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Technical Brief: Overcoming RC Feedback Limitations to Trans-Impedance Amplifier Bandwidth

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In a typical trans-impedance amplifier (TIA) circuit for a photodiode, the main feature that limits the bandwidth is the feedback network. The typical feedback network includes a parallel combination of a resistor and capacitor which gives a -3dB pole frequency given by $1/(2\pi R_f C_f)$. If a high gain and a high bandwidth TIA is required, then often the achievable bandwidth is lower than desired due to the small value needed for the feedback capacitor (C_f, often sub pico-farads).

Figure 1 shows a simple high gain TIA. Barring any miscellaneous currents, the magnitude of the output voltage is simply the photodiode output current times the feedback resistance (R_f).

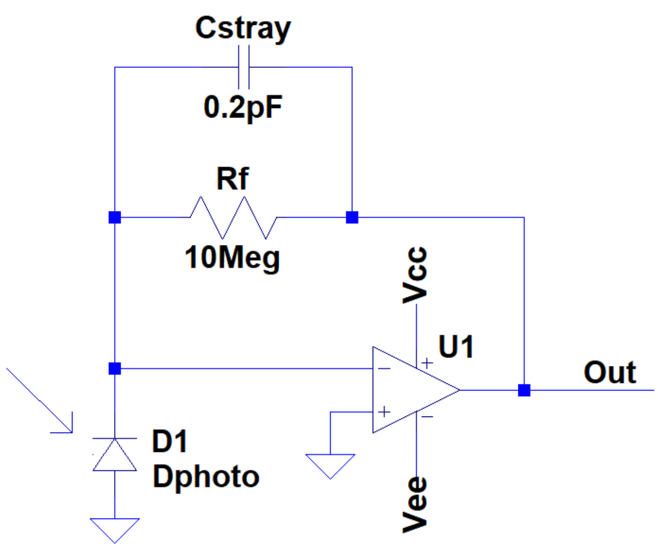

Figure 1: Simple High-Gain TIA (Note that the photodiode inherently has capacitance.)

The issue with this circuit is that the bandwidth is limited by the value of the feedback resistor and its parasitic/stray capacitance (C_{stray}). For example, an 0805 resistor can have 200fF of stray capacitance that can be variable and unreliable for use. A 10MΩ resistor and a 200fF capacitor produces a -3dB corner frequency of approximately 79.6kHz. In this technical brief, we present three circuit techniques to increase the bandwidth: (1) reduce the parasitic capacitor value; (2) reduce the resistor value; and (3) add a pole/zero compensation network.

1. <u>Reduce the Parasitic Capacitor Value</u>: The first approach to increase the bandwidth of a TIA is to use multiple feedback resistors in series. For example, if an 0805 resistor has a parasitic capacitance of approximately 200fF, and if the value of the feedback resistor is 10MΩ, four 2.5MΩ resistors connected in series will yield a 10MΩ feedback resistance (see *Figure 2*). Each resistor will have a similar 200fF stray capacitor and since they are in series with each other, the total equivalent capacitor value across the equivalent 10MΩ resistor is 50fF. This new RC network yields a -3dB corner frequency of approximately 318kHz which is four times greater than the one with a single 10MΩ resistor.

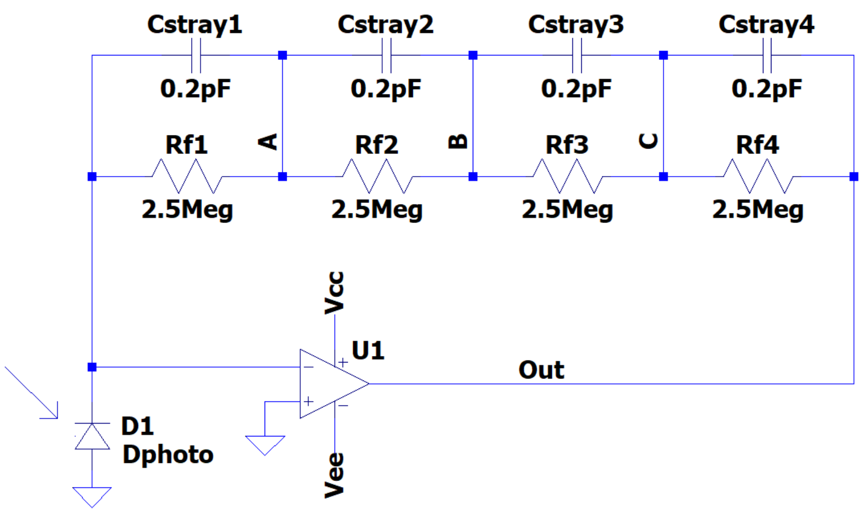

Figure 2: High-Gain TIA with Four Series Resistors

As in life, there are always pros and cons to everything. Here are some of the potential downsides of this technique:

a. Possible Instability with Uncertain Stray Capacitance: Some minimum value of feedback capacitance is generally required for TIA stability. The voltage noise gain of a TIA circuit with feedback capacitance is $(1 + Z_f/Z_{in}) = 1 + s\ R_f\ C_{Pd}/(1 + s\ C_f\ R_f)$ where C_{Pd} is the photodiode capacitance and C_f is the equivalent feedback capacitance.

   In actuality, the value of the stray capacitance is not known. While stray capacitance can be found experimentally, it may vary significantly from board to board even with the same PCB layout. Since relying on stray capacitance in order to control bandwidth and stability isn't always a good idea, an effective external capacitor from the output to inverting input is needed. One might try adding a small capacitor (e.g., 1pF) in parallel with each resistor (adding a total of 1pF/4 = 250fF (in addition to the stray capacitance). However, the 1pF capacitors in this example do not completely swamp out the stray capacitance from each resistor and the capacitor itself, and larger capacitors may limit the bandwidth too much. Careful PCB layout design techniques can help mitigate some of these board-to-board variations. For some layout tips, please see Analog Devices' application note, *Op Amp Combines Femtoamp Bias Current with 4GHz Gain Bandwidth Product, Shines New Light on Photonics Applications*.

b. Larger Loop Area: More board space is required for the extra resistors and capacitors which also creates a larger loop area for potential noise infiltration via magnetic fields. The larger loop area may contribute to circuit instability.

c. Nodal Capacitances: At each junction of the resistors, labeled A, B, and C, there will be a small parasitic capacitance to ground which will make the equivalent impedance of the feedback network unpredictable. Good layout techniques will help mitigate this but it is an important factor to consider. The above app note presents some ideas for this.

2. Reduce the Resistor Value: Another method available to designers is to reduce the value of the feedback resistor by using a resistive-Tee network. The value of the feedback resistor can be reduced by adding

two additional resistors as shown in *Figure 3*. When R_f is reduced and the stray capacitance is the same, then the bandwidth will increase. With the values shown, the new bandwidth is approximately 796kHz or ten times the original value. The two resistors, R1 and R2, create a voltage divider which yields an equivalent value of approximately R_f times (1 + R1/R2), which in *Figure 3* equals 10MΩ. Extensive literature is available online which goes into detail of this circuit's behavior. For example, see the Texas Instruments *Understanding Basic Analog - Ideal Op Amps*.

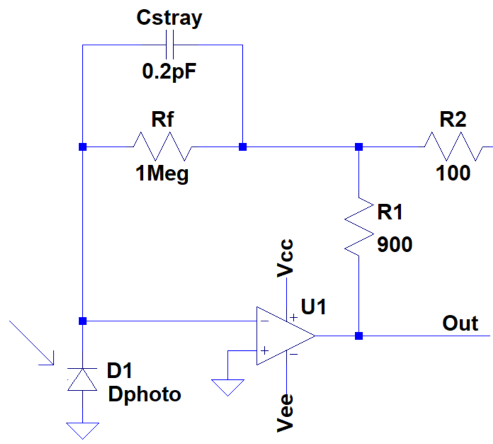

Figure 3: TIA with Resistive Tee-Network ***(Note that D1 can be modeled as a current source with C_{Pd} in parallel)***

A simple way to think of the resistive-Tee network is the following: Imagine that the photodiode is removed and a signal is applied to the non-inverting input as shown in *Figure 4-A*. (This is valid because the inverting input of either the circuit of *Figure 1* or *Figure 4* is at the same potential as the non-inverting input.) Then, the circuit reduces to a simple voltage follower with a closed loop-gain of one. However, by adding a resistive-Tee network, the circuit in *Figure 4-B* has a closed-loop gain of ten (1 + R1/R2).

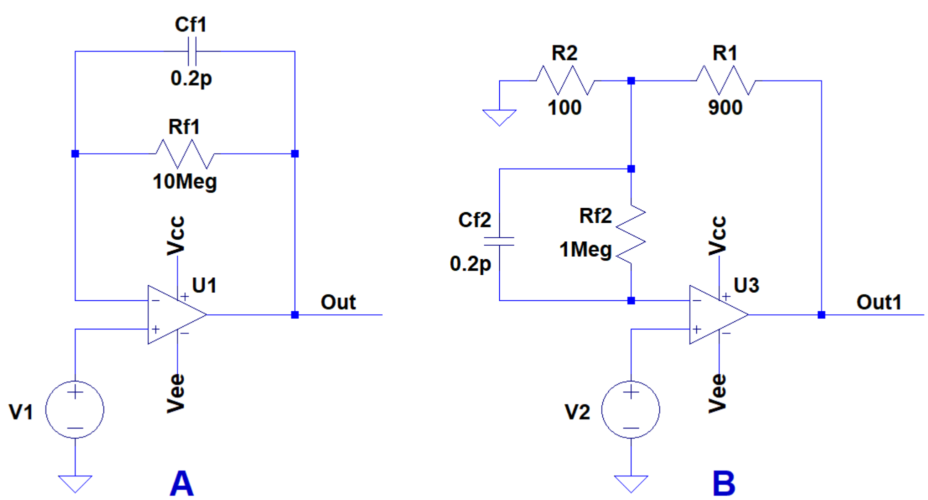

Figure 4: Useful Circuits for Understanding Resistive-Tee Network

Unfortunately, the negative aspects of this method are seldom discussed. The major issue is that it adds more output noise than using a single resistor for R_f by a minimum of $\sqrt{(1 + R1/R2)} \approx 3.16$ in the example of *Figure 3*. (See Bob Pease's article, *What's All this Noise Gain Stuff Anyhow?)*. So, if low noise is required, then using a resistive-Tee may not be the best method. Here are a few more references that discuss the potential downsides to a resistive Tee-Networks:

a. Page 36 of the *ADA4350 Datasheet*: "As compared to a standard TIA design, the T network is noisier because the dominant voltage noise density is amplified by the gain factor 1 + R1/R2."

b. More from Bob Pease: "Meanwhile, try to avoid Tee networks in the feedback network. They often cause poor signal-to-noise ratios…. Yes, a Tee network might help you avoid buying 1,000-MO resistors, but that's only okay when you have proven that the noise is okay (*What's All this Transimpedance Amplifier Stuff, Anyhow?*)

3. Pole/Zero Compensation: See *Figure 5*. This is somewhat similar in appearance to the resistive Tee network, but with the addition of a capacitor, C1. C1 ensures that at low frequencies, the compensation network is not active.

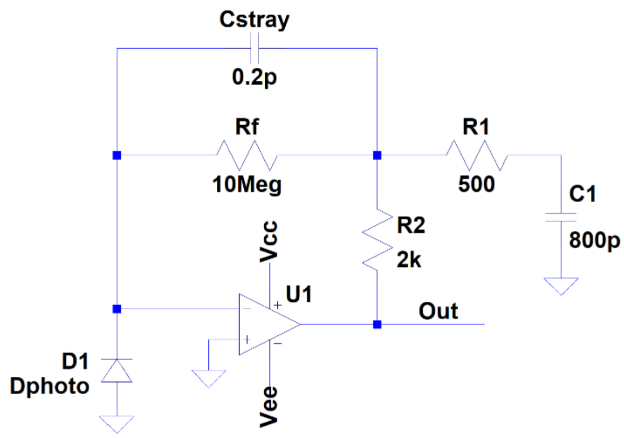

Figure 5: High-Gain TIA with Compensation (Note that D1 can be modeled as a current source with C_{Pd} in parallel)

With this method, bandwidth extension may be controlled by the correct selection of the three new components, R1, R2, and C1. The "trick" here is to make the time constant of the new network close to the feedback network time constant to partly-compensate for the R_fC_f pole. The RC time constant of the feedback network is R_f x C_{stray} which, in *Figure 5*, equals 2μs. The time constant of the extra three components, R1, R2, and C1 is (R1 + R2) x C1, which here also equals 2 μs. The amount of bandwidth extension is approximately 1+ (R2/R1). With the values in *Figure 5*, there is approximately a five-fold bandwidth extension. (See *Figure 6* for a bandwidth comparison of the uncompensated op amp [green] with the compensated op amp [pink].)

Note that in this example, we still have to deal with the poor and uncontrollable value of the stray capacitance. The solution to this is to add an extra capacitor across R_f, then modify the time constant of the compensation circuit. For example, let's add a 2pF capacitor across R_f. This will tend to stabilize the equivalent value for C_f. The new time constant becomes 22us. Then just change the value of C1 to 8.8nF and the compensation network's time constant is also 22us.

What about the noise gain? The op amp noise gain of this circuit is equivalent to the noise gain of the circuit in *Figure 1* except at frequencies above which R1 starts to conduct significant current $1/(2\pi R_1 C_1)$ where the noise gain starts to approach what it is for the resistive Tee. In addition, there is more total noise than that of *Figure 1*, due to the noise increase that increased bandwidth brings.

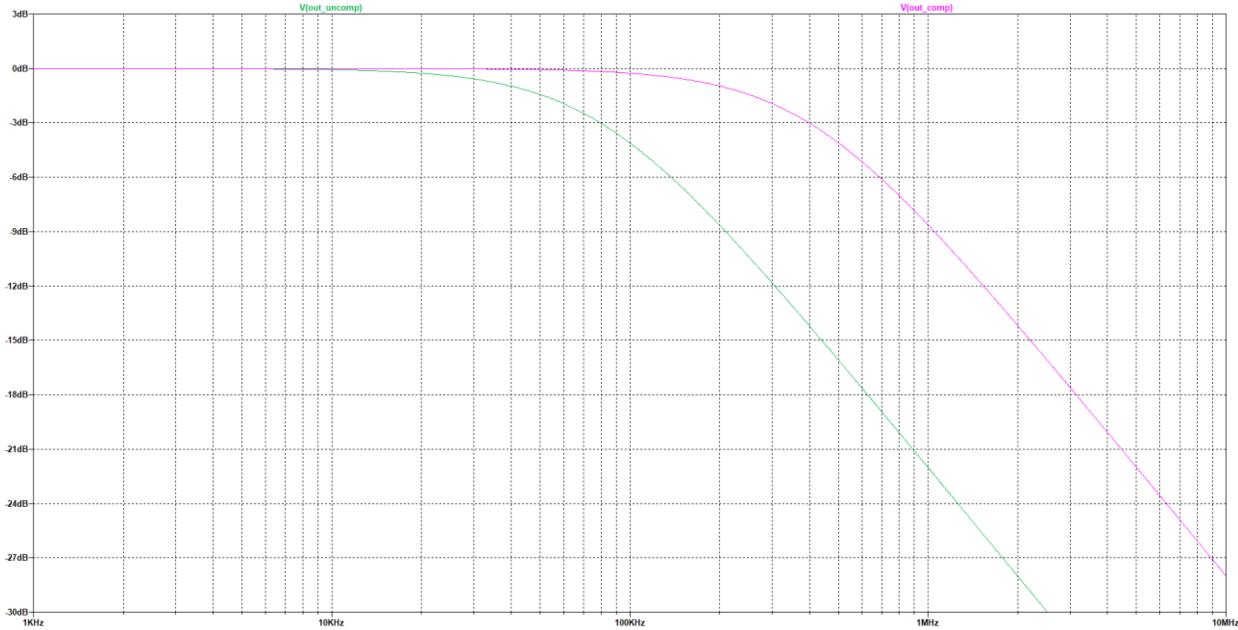

Figure 6: Magnitudes of Uncompensated Op Amp of Figure 1 and Compensated Op Amp of Figure 5

Please remember that as noted in *1.a* above some amount of C_f is needed for stability, so don't completely cancel out C_{stray}! For the circuit values shown in *Figure 5*, with any appreciable C_{Pd}, the circuit may be unstable unless the amount of bandwidth extension is still rolled off at higher frequencies with a useful value of C_f.

For mor information on the pole/zero compensation technique, see page 15 of *A Guide to Using FETs for Sensor Applications*.