Application Report

Build a Programmable Gain Transimpedance Amplifier Using the OPA3S328

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ABSTRACT

The OPA3S328 is a 40-MHz, dual, precision, low input bias current, CMOS operational amplifier (op-amp) with integrated switches optimized for programmable gain transimpedance amplifier applications. The device offers a combination of low input bias current, DC precision performance, low noise, high bandwidth, and integrated analog switches, providing an optimal choice for transimpedance amplifier applications. The OPA3S328 offers a compact solution supporting various transimpedance amplifier circuit blocks, including switched-gain transimpedance amplifiers (TIAs). This document provides a step-by-step example for designing a low noise, high bandwidth, high accuracy programmable gain TIA using the device's integrated switches with Kelvin sense connections.

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1 Introduction

Photodiode sensors produce a current output that changes with incident light, where the typical photocurrent changes orders of magnitude from hundreds of pico-amps to a few milliamps. Transimpedance amplifiers are essential circuits in photodiode acquisition systems to convert photocurrent to voltage that will drive a typical Analog-to-Digital (ADC) converter.

TIAs are required to amplify a photodiode's signal while meeting low-noise, high-resolution, and high-bandwidth constraints. A programmable gain TIA stage allows flexibility to measure the wide range of photodiode current while ensuring the amplifier remains inside its linear range. Programmable gain TIAs are essential in many systems. Applications include photosensor devices such as chemical analysis systems, infrared spectroscopes, data acquisition systems and optical communication applications where the optical power in a fiber can vary widely, and, as a result yield wide current ranges from an optical detector.

The OPA3S328 is a dual precision CMOS operational amplifier (op-amp) with integrated switches optimized for programmable gain transimpedance amplifier applications. The dual op-amp offers low input bias current, DC precision performance, low noise, high bandwidth, providing an optimal choice for transimpedance amplifier applications.

The simplified circuit diagram shown in Figure 1-1 shows a programmable gain TIA circuit implemented with the OPA3S328. The OPA3S328 integrates analog switches useful to select the TIA gains across multiple decades of photodiode current. The second-stage amplifier buffers the programmable gain TIA stage using Kelvin sense connections to eliminate errors due to the switch on-resistance, switch resistance drift, and non-linearity. This document provides a step-by-step example for designing a low noise, high bandwidth, high accuracy programmable TIA to perform optical power measurements using a near infrared (NIR) wavelength photodiode.

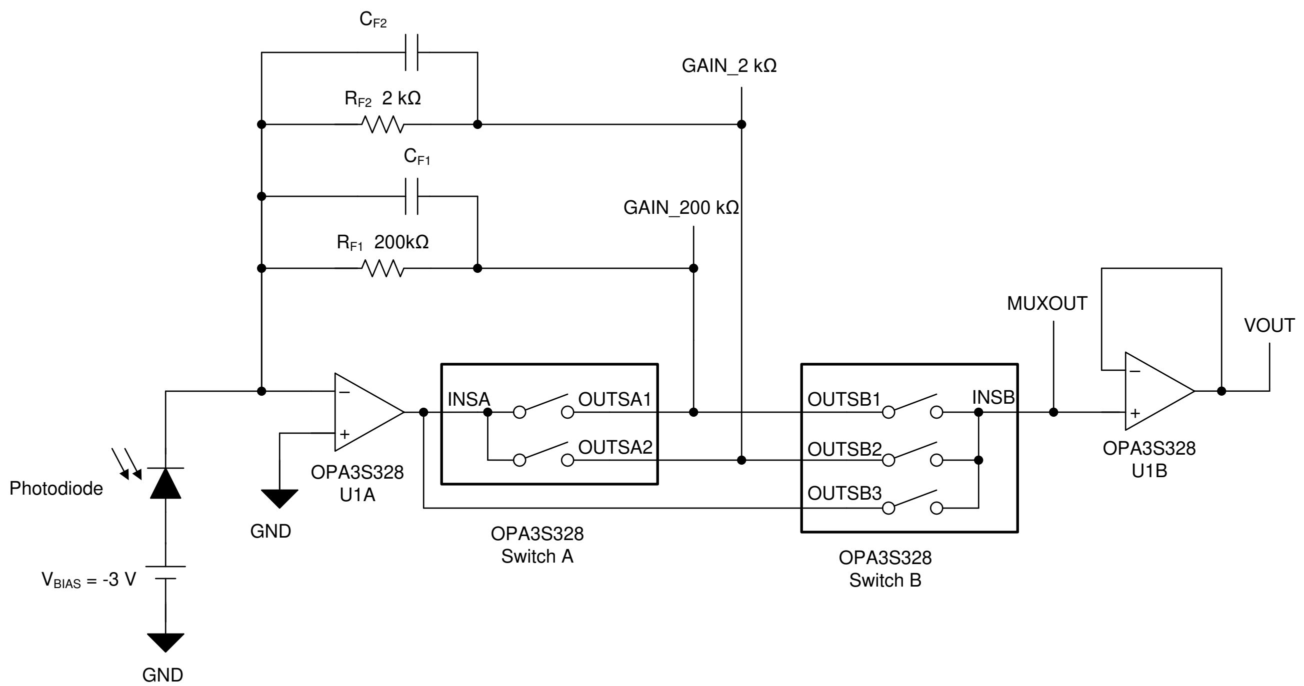

Figure 1-1. Switched Gain Transimpedance Amplifier

2 The Transimpedance Amplifier and Photodiode Sensor

A transimpedance amplifier consists of an op amp and a feedback resistor. The photosensor current to be amplified is applied to the inverting input, causing the output voltage of the amplifier to change, as shown in Figure 2-1:

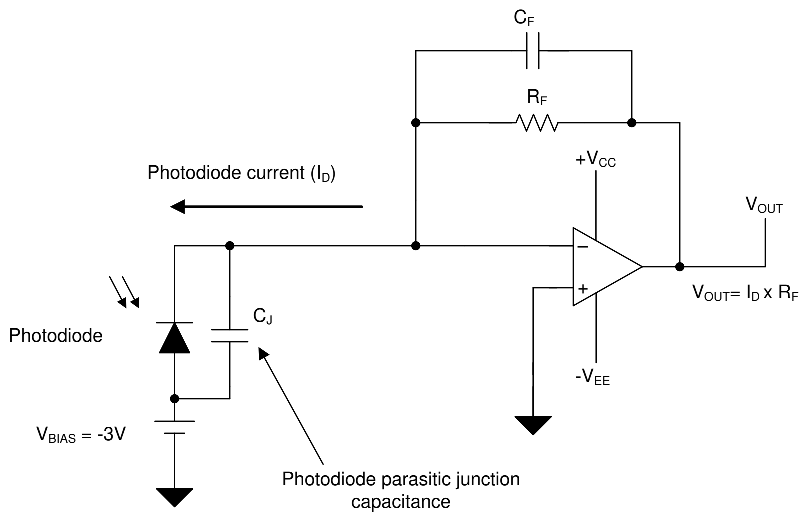

Figure 2-1. Photodiode Transimpedance Amplifier

The feedback resistor (R_F) across the op amp converts the photodiode current (I_D) to a voltage (V_{OUT}) using Ohm's law, as shown in Equation 1.

$$V_{OUT} = I_D \cdot R_F \tag{1}$$

The feedback resistor (R_F) determines the gain of the transimpedance op-amp. For the transimpedance current to voltage conversion to be accurate, the amplifier's input bias current and input offset voltage must be small. The OPA3S328 offers low offset voltage, 25µV (max) and low input bias current, 0.2 pA. The photodiode parasitic junction capacitance plays a significant role in the stability and bandwidth of the TIA circuit, as we will discuss in detail in the following sections. The feedback capacitor (C_F) is required to compensate the circuit for stability.

This example shows a large area near-infrared (NIR) wavelength Indium Gallium Arsenide (InGaAs) photodiode for the design. In this specific application, the photodiode operates on the photoconductive mode, where exposure to light causes a reverse current through the detector. A reverse bias is applied to the photosensor to reduce the junction capacitance. The reverse bias voltage (V_R) dramatically improves the speed of response and linearity of the photodiode. The reverse bias increases the depletion region width and consequently decreases the junction capacitance. The dark current of this photosensor is about 50nA in this mode of operation. Table 2-1 shows the photodiode parameters.

Table 2-1. NIR (InGaAs) Photodiode Sensor Specifications

Parameter	Symbol	Value	Unit
Reverse Voltage	V_R	-3	V
Junction Capacitance (V_R=-3V)	C_J	100	pF
Reverse Current Range	I_D	0-2000	µA
Dark Current	I_{dark}	50	nA

There are different ways to bias the photodiode in the TIA circuit. A common method used on unipolar supply applications is to bias the op-amp non-inverting input (+IN) with a positive dc voltage. The positive voltage at the non-inverting input will reverse bias the photodiode while allowing the amplifier output to reach true zero when the photodiode is unexposed to light and respond without the added delay that results from coming out of the negative rail. Figure 2-2 shows a typical way to reverse bias the photodiode, when the reverse voltage required is relatively small.

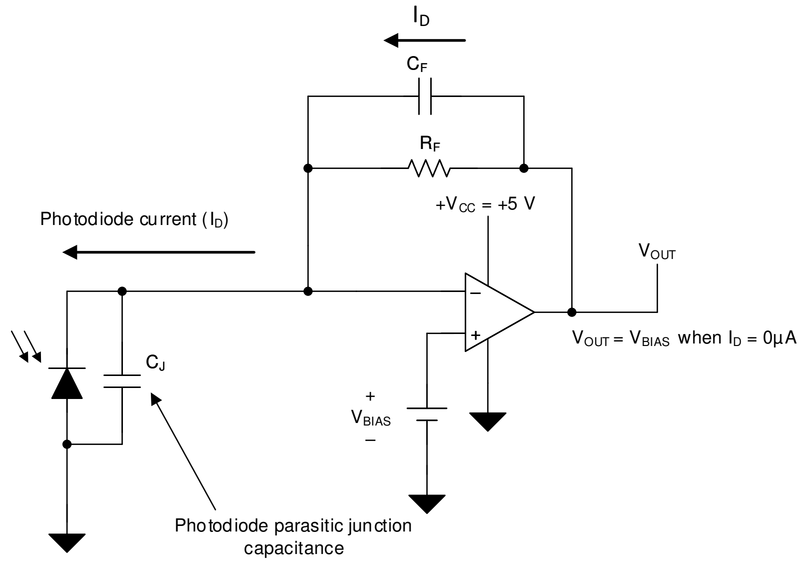

Figure 2-2. Unipolar-Supply Transimpedance Amplifier

However, in this example, the diode requires a relatively large reverse bias voltage of -3V when compared to the 5.5V maximum voltage supply range of the OPA3S328. A different method to reverse bias the diode is to apply the negative bias voltage (V_R = -3V) directly to the photodiode's anode. This configuration is shown in Figure 2-3.

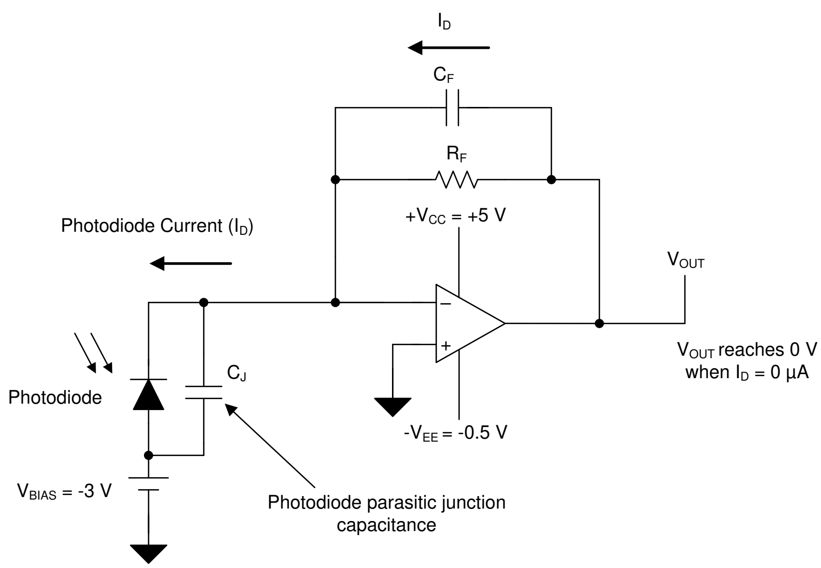

Figure 2-3. Bipolar-Supply Transimpedance Amplifier

The non-inverting OPA3S328 terminal connects to ground and the amplifier is powered with bipolar asymmetrical supplies, Vcc = +5 V and Vee = -0.5 V, allowing the dc voltage output to reach true zero when the diode is not exposed to light. In addition, this circuit makes better use of the OPA3S328 output voltage range, allowing a large diode reverse bias voltage without impacting the voltage range of the output signal.

3 The Programmable Gain Transimpedance Amplifier

One method to implement a programmable gain TIA is to use a TIA stage cascaded by a second Programmable Gain Amplifier (PGA) stage, as shown in Figure 3-1. The TIA gain is set according to the maximum current range from the photodiode. Then, the user adjusts the PGA according to the photodiode current conditions; in other words, the user sets the gain to 1V/V under high photodiode current conditions, or selects a higher gain under low-light current conditions producing an optimal output voltage range. The total output noise of the cascaded TIA and PGA circuit is the TIA's output noise multiplied by the PGA gain plus the noise contribution of the PGA gain stage.

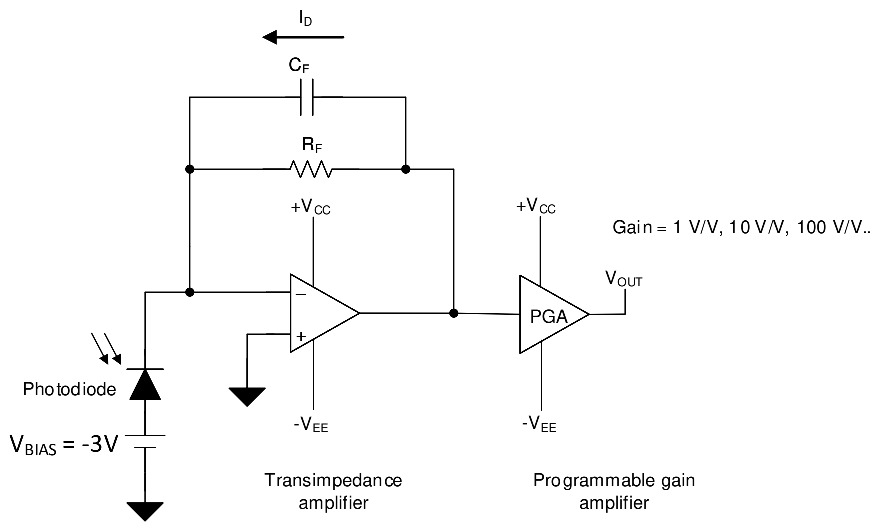

Figure 3-1. TIA Stage Cascaded with PGA Stage

A better approach is to use a single-stage transimpedance amplifier with programmable gain, adjusting the TIA feedback resistor according to the photodiode current condition. This approach provides a significant advantage from the noise performance perspective since the signal is gained on a single transimpedance stage, resulting in lower total output noise. Figure 3-2 shows a programmable gain TIA using the OPA3S328. The integrated 1:2 analog switch selects the different transimpedance feedback resistor. Each transimpedance gain resistor R_{F1} and R_{F2} requires its feedback capacitor, C_{F1}, and C_{F2}, to stabilize the amplifier and compensate for the photodiode junction capacitance.

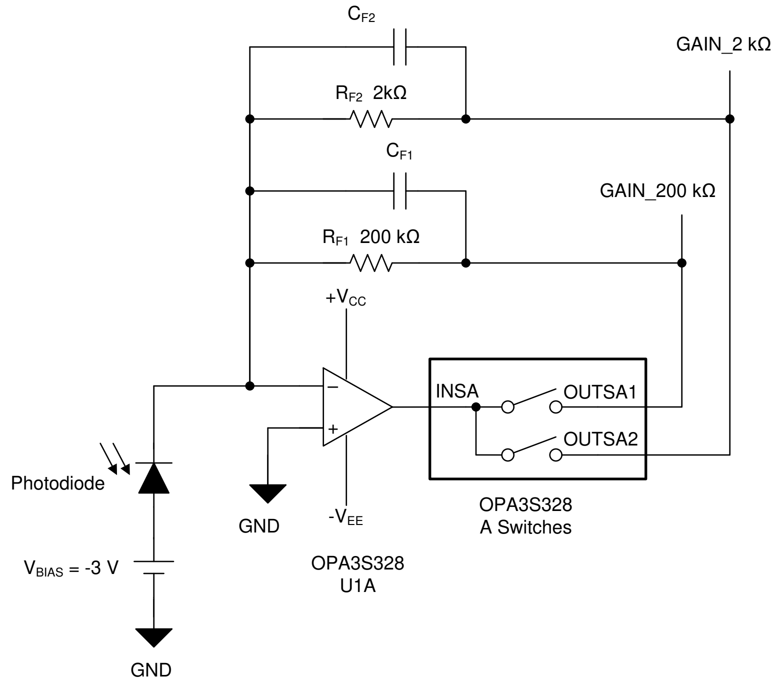

Figure 3-2. Switched Gain Transimpedance Amplifier

The TIA gain needs to be selected to align with the voltage range of the data acquisition system. In this example, the OPA3S328 drives a 16-Bit ADC with a full-scale range of 4V. Select the feedback resistor values R_{F1} and R_{F2} by dividing the full-scale voltage range by the photodiode current range for each gain. In this design, let R_{F1} = 200-kΩ and R_{F2} = 2-kΩ for a 0-20µA and 20µA - 2mA photodiode current range respectively.

Equation 2 provides the current measurement resolution least significant bit size (I_{LSB}), for each gain, where FSR is the full-scale range of the ADC in volts, and N represents the bit resolution of the ADC:

$$I_{LSB} = \frac{FSR(V)}{R_F \cdot 2^N} \tag{2}$$

Equation 2 yields 305pA per bit resolution for the 200kΩ feedback resistor, and 30.5nA resolution for a 2kΩ resistor. Table 3-1 shows the current range, output voltage range, and the desired TIA bandwidth and resolution for this design.

Note

Equation 2 yields the current resolution based on the ideal N-bit ADC resolution. In practice, the noise performance of the transimpedance amplifier and the noise of the ADC limit the effective system resolution.

Table 3-1. Programmable TIA Specifications

Current Range	Gain	Vout (Max)	Resolution
0-20µA	200kV/A	4 V @ 20µA	0.305 nA/bit
20µA - 2mA	2kV/A	4 V @ 2mA	30.5 nA/bit

4 Stability of the Transimpedance Amplifier

The circuit designer must verify the minimum necessary op-amp gain-bandwidth to guarantee stability and select the appropriate feedback compensation capacitor for each TIA gain. Therefore, it is essential to consider factors that affect TIA circuit stability carefully: the junction capacitance of the photodiode (C_J), the TIA gain, the desired closed-loop TIA bandwidth, and the unity gain-bandwidth product of the op-amp (f_{GBW}).

The circuit diagram on Figure 4-1 shows the photodiode reverse junction capacitance (C_J) and the differential and common mode input capacitance of the of-amp (C_{DIFF}, $C_{CM1,2}$).

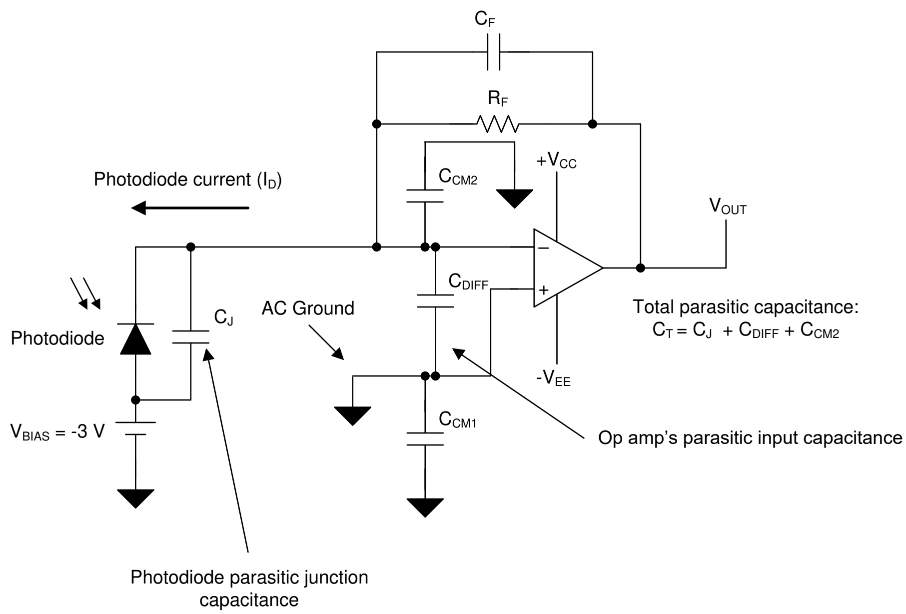

Figure 4-1. Photodiode Transimpedance Amplifier and Total Parasitic Capacitance

Figure 4-1 shows the total capacitance at the input of the amplifier. This capacitance is the parallel combination of the photodiode capacitance, and the amplifier differential and common-mode input capacitance. Since the non-inverting terminal connects to an AC ground, the C_{CM1} common-mode capacitor does not contribute to the total input capacitance:

$$C_T = C_J + C_{DIFF} + C_{CM2} \tag{3}$$

The OPA3S328 offers a differential capacitance of approximately, C_{DIFF} = 3.8pF, and the common-mode capacitance, C_{CM2} = 1.2pF. Accounting for the photodiode junction capacitance, the total capacitance at the input of the amplifier C_T is approximately 105pF.

The TIA circuit stability is related to the amplifier's loop gain and the loop gain phase response. The loop-gain is the product of the op amp's open-loop gain (AOL) and the circuit feedback factor (β), where the circuit's loop-gain is (AOL * β). Phase margin is a stability metric which compares the phase of the loop-gain (AOL * β) of an amplifier to 180 degrees at the point where loop gain equals 0-dB and marks the frequency where AOL and the 1/ β bode plots intersect.

One method to determine the stability of the circuit is called the rate of closure analysis. In this method, we consider the rate of closure of AOL and 1/ β at frequency f_C, the point in frequency where the magnitude plots intersect. This method's rule is that the difference in the slope of the AOL magnitude and the slope of the 1/ β magnitude plots must be ideally close to 20-dB or less to ensure optimal stability.

Figure 4-2 shows the bode plots of the AOL for a high bandwidth amplifier and the AOL for a lower bandwidth amplifier, along with the 1/β curve of a typical TIA.

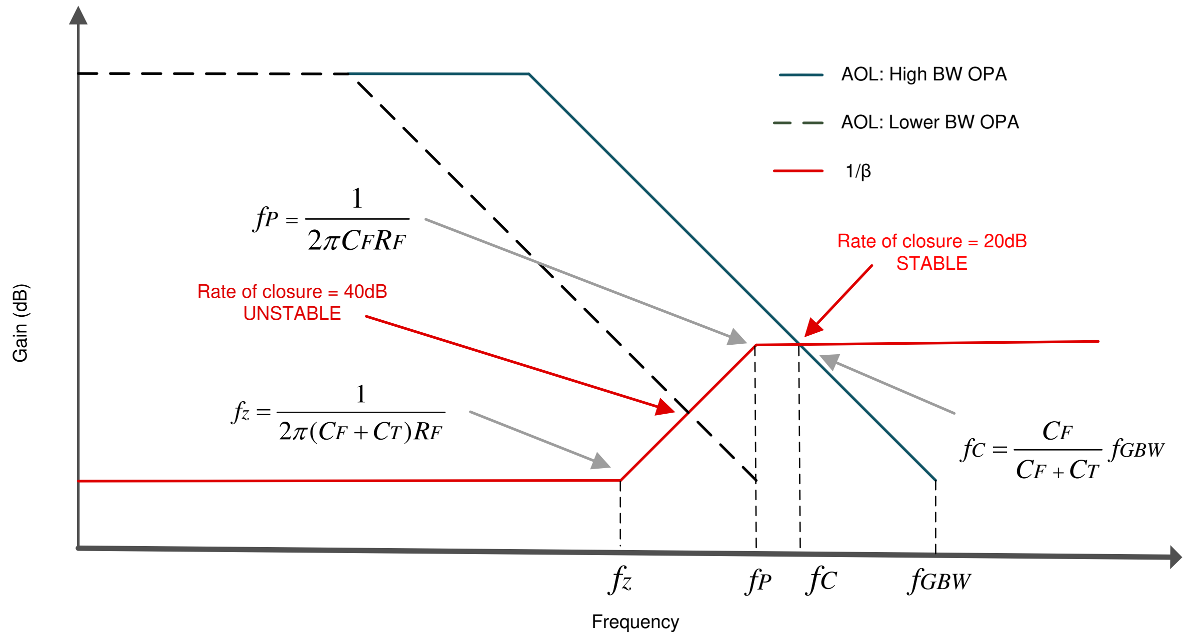

Figure 4-2. AOL and 1/β plot for Transimpedance Op Amp Circuit

The 1/β magnitude plot, also referred to as the non-inverting gain or noise gain, presents a zero (f_Z) and a pole (f_P) on its frequency response. Above the zero frequency (f_Z), the 1/β plot increases a rate of +20dB per decade. At frequencies above the pole (f_P), the 1/β curve remains flat. The frequency f_C is the frequency point where the AOL and 1/β magnitude plots intersect, and this frequency is a function of the unity gain-bandwidth product of the amplifier f_{GBW}, the feedback capacitor, C_F, and the total input capacitance of the amplifier, C_T:

$$f_C = \frac{C_F}{C_F + C_T} f_{GBW} \quad (4)$$

By analyzing the rate of closure (ROC) of AOL and 1/β when the curves intersect, we can determine the stability of the circuit. The rule of thumb for this method is that the rate of closure must ideally be close to 20-dB/decade for optimal stability. Therefore, to maintain stability, the AOL curve must intersect the 1/β curve when the 1/β curve is flat. If the AOL curve intersects the 1/β curve when the 1/β curve is rising, as shown by the lower bandwidth op amp AOL curve in Figure 4-2, the rate of closure is 40-dB and the circuit will likely be unstable, leading to unwanted oscillations, long settling time and intermittent or unfavorable circuit behaviors.

Equation 5 provides the necessary condition for the transimpedance amplifier stability:

$$f_C > f_P \quad (5)$$

Substituting the equations for f_C and f_P into the inequality provided on Equation 5 yields to Equation 6

$$\frac{C_F}{C_F + C_T} f_{GBW} > \frac{1}{2\pi C_F R_F} \quad (6)$$

The inequality can be re-arranged as a quadratic equation in terms of the feedback capacitor, C_F, as shown in Equation 3:

$$2\pi R_F f_{GBW} C_F^{\,2} - C_F - C_T > 0 \quad (7)$$

Solving for C_F using the general quadratic formula and obtaining the only real positive solution yields the result shown in Equation 8:

$$C_F > \frac{1}{4\pi R_F f_{GBW}} * \left(1 + \sqrt{1 + 8\pi R_F f_{GBW} C_T}\right) \tag{8}$$

Equation 8 determines the minimum compensation capacitor to guarantee stability for the TIA design. Table 4-1 shows the minimum calculated compensation capacitors C_{F1} and C_{F2} to ensure stability for each TIA gain for the unity gain-bandwidth of the OPA3S328. The dominant pole frequency f_P is a function of the feedback resistor and feedback capacitor for each TIA gain.

Table 4-1. Calculation of Minimum Compensation Capacitor

f_{GBW} Amplifier Unity Gain Bandwidth	TIA Gain	C_T TIA Total Input Capacitance	R_F TIA Feedback Resistor	C_F Min Feedback Capacitor for stability	f_P Dominant Pole frequency
40 MHz	200 kV/A	105 pF	200 kΩ	>1.5pF	530kHz
40 MHz	2 kV/A	105 pF	2 kΩ	>16pF	4.97MHz

A different approach to ensure stability while meeting a TIA gain and bandwidth requirement, is to use the inequality provided in Equation 6, and solve for the amplifier's minimum unity gain-bandwidth (f_{GBW}). Equation 9 provides the amplifier's minimum f_{GBW} as a function of the feedback resistor R_F, the feedback capacitor C_F, and the total input capacitance of the amplifier C_T:

$$f_{GBW} > \frac{C_F + C_T}{2\pi C_F^{\,2} R_F} \tag{9}$$

Equation 9 determines the amplifier's minimum required unity gain-bandwidth to guarantee stability for a TIA design. Therefore, higher bandwidth amplifiers support higher gain and bandwidth TIA circuits, and tolerate higher photodiode capacitance while remaining stable.

On this programmable gain TIA example, the desired closed-loop bandwidth TIA_{BW} is 500kHz. Therefore, Equation 10 provides the maximum compensation capacitance C_F while meeting the closed loop TIA bandwidth requirement:

$$C_F < \frac{1}{2\pi R_F TIA_{BW}} \tag{10}$$

Equation 10 shows the calculated compensation capacitors C_{F1} and C_{F2} for each gain to meet the TIA closed-loop bandwidth requirement and the required amplifier's minimum unity gain-bandwidth to ensure stability:

Table 4-2. Calculation of the Amplifier's Minimum Unity Gain Bandwidth

TIA Gain	TIA_{BW} Desired TIA Bandwidth	C_T TIA Total Input Capacitance	R_F TIA Feedback Resistor	C_F Feedback Capacitor for TIA_{BW}	f_{GBW} Min Amplifier Unity Gain BW
200 kV/A	500 kHz	105 pF	200 kΩ	1.6pF	> 33.8MHz
2 kV/A	500 kHz	105 pF	2 kΩ	159pF	> 834 kHz

The OPA3S328 offers a unity gain bandwidth of 40 MHz, and therefore, can support the desired TIA gain and bandwidth requirements for the design. Select standard values for the compensation capacitor, C_{F1} = 1.6pF for TIA gain of 200kV/A and C_{F2} of 150pF for TIA gain of 2kV/A.

Verify the stability for each gain using TINA SPICE simulations. Figure 4-3 shows the TINA-TI circuit schematic used to analyze stability. Use a large inductor (L1) to break the loop at the input of the amplifier. The test voltage source is AC coupled through the large capacitor (C1). Since the feedback loop is open at the op-amp input, add the op-amp input capacitance, C_{DIFF} and C_{CM2} into the schematic next to inductor L1. Use the simulator post-processor to generate the open-loop gain (AOL) and noise gain (1/β) curves for each gain setting. Figure 4-4 shows the stability analysis simulation results for R_{F1} = 200kΩ, C_{F1} = 1.6pF and Figure 4-5 for R_{F2} = 2kΩ, CF2=150pF.

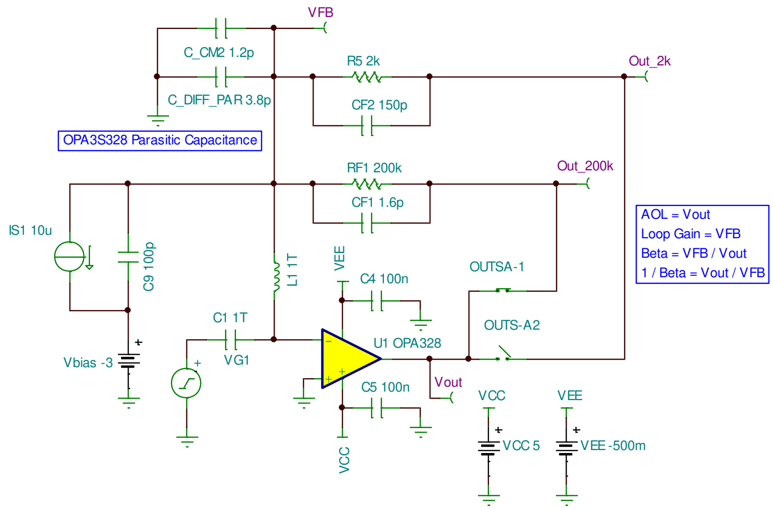

Figure 4-3. TINA-TI Circuit Schematic to Analyze Programmable Gain TIA Stability

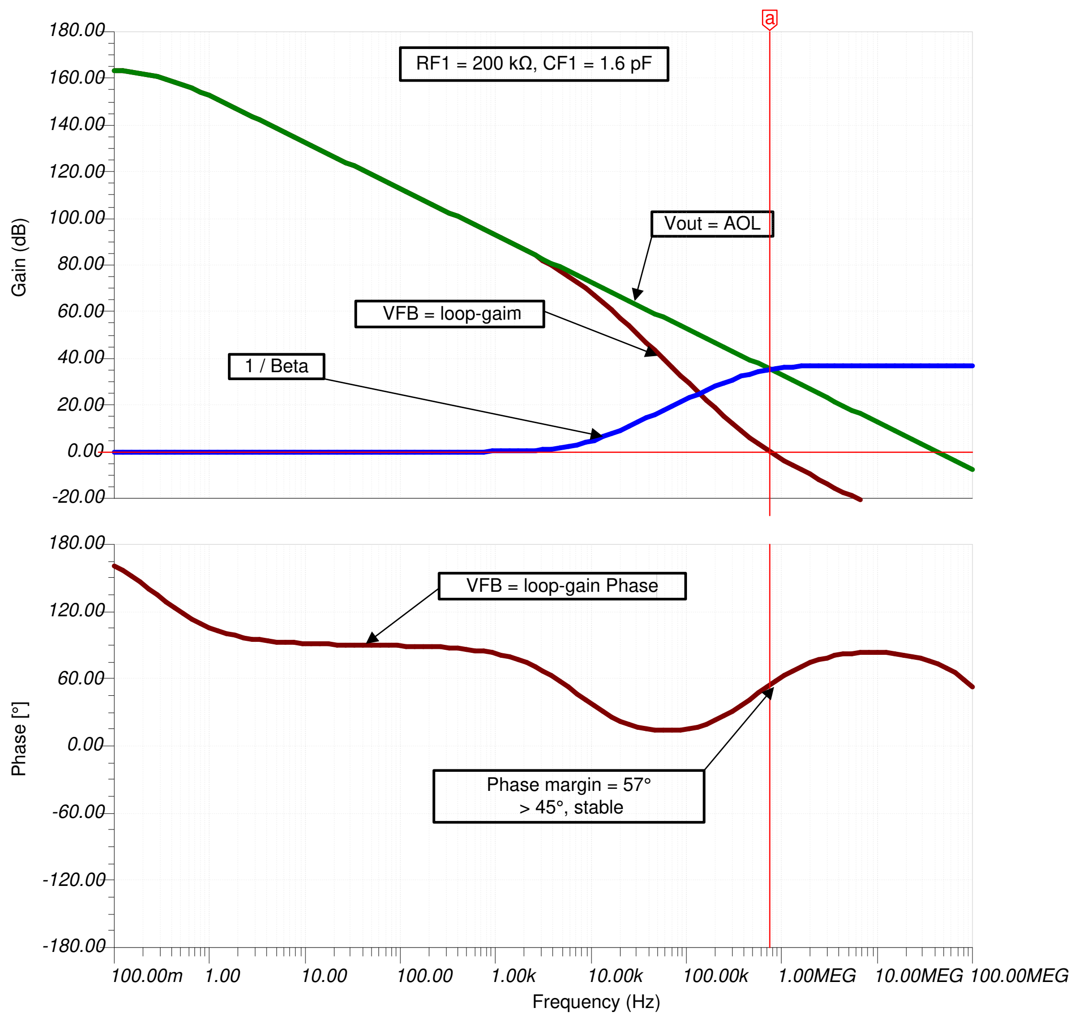

Figure 4-4. Stability Analysis for R_{F1} = 200kΩ

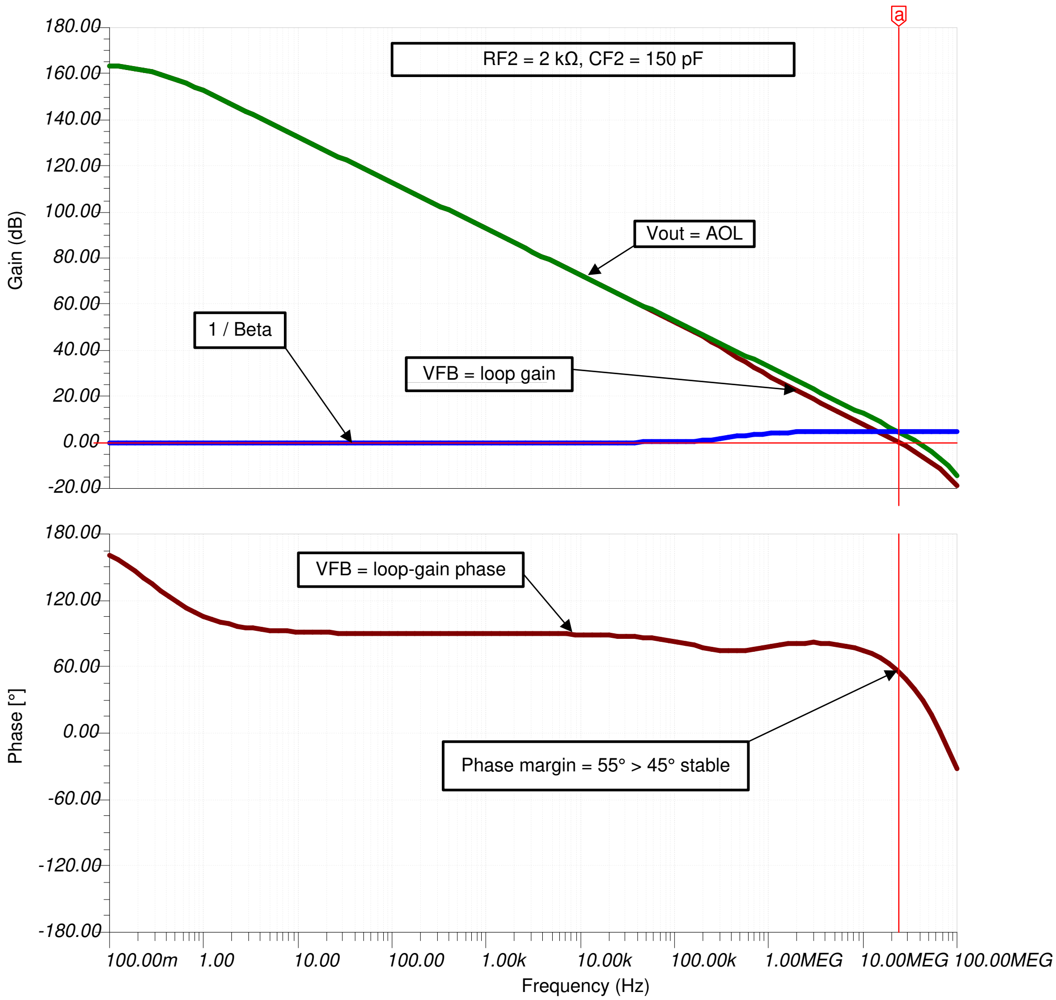

Figure 4-5. Stability Analysis for R_{F2} = 2kΩ

5 Integrated Switch Characteristics

The OPA3S328 incorporates two sets of low leakage, low capacitance and low on-resistance switches useful for different circuit configurations, including programmable gain transimpedance applications. The QFN package version of the OPA3S328 device features switch 1 in a 1:2 matrix configuration, one input (INSA) with two outputs (OUTSA1, 2) and switch 2, in a 1:3 matrix configuration, one input (INSB) with three outputs (OUTSB1, 2, 3). On this circuit example, switch 1 is used to build the programmable gain TIA.

Table 5-1 shows key switch parameters based on the OPA3S328 data sheet specifications:

Table 5-1. Integrated Switches Characteristics

Parameter	Test Condition	Min	TYP	Max	Unit
C_{IN} Switch input capacitance	Switch open, INSA/B = 2.5 V		2.3		pF
C_{OUT} Switch output capacitance	Switch open, OUTSA/B/1/2/3 = 2.5 V		0.7		pF
C_{INOUT} Switch total capacitance	Switch closed, INSA/B = OUTSA/B/1/2/3 = 2.5 V		6		pF
R_{ON} Switch on resistance	Switch closed, V+ = 5 V, INSA/B = 2.5 V		90	125	Ω

C_{IN} and C_{OUT} represent the open switch parasitic switch capacitance, while C_{INOUT} represents the total switch capacitance while the switch is closed. R_{ON} is the switch series resistance when the switch is closed. Figure 5-1 shows a simplified model based on the switch data sheet parameters used in the TINA simulations using the switch input and output capacitances and the switch on resistance:

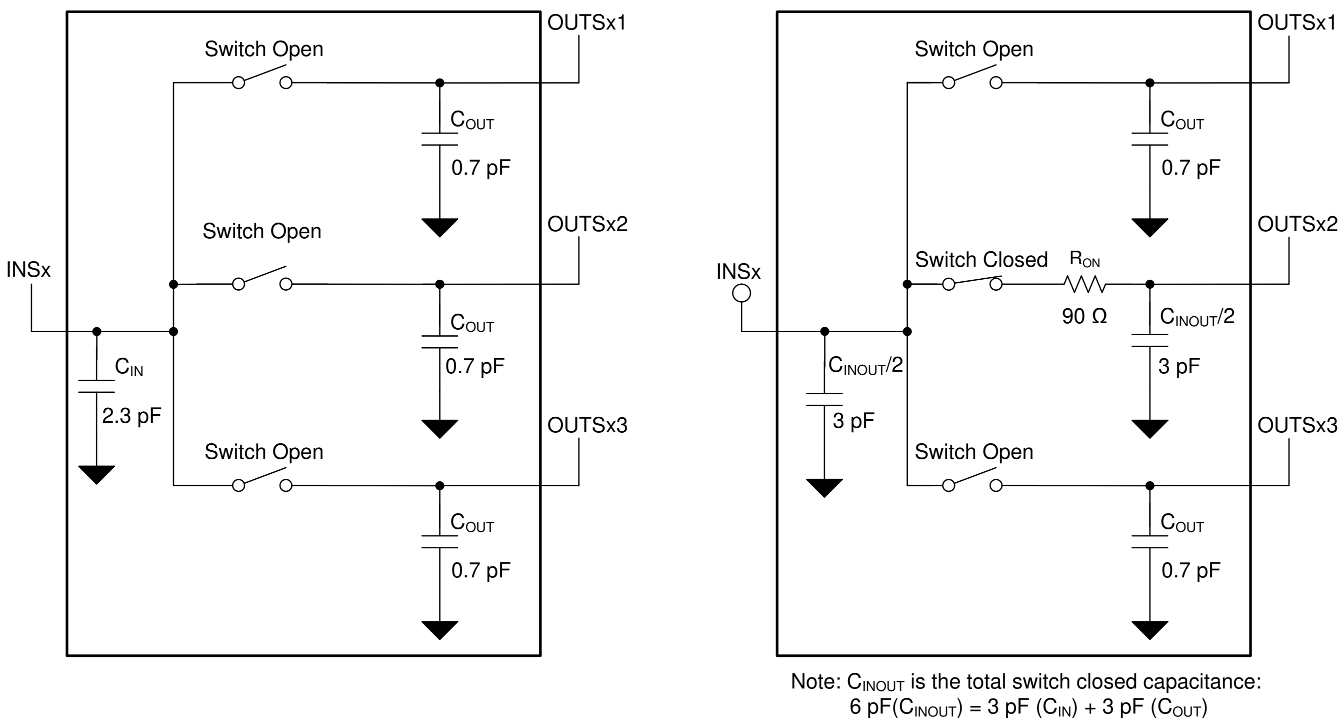

Figure 5-1. OPA3S328 Simplified Switch Model

When designing the switch gain transimpedance amplifier, the designer needs to consider the non-ideal characteristics of the switches. The bandwidth and stability of the transimpedance will be affected by the capacitances and resistances of the switch. Furthermore, the on-resistance R_{ON} of the switch can be a source of error on the gain of the transimpedance amplifier. The following sections discuss errors due to the switch non-ideal behavior and proposes circuits to overcome these errors.

5.1 TIA Stability and Switch Capacitance

Although the OPA3S328 integrated switches offer relatively low parasitic capacitance and low on resistance, the designer needs to verify the effect of the switches to ensure the stability of the circuit. Using the same open-loop simulation circuit of Figure 4-2, we add the simplified switch model and plot the loop gain, AOL, and 1/Beta to analyze stability.

Figure 5-2 show the TINA-TI circuit schematic used to analyze stability incorporating the simplified switch model for each gain. Perform an AC transfer characteristic simulation and use the post-processor to generate the open-loop gain (AOL) and noise gain (1/β) curves for each gain setting. Figure 5-2 shows the stability analysis simulation results for R_{F1} = 200kΩ, C_{F1}=1.6pF including the integrated switch capacitance.

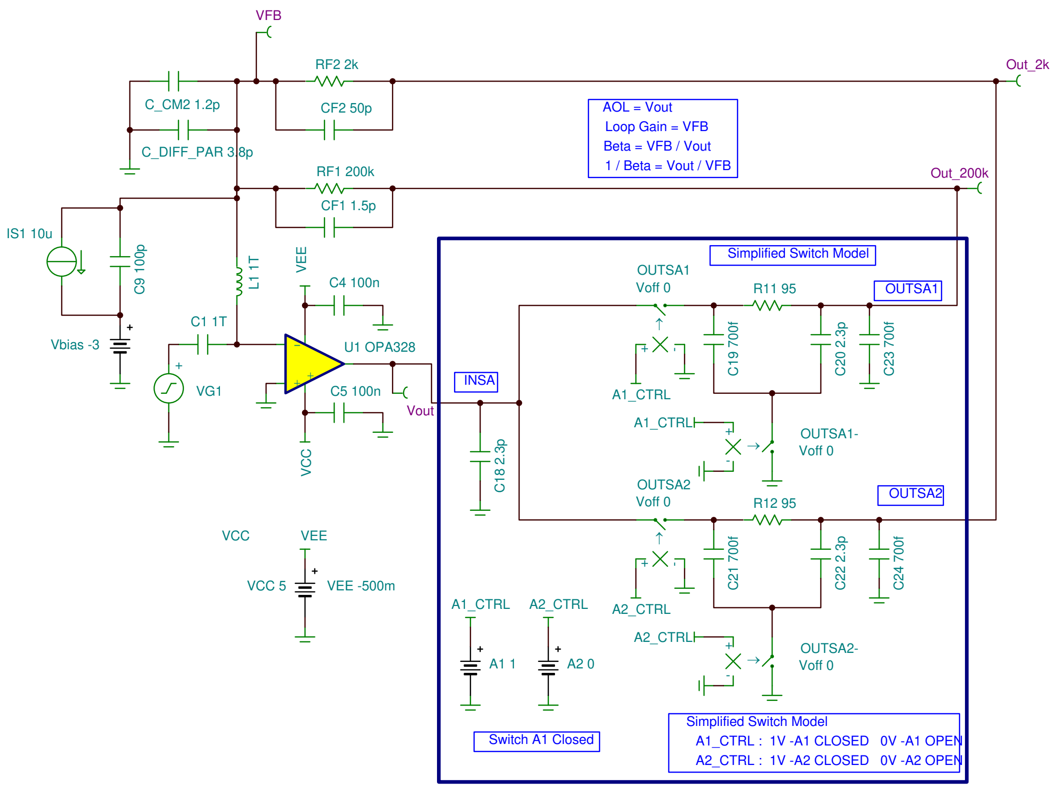

Figure 5-2. TINA-TI Schematic for Stability Analysis Including Switches

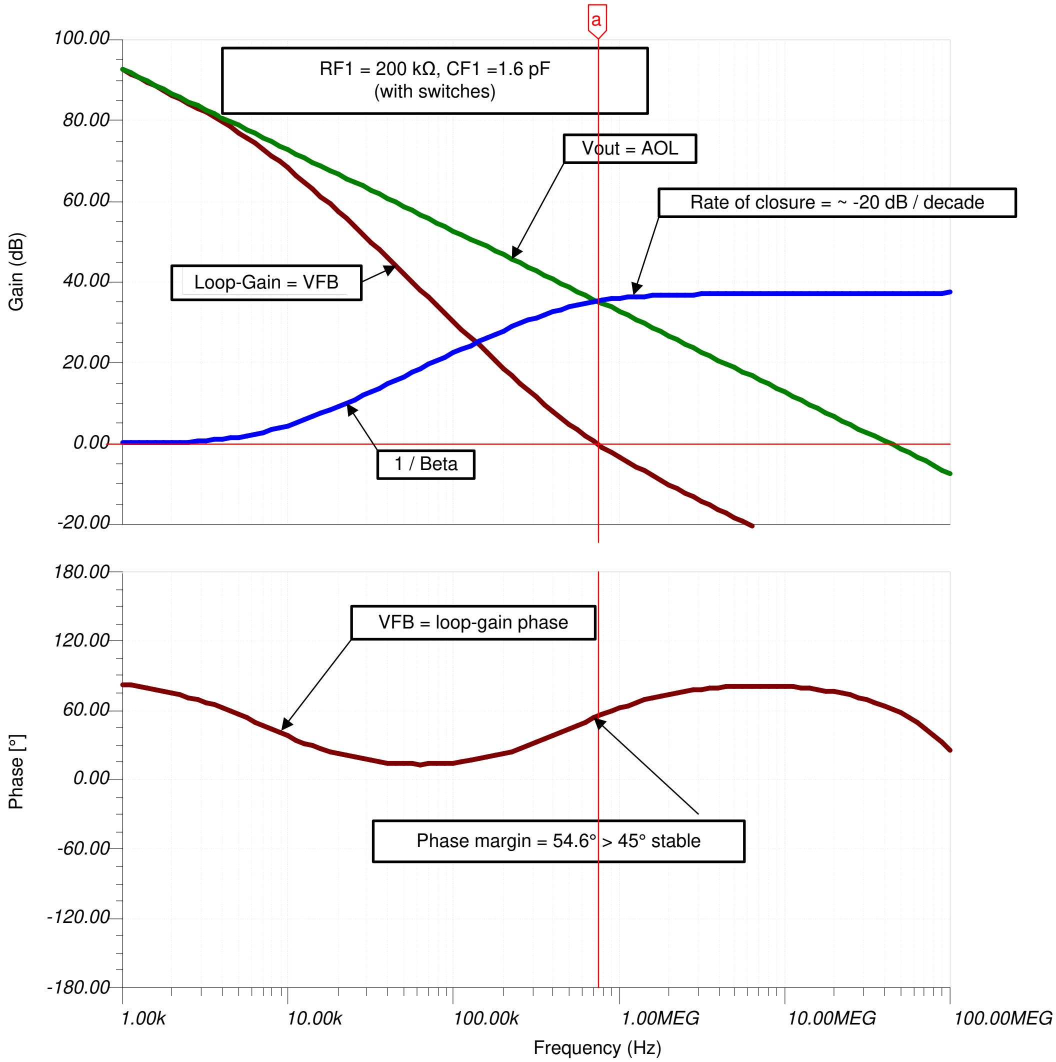

Figure 5-3. Stability Analysis for R_{F1} = 200kΩ, C_{F1} = 1.6pF with Switch

After adding the switch parasitic components, the stability analysis for R_{F1} = 200kΩ and C_{F1} = 1.6pF shows the AOL and 1/β curves intersect with a rate of closure of -20 dB/decade. The phase margin remains higher than 45-degrees, guaranteeing robust circuit stability for this gain.

Figure 5-4 displays the results for R_{F2}= 2kΩ and C_{F2}=150pF.

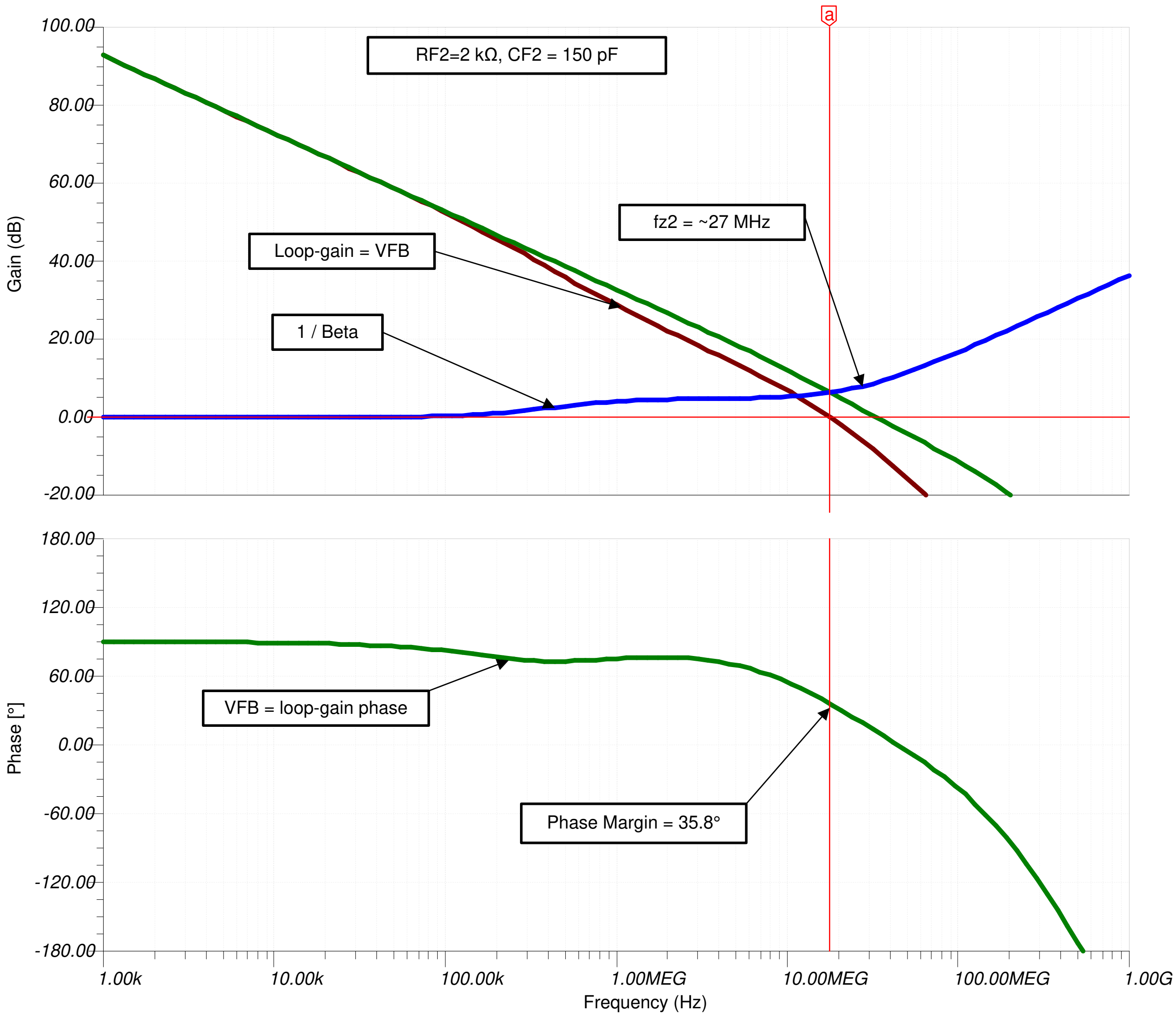

Figure 5-4. Stability Analysis for R_{F2} = 2kΩ, C_{F2} = 150pF with Switch

The R_{ON} switch resistance interacts with the series combination of the feedback capacitor C_{F2} and the total capacitance at the input of the amplifier C_T, generating an additional zero f_{Z2} on the 1/β curve. Equation 11 defines the second zero frequency on the 1/β curve:

$$f_{Z2} = \frac{C_F + C_T}{2\pi R_{ON} C_F C_T} \tag{11}$$

f_{Z2} degrades the phase margin to ~36-degrees. The previous calculation in Table 4-1 and Table 4-2 shows that the permissible feedback capacitor range for C_{F2} is between 16pF and 159pF. To improve phase margin, reduce the feedback capacitor C_{F2} to 50pF, moving the second zero f_{Z2}, to a higher frequency than the amplifier's unity gain-bandwidth of 40-MHz, where the effect f_{Z2} on the circuit stability is negligible. Figure 5-5 displays the stability analysis results for the revised circuit with R_{F2}= 2kΩ and C_{F2}=50pF. The phase margin improves to 57-degrees, guaranteeing robust circuit stability.

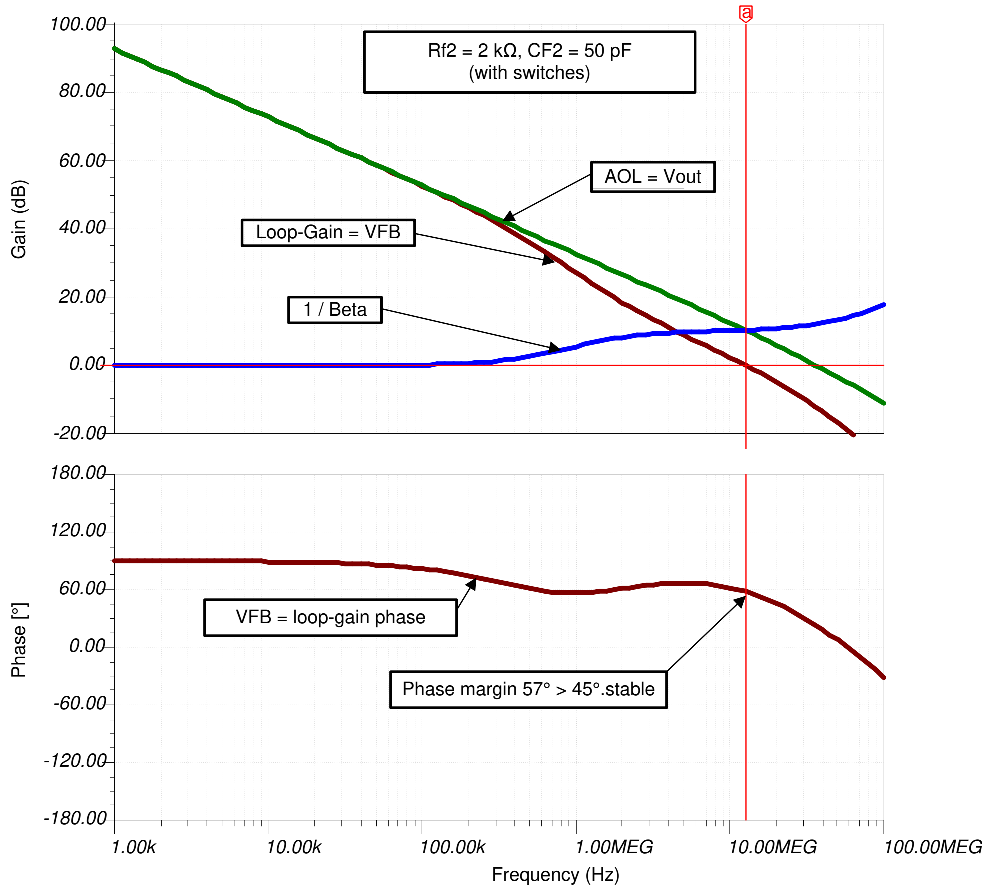

Figure 5-5. Stability Analysis for Revised Circuit with R_{F2} = 2kΩ, C_{F2} = 50pF

5.2 TIA Output Swing and Switch On-Resistance

When building a programmable gain TIA with analog switches, the circuit designer needs to account for the voltage drop across the switch R_{ON} resistance when the photodiode current flows through the amplifier's feedback. This voltage drop is significant at the higher photodiode current ranges.

Amplifier output stages that can swing close to the complete span between negative and positive supply voltage are generally known as rail-to-rail output (RRO) stages. Most RRO stages can swing within tens of millivolts of the rails. The amplifier's data sheet specifies the output voltage range from the supplies as output swing (output voltage low/high). Although the OPA3s328 offers an RRO stage and the amplifier functions in this region, the performance gradually degrades as the output gets closer to the rails where the amplifier open-loop gain decreases. Therefore, it is advisable to allow extra headroom in applications that require very low distortion. A conservative approach to ensure the amplifier remains well within its linear region is to use the output swing headroom from supply from the data sheet open-loop gain (A_{OL}) specification:

Table 5-2. Open-Loop Gain (A_{OL}) Specification

Parameter	Test Condition	Min	TYP	Max	Unit
A_{OL} Open-loop voltage gain	(V–) + 200 mV < VO < (V+) – 200 mV RL = 2 kΩ	108	123		dB

The OPA3S328 data sheet output swing specification during the A_{OL} test is 200mV from the rail with a 2kΩ load referred to mid-supply, while the device is powered with a 5.5V supply. This A_{OL} test condition corresponds to an equivalent load current of approximately 1.275mA. In this TIA example, the OPA3S328 sources a maximum of 2mA of current, therefore, the designer must allow headroom exceeding >200mV.

The designer must carefully choose the maximum feedback resistor to meet the minimum headroom requirement. Equation 12 provides the maximum TIA feedback resistor value (R_F) as a function of the supply voltage (V_{CC}), the maximum diode current (I_{D_Max}), the maximum on-resistance (R_{ON_Max}) while allowing the necessary output swing supply headroom ($V_{Headroom}$).

$$R_F < \frac{V_{CC} - V_{Headroom}}{I_{D\_Max}} - R_{ON\_Max} \tag{12}$$

In this example, the calculation yields a resistance less than <2275Ω for a max current of 2mA, max on-resistance of 125Ω, allowing a 200mV headroom from the supply. For the circuit design, we choose R_{F2} =2kΩ exceeding the minimum headroom condition. Figure 5-6 shows the voltage drop across the worst-case R_{ON_Max} resistance of 125Ω with I_{D_Max} = 2mA and the resulting output swing headroom.

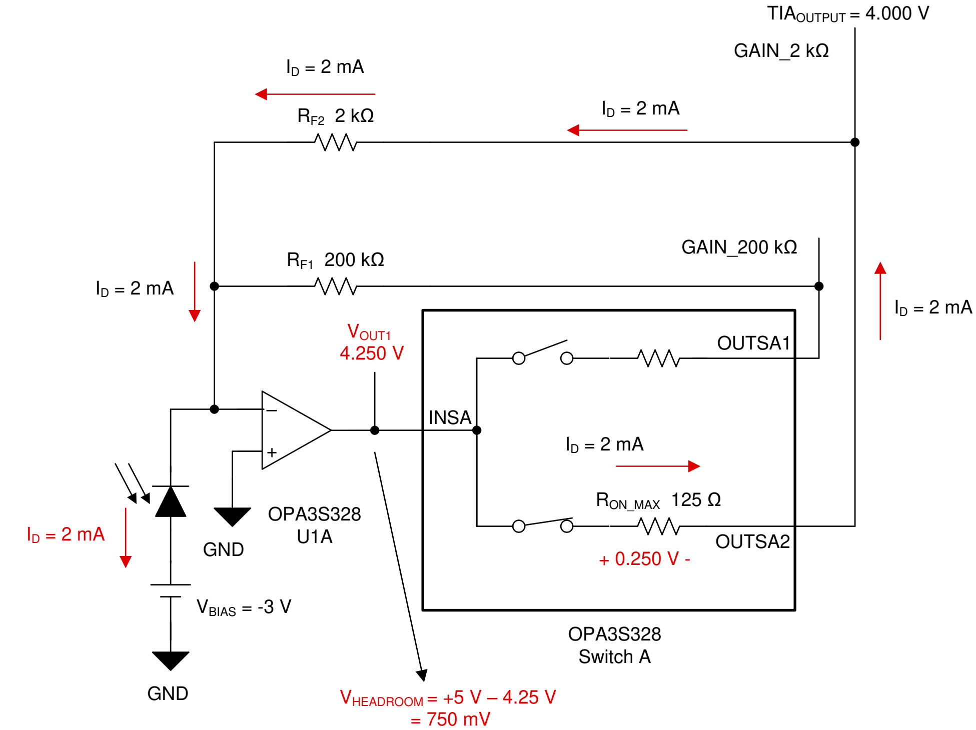

Figure 5-6. Switch R_{ON} Resistance and Output Swing Headroom

5.3 TIA Gain Error due to Switch On-Resistance

The switch R_{ON} resistance will produce DC gain errors and distortion on the transimpedance amplifier. The percent gain error is dependent on the TIA feedback resistor value; and the gain errors are relatively large at the lower feedback resistor values. For example, with the R_{F1} = 200kΩ resistor, the maximum switch R_{ON} resistance of 125Ω will contribute about 0.063% gain error. In the case of the lower R_{F2}=2kΩ resistor, the gain error due to the switch R_{ON} resistance is much more significant, about 6.25% gain error. In addition, the switch on resistance changes with temperature producing TIA gain drift errors.

Furthermore, the R_{ON} switch resistance of each selectable gain varies over the TIA output voltage. Figure 5-7 shows the change of RON resistance vs the voltage difference across the switch.

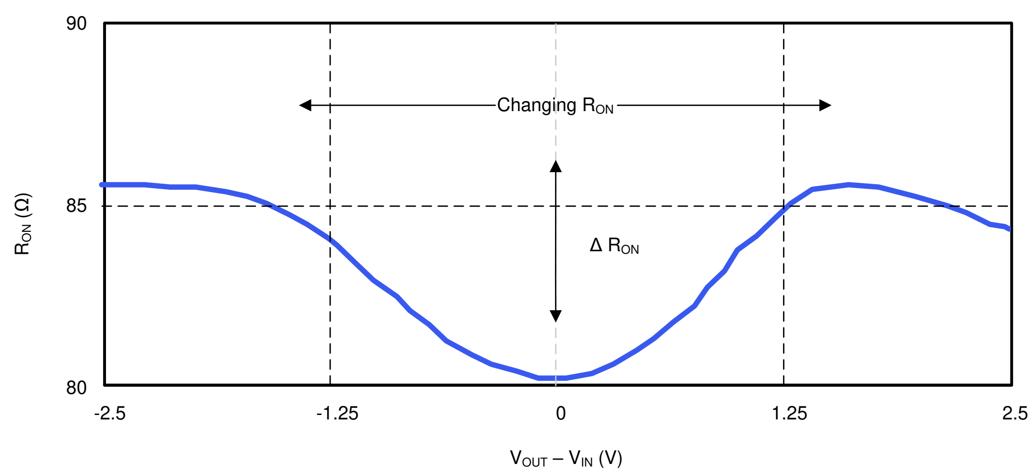

Figure 5-7. R_{ON} Resistance Vs Voltage

This ΔR_{ON} change in switch resistance introduces signal-dependent distortion and gain error linearity based on the switch impedance.

One way to address this issue is to build a multiplexer using the second integrated switch of the OPA3S328. The multiplexer input senses the TIA output connection for the selected gain right at the R_F feedback resistor terminal. The second amplifier stage is configured in a high impedance non-inverting configuration, buffering the multiplexer and providing an accurate Kelvin sense connection of the TIA output for each gain. Since the input bias current of the op-amp is minimal, < 10pA, the voltage drop across the switch R_{ON} resistance is negligible. Figure 5-8 shows the OPA3S328 circuit using the 3:1 switch B to build the Kelvin sense connection multiplexer, buffered with a second-stage amplifier. The voltage drop across the R_{ON} resistance of switch SB2 is negligible.

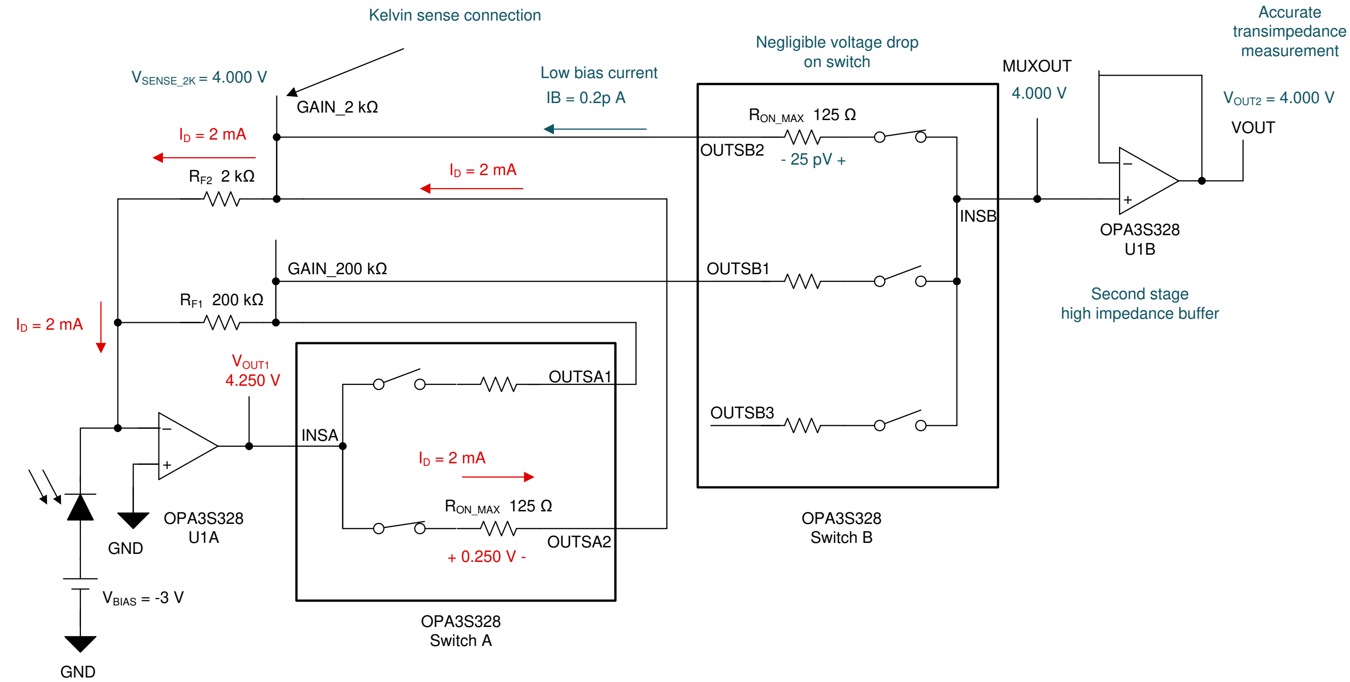

Figure 5-8. Switch Kelvin Sense Connections and High Impedance Buffer

The Kelvin sense connections eliminate the gain error, gain error drift and gain non-linearity due to the switch R_{ON} resistances though the high impedance second-stage amplifier. The second-stage could also be configured in a non-inverting gain configuration, adding the flexibility for even higher gains while maintaining the circuit bandwidth.

6 Frequency Response Simulations

Figure 6-1 shows the TINA-TI Schematic of the complete programmable gain transimpedance amplifer, including the buffer amplifier with Kelvin sense connections. Sub-circuits SWA and SWB model the switches capacitance and on-resistance.

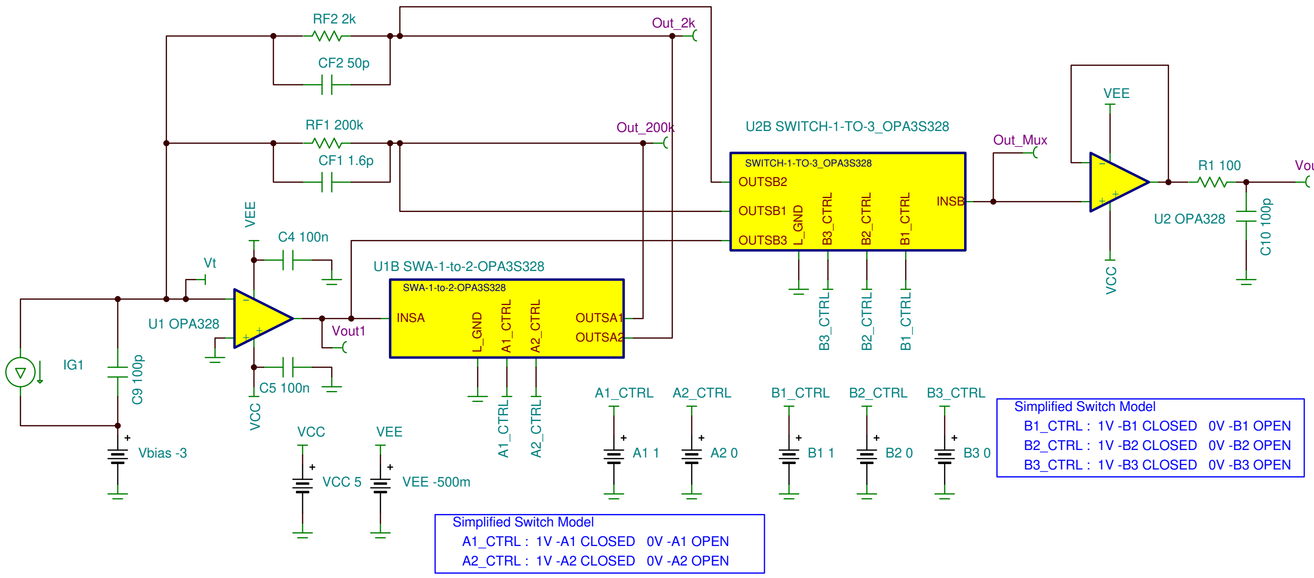

Figure 6-1. TINA-TI Schematic of Complete Programmable Gain TIA

Figure 6-1 displays the simulation result for the TIA closed-loop frequency response with a gain of 200-kV/A, showing a corner frequency of 670kHz, exceeding the frequency response requirement.

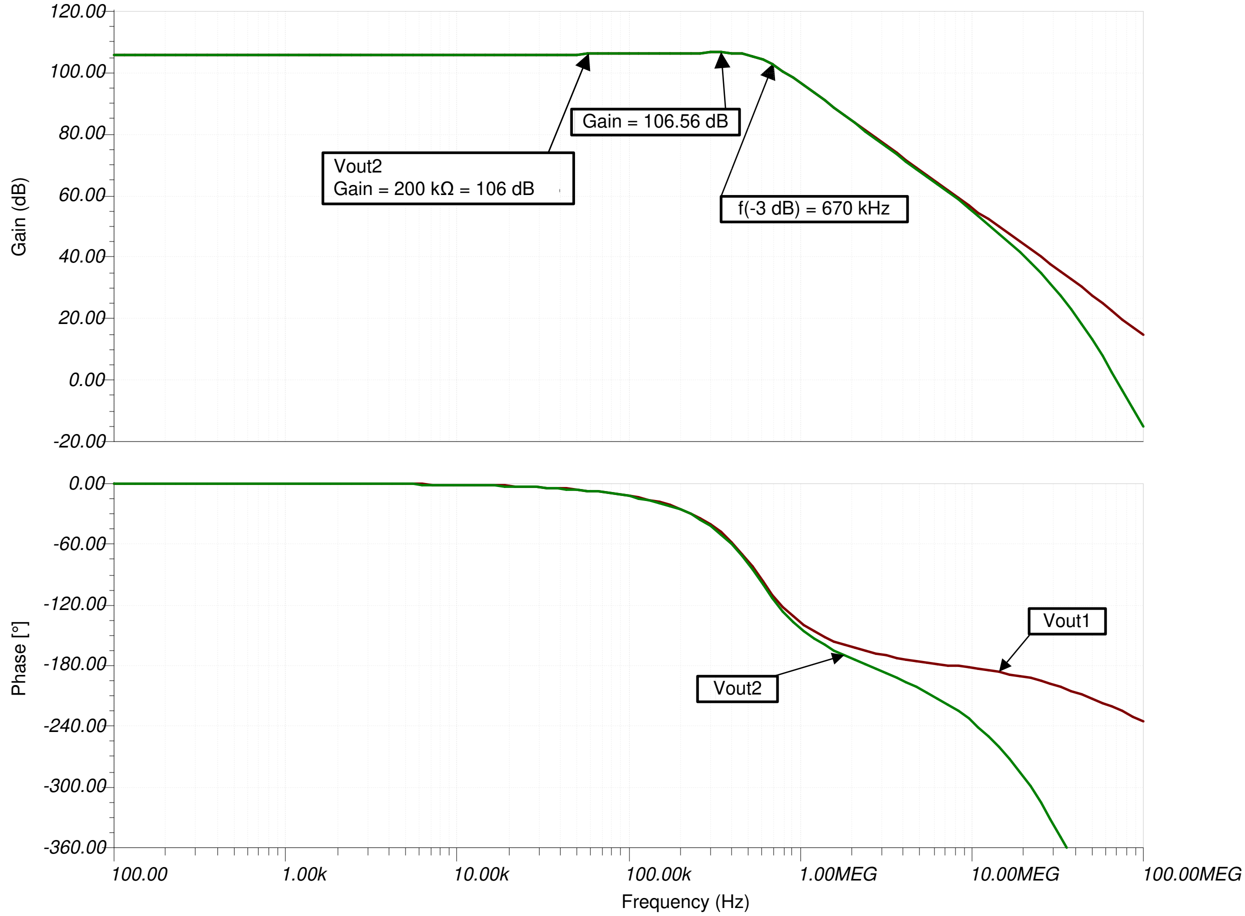

Figure 6-2. Frequency Response Simulation Result for R_{F1} = 200kΩ, C_{F1}=1.6pF

Figure 6-1 displays the simulation result for the TIA closed-loop frequency response with a gain of 200-kV/A, showing a corner frequency of 1.6MHz.

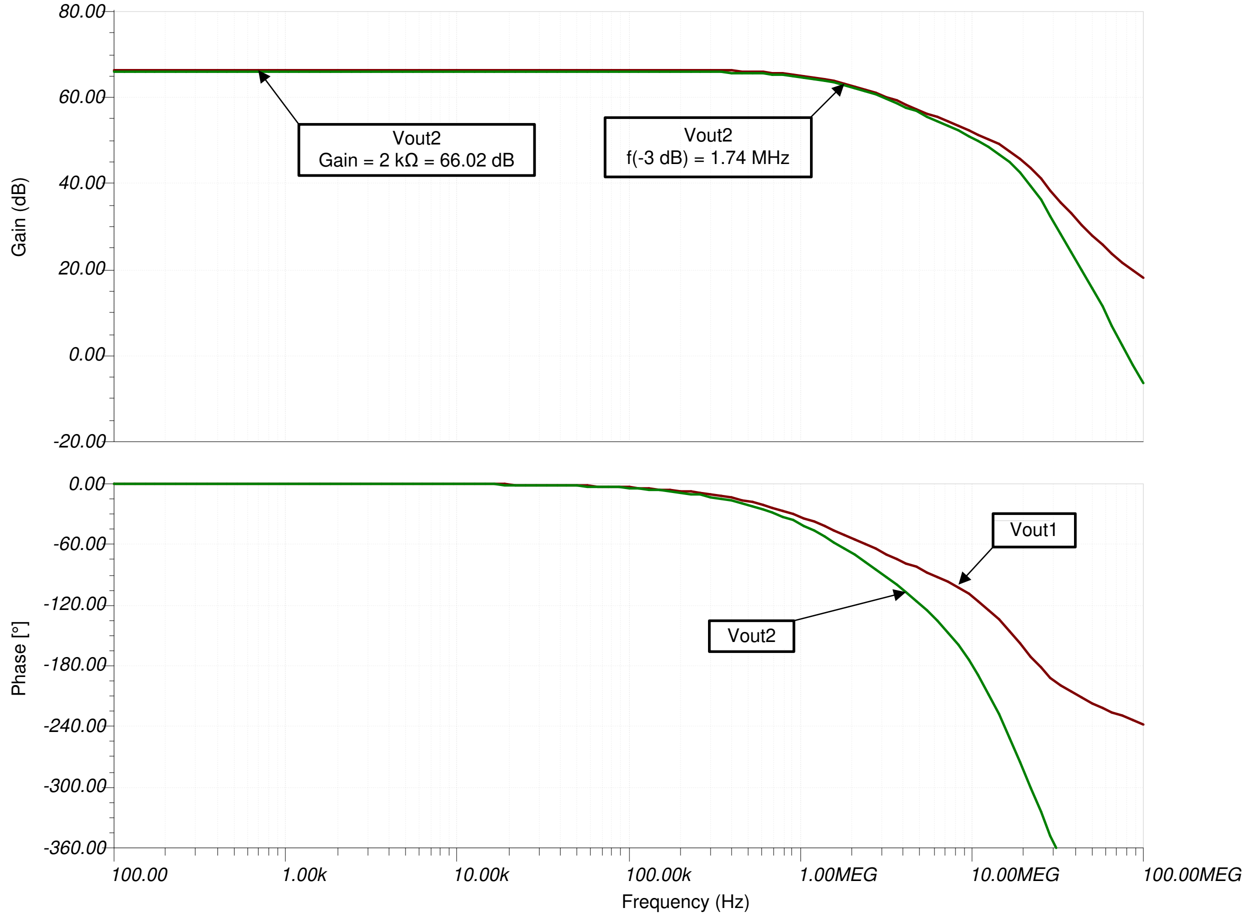

Figure 6-3. Frequency Response Simulation Result for R_{F2} = 2kΩ, C_{F2}=50pF

Both transimpedance amplifier gains showcase an AC response meeting the frequency response requirement with robust stability with very subtle peaking at the TIA output (less than <0.5dB, consistent with the ~55-degree phase margin of the circuit.

7 Conclusion

The programmable gain TIA provides flexibility to measure a wide range of photodiode current while ensuring the amplifier remains inside its linear range. The OPA3S328 dual op-amp offers low input bias current, high DC precision performance, low noise, and high bandwidth, providing an optimal choice for transimpedance amplifier applications. The device incorporates two sets of low leakage, low capacitance, analog switches useful for the configuration of programmable gain amplifiers in a single device integrated solution.

The preceding discussion shows some of the design trade-offs when implementing programmable transimpedance amplifiers using analog switches, and a Kelvin-sense circuit topology to eliminate TIA gain error, gain error drift, and non-linearity due to the switch on-resistance. This document provides the information to assist the design engineer in implementing the programmable TIA design according to the specific application needs.

8 References

1. Texas Instruments Precision Hub, *What op amp bandwidth do I need? (Transimpedance Amplifiers)*, May 2014, John Caldwell, Texas Instruments Blog: Part I, Part II and Part III.
2. Texas Instruments, *Compensate Transimpedance Amplifiers Intuitively* application report.

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