and f_z create a total phase shift of 180°. The phase reclaimed by f_{p1} is $\tan^{-1}\left(\frac{14MHz}{7MHz}\right) = 63.5°$, which is very close to the simulated 65°.

When designing a TIA, you must know the photodiode's capacitance, as this is usually fixed by the application. Given the photodiode capacitance, the next step is to select the correct amplifier for the application.

Choosing the right amplifier requires an understanding of the relationship between an amplifier's GBP, the desired transimpedance gain and closed-loop bandwidth, and the input and feedback capacitances. You can find an Excel calculator incorporating the equations and theory described in this post here. If you are designing a TIA, be sure to check the calculator out. It will save you a lot of time and manual calculations.

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Additional Resources

- Download the application report, “Transimpedance Considerations for High-Speed Amplifiers,” for a quantitative derivation of Equations Figure 7 and Figure 8 in this post.
- Get online support in the TI E2E™ Community Amplifier forums.
- Browse more than 40 training videos on op-amp topics like noise, bandwidth and stability.
- Learn more about selecting the correct amplifier in the application note, “Transimpedance Amplifiers (TIA): Choosing the Best Amplifier for the Job.”
- Search TI high-speed op amps and find technical resources.

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