Application Note

Perform Accurate Optical Current Sense Measurements Using the LOG200 Logarithmic Amplifier

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ABSTRACT

The LOG200 is a precision, high-speed, current-to-voltage logarithmic amplifier with integrated adaptive photodiode bias. The device is designed for current measurements across a wide dynamic range of 10pA to 10mA (180dB). It features a high-speed response spanning several decades of input current, allowing for a unique combination of fast transient response with high accuracy and logarithmic conformity.

This document provides guidelines, examples, and bench measurements, interfacing the LOG200 with photosensors for optical current sensing applications.

Table of Contents

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1 Introduction

Optical systems frequently require wide dynamic range current-voltage conversion. Photodiode sensors produce a current output that changes with incident light, where the typical photo current changes orders of magnitude from hundreds of pico-amperes to a few milliamps; therefore, a wide current range spanning several decades of magnitude must be accommodated.

The LOG200 features two logarithmic amplifiers followed by a differential amplifier to convert current signals into a single-ended voltage representing the log-compressed ratio of the two currents. The device incorporates a photodiode bias and dark current correction adaptive biasing circuit, a precision 1μA current reference, precision 1.65V and 2.5V voltage references, and an auxiliary op-amp to facilitate the device's interface with photodiodes. The LOG200 amplifier ratio is 250mV/decade of current-to-voltage conversion. The simplified circuit diagram in Figure 1-1 shows the LOG200 on a typical photodiode current sense measurement application. The block diagram does not show all the decoupling capacitors for brevity.

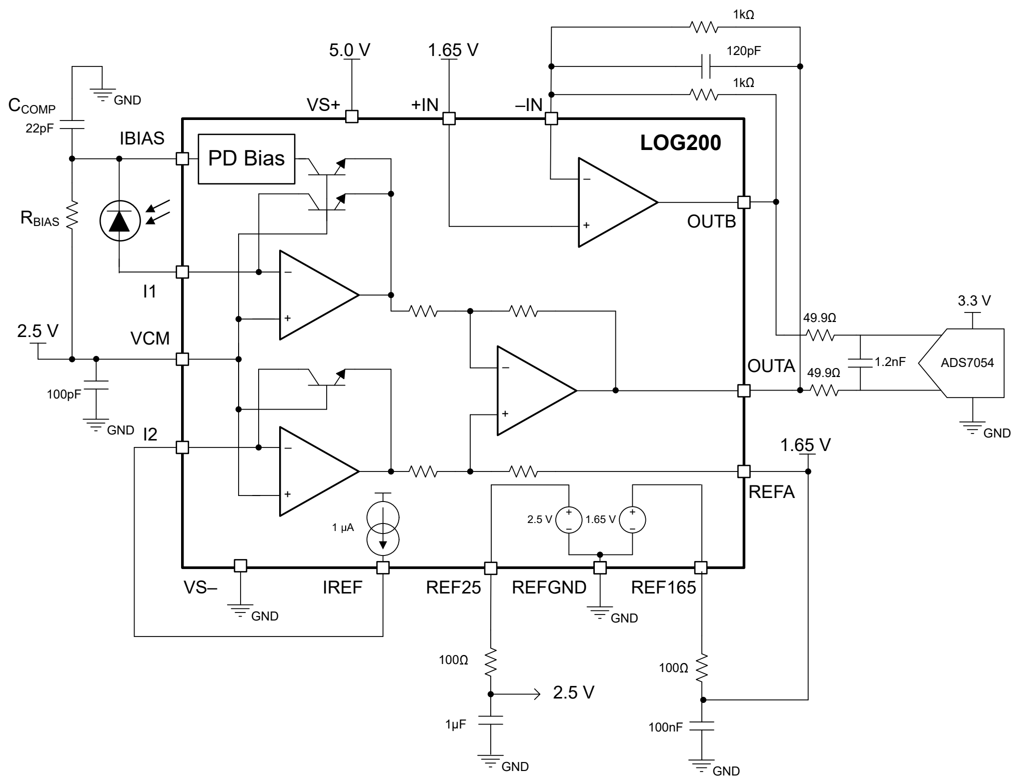

Figure 1-1. LOG200 Typical Application Block Diagram

The LOG200 offers a versatile design faster than previous generation logarithmic amplifier designs, offering 90kHz bandwidth at 1nA of input current, ±0.2% max logarithmic conformity error from 10nA to 100μA. With a rise time of 60ns and a fall time of 150ns on a 100nA-1μA step, the LOG200 can quickly detect changes in optical power across many decades of current. For more information on the LOG200 device specifications and features, refer to the *LOG200 Precision, High-Speed Logarithmic Amplifier With Integrated Photodiode Bias Data Sheet*.

2 Critical Photodiode Specifications

Photodiodes are one of the most common detectors for measuring a light source's optical power. A photodiode can be operated in one of two modes: photoconductive (reverse bias) or photovoltaic (zero bias). The photodiode bias condition depends upon the application's speed requirements and the amount of tolerable dark current (I_{dark}) on the sensor. Dark current is the current in the photodiode when there is no incident light and can be a large source of error during low photodiode current measurements.

In photoconductive mode, an external reverse bias is applied, and the measured output current is linearly proportional to the input optical power. Applying a reverse bias increases the width of the depletion junction, producing an increased responsivity and a decrease in junction capacitance, which creates a very linear response. However, operating in a reverse bias condition tends to increase the dark current. Figure 2-1 shows the dark current when the photodiode is reverse biased.

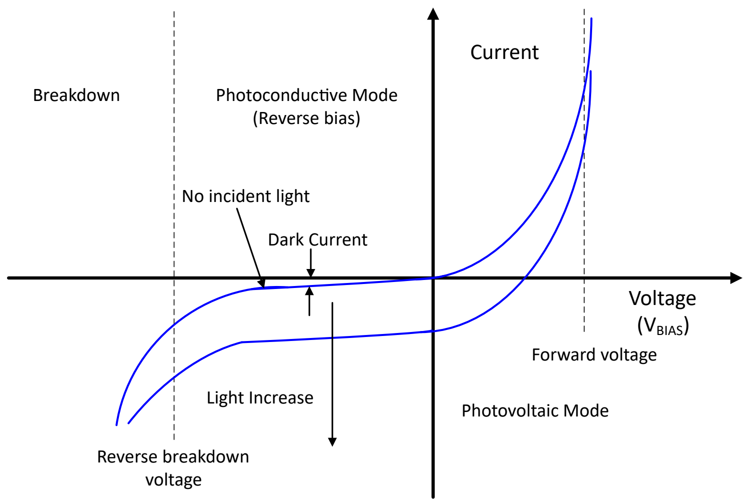

Figure 2-1. Photodiode Dark Current in Photoconductive Mode

This example shows a near-infrared (NIR) wavelength Indium Gallium Arsenide (InGaAs) photodiode for the design. In this application example, the photodiode operates in 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) increases the depletion region width and consequently decreases the junction capacitance; therefore, increasing V_R improves the speed of response and linearity of the photodiode, with a trade-off of larger dark current.

Table 2-1 shows the NIR G8195-12 photodiode parameters.

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

Parameter	Symbol	Test Conditions	Min.	Typ.	Max.	Unit
Max Reverse Voltage	V_R	T_A = 25°C			20	V
Spectral Response Range	ƛ	T_A = 25°C		0.9 to 1.7		µm
Photodiode Respositivity	R(ƛ)	T_A = 25°C ƛ = 1.3 µm	0.75	0.9		A/W
Junction Capacitance	C_J	T_A = 25°C V_R = 5V f = 1 MHz		1.0	1.5	pF
Dark Current	I_{dark}	T_A = 25°C V_R = 5V		0.02	0.4	nA

3 Interfacing the LOG200 With the Photosensor

3.1 Photodiode Connections

The *LOG200EVM* PCB board layout includes a photosensor footprint (D1) to install a radial photodiode on current input I1 for the logarithmic numerator and optional passive component footprints for compensation and photosensor biasing circuits. Refer to Figure 3-1 for the *LOG200EVM* photosensor biasing connections.

The LOG200 photodiode IBIAS adaptive biasing current output is accessible through an optional jumper resistor R2. The adaptive current output biasing scheme creates a voltage to bias a photodiode with a current proportional to the photocurrent. Compensation capacitor C1 (C_{COMP}) helps providing dynamic currents during fast transients to improve stability. The following section discusses the current adaptive biasing feature in detail.

Alternatively, the photosensor cathode can be reverse-biased via test point TP1, DBIAS. When not using the photodiode adaptive biasing feature, leave the IBIAS pin floating. Remove resistor R2 when biasing the photosensor through TP1.

3.2 Photodiode Adaptive Biasing Current Output

The LOG200 includes an IBIAS current source to bias a photodiode with a reverse voltage proportional to the photocurrent. The adaptive biasing circuit produces a small reverse bias voltage across the photosensor during low photodiode current measurements, reducing the photodiode's dark current and improving the measurement's accuracy. During the measurement of high photodiode currents, a higher reverse-bias voltage is developed across the photodiode, reducing the photodiode's effective capacitance, increasing the circuit bandwidth, and providing a faster transient response.

Figure 3-1 shows a block diagram with the adaptive biasing circuit and photodiode connections on the LOG200EVM. Internal transistor Q3 is used to measure the input current, and the IBIAS circuit produces a current output of approximately 1.14 times (typ) the input current of the I1 pin. The IBIAS pin connects to the photodiode cathode, and the R_{BIAS} resistor connects in parallel to the photodiode cathode and VCM.

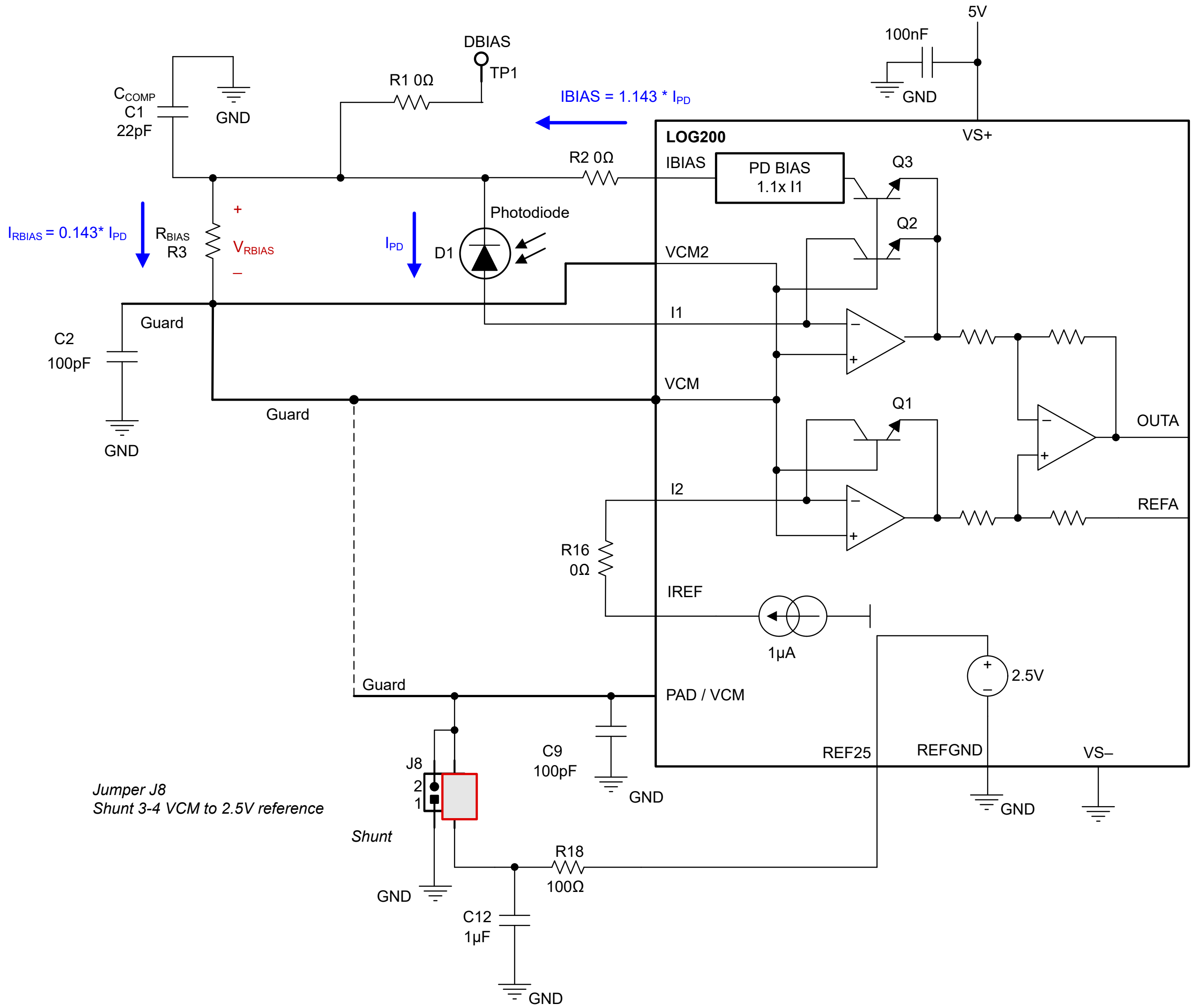

Figure 3-1. IBIAS Photodiode Adaptive Biasing Current Output

When using the IBIAS circuit, 1.0 times the input current flows through the photodiode, and the remaining 0.143 times of the input current flows through R_{BIAS}. This configuration establishes a bias voltage across the RBIAS resistance. The photodiode anode is connected to the I1 input and held at a constant VCM voltage. The cathode voltage effectively rises by 0.143 × R_{BIAS} × I1, thus providing a current-dependent reverse bias voltage for the photodiode. Select the proper R_{BIAS} resistor for the designed for photosensor reverse bias voltage.

Scale the R_{BIAS} resistor to allow a 1V headroom for the positive (VS+) supply while considering the maximum current of the photodiode. Also, a C_{COMP} capacitor from IBIAS to GND needs to be placed for stability; a suggested value is 22pF.

For example, the circuit of Figure 3-1, consider the case where the LOG200 is to support a photodiode application with an IPD current in the range of 20nA to 2.5mA, with VCM set to +2.5V while a unipolar 5V supply powers the LOG200.

Equation 1 provides the maximum possible bias voltage across R_{BIAS}:

$$V_{RBIAS\_MAX} = [(VS+) - 1V] - VCM \quad (1)$$

Equation 2 provides the maximum possible I_{BIAS} current:

$$I_{RBIAS\_MAX} = \left(IBIAS_{RATIO\_MAX} - 1\right) \times I_{PD\_MAX} \tag{2}$$

Equation 3 solves for the maximum possible R_{BIAS} resistance:

$$R_{BIAS\_MAX} = \frac{V_{RBIAS\_MAX}}{I_{RBIAS\_MAX}} \tag{3}$$

Equation 4 calculates the maximum RBIAS resistor allowing a 10% margin for error:

$$R_{BIAS} = 90\% \times R_{BIAS\_MAX} \tag{4}$$

Table 3-1 shows the calculation results as a function of I_{PD_MAX}

Table 3-1. RBIAS Resistor Calculations

I_{PD_Max} (mA)	$I_{BIAS\_Ratio\_Max}$ @ 1mA (A/A)	I_{BIAS_Max} (mA)	V_{BIAS_Max} (V)	R_{BIAS_Max} (kΩ)	R_{BIAS} (kΩ)
2.5	1.195	0.488	1.5	3.077	2.770

Figure 3-1 shows the typical VBIAS voltage across RBIAS when IPD = 2.5mA.

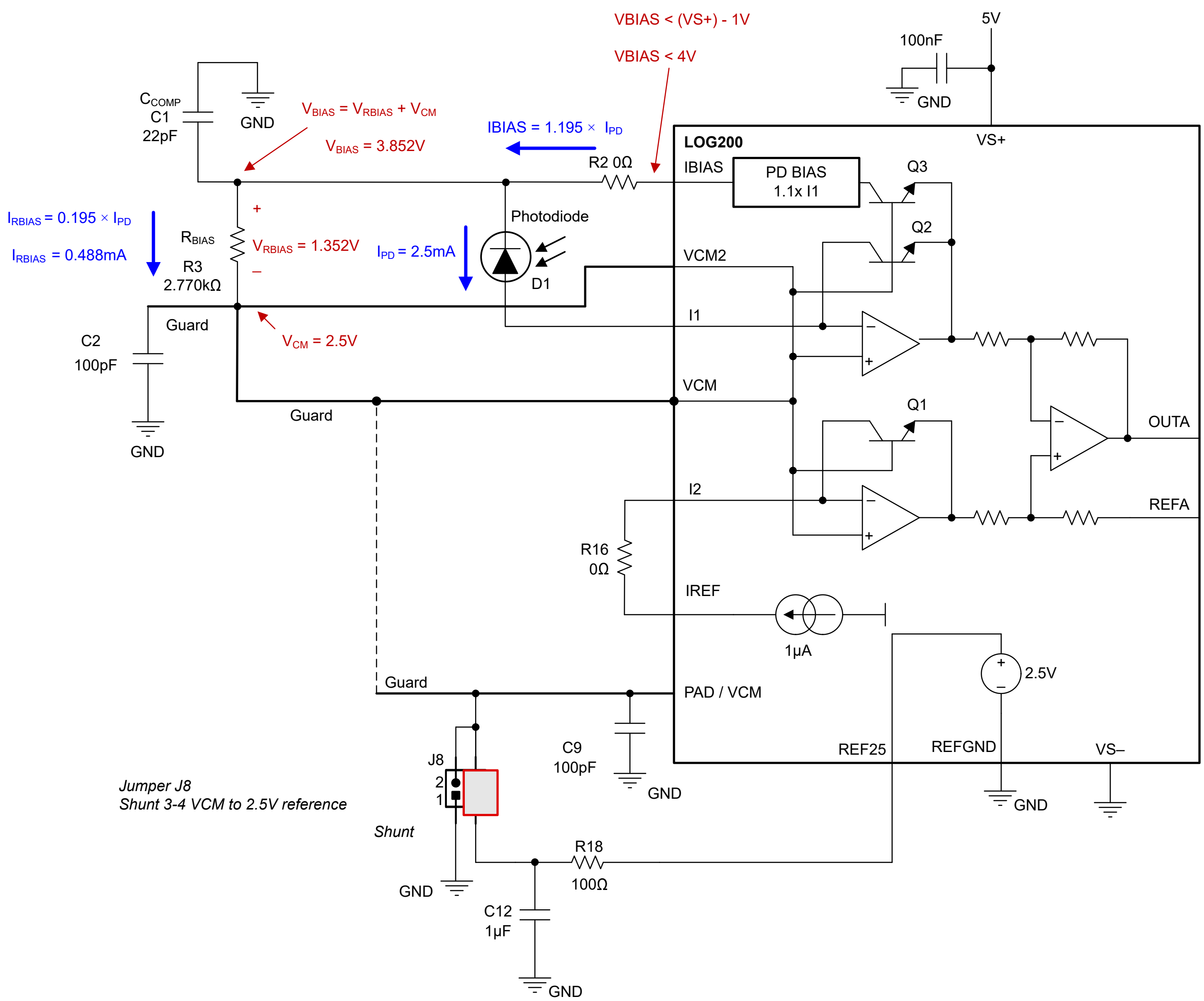

Figure 3-2. Example of RBIAS Calculation

4 Optical Bench for Current Sensing Measurements

The LOG200EVM is configured on the bench, with the G8195-12 photodiode installed,as shown in Figure 3-1.

The REF25 (2.5V reference) sets the VCM potential. The IREF current (1μA) feeds I2 via resistor R16. RBIAS (R3 on the LOG200EVM) is set to 1.65kΩ, with a compensation capacitor of C_{COMP} (C1) of 22pF. The difference amplifier reference input (REF) connects to the REF165 (1.65V Reference).

Figure 4-1 shows the current sense bench fixture.

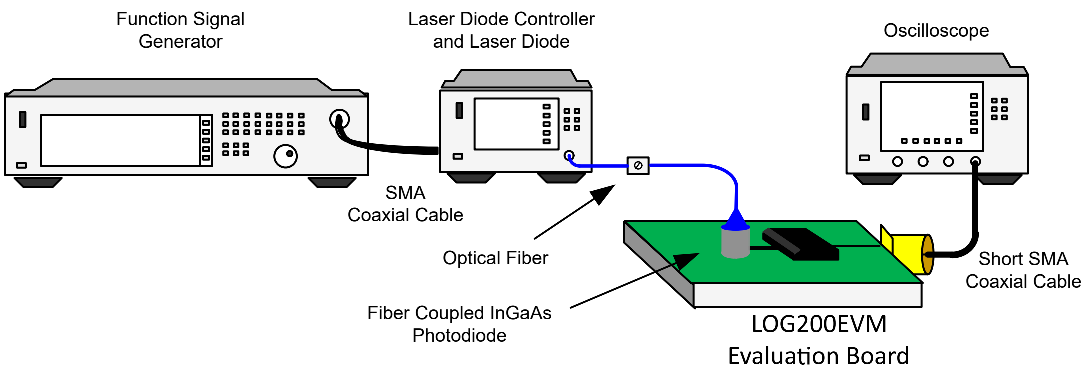

Figure 4-1. LOG200 Optical Current Sense Test

Table 4-1 lists the bench equipment used during these measurements.

Table 4-1. LOG200 Optical Bench Equipment

Device	Manufacturer	Part #	Description / Comments
Function Generator	Agilent	Agilent 33500	30MHz signal function waveform generator for laser modulation
Laser Controller	Thorlabs	CLD1010	Set to current control Mode Driven with Function Gen
Laser Diode	Thorlabs	LPS-1310-FC	λ = 1.31µm Threshold current 5mA to 20mA
Variable optical attenuator	Thorlabs	VOA50-FC-SM	1310/1550nm 50dB, FC/PC Connectors
Evaluation Board	Texas Instruments	LOG200EVM	LOG200 eval board with photodiode
Photodiode	Hamamatsu	G8195-12	λ = 1.31µm 1pF typical cap Response range, λ = 0.9µm to λ = 1.7µm Responsivity: 0.9A/W typ, λ = 1.55µm

The LOG200EVM jumpers are set as shown on Figure 4-2 and Table 4-2.

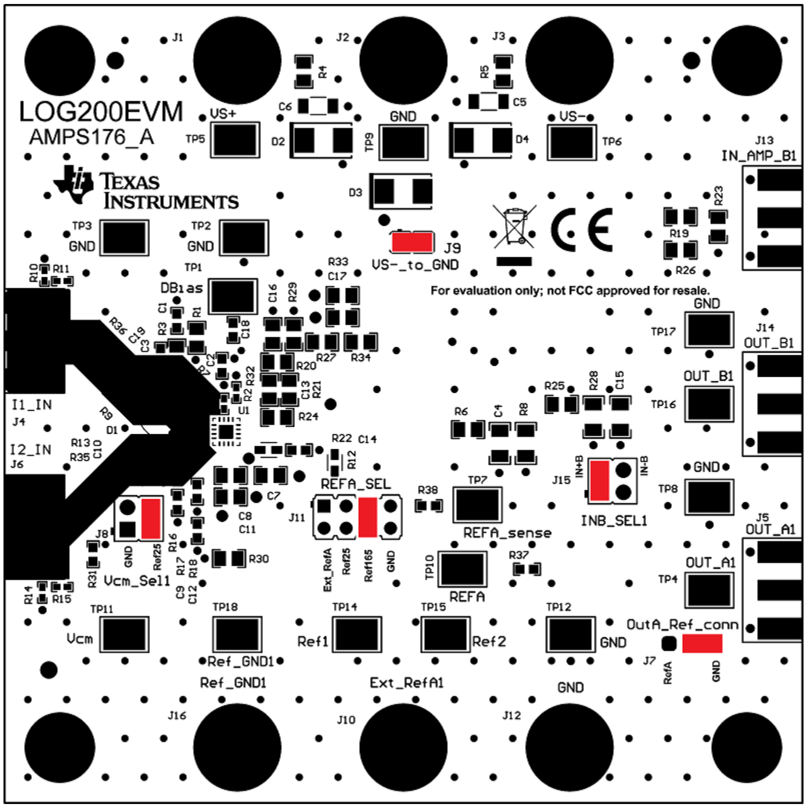

Figure 4-2. LOG200EVM Jumper Settings

Table 4-2. LOG200 Jumper Description

Jumper	Function	Bench Position	Description
J7	Out_ASMA J5 reference	Shunt 2-3	Shunt 2-3: SMA connector J3 referred to GND Shunt 1-2: SMA connector J3 referred to REFA
J8	VCM Select	Shunt 3-4	Shunt 1-2: VCM input connected to GND Shunt 3-4: Connects VCM input to 2.5V reference
J9	VS– connection	Shunt 1-2	Open: Bipolar supply configuration Shunt 1-2: Connects VS– to GND for unipolar supply configuration
J11	REF A Select	Shunt 5-6	Shunt 1-2: Sets log voltage REFA to external voltage through J10 Shunt 3-4: Sets REFA to REF25 Shunt 5-6: Sets REFA to REF165 Shunt 7-8: Sets REFA to GND
J15	Secondary op-amp input	Shunt 1-2	Shunt 1-2: Connects Aux AMP+IN to OUTA Shunt 3-4: Connects Aux AMP -IN to OUTA

4.1 Transient Response with Photosensor

The LOG200 achieves fast transient response using a new amplifier topology. The logarithmic amplifier stage dynamically changes the amplifier open-loop gain as a function of the input current. This circuit topology allows for a stable transient response across several current ranges without requiring a very high bandwidth amplifier. The LOG200 achieves transient response from low-to-high and high-to-low current measurements significantly faster than the previous-generation logarithmic amplifiers.

The following figures show oscilloscope captures of the LOG200 output as the device responds to one-decade shifts in the input current. The optical laser driver produces a sharp square waveform to measure the rising and falling steps between 100µA and 1mA, and between 10nA and 100nA. A 30MHz, 16-Bit voltage resolution function generator drives the laser driver for laser modulation.

Figure 4-3 and Figure 4-4 show the oscilloscope captures of the 20nA to 200nA current-step. The LOG200 measured a 154ns rise time and a fall time of approximately 472ns.

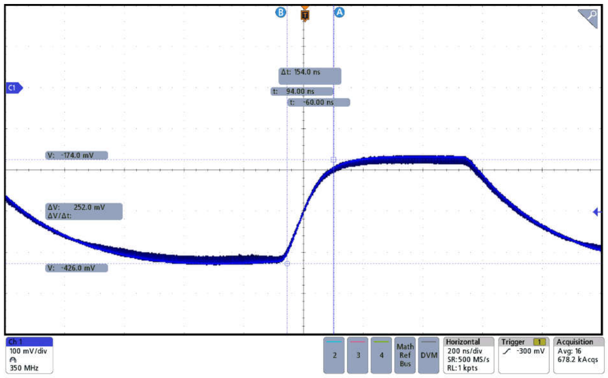

Figure 4-3. Oscilloscope Capture of a 20nA-200nA Current Step

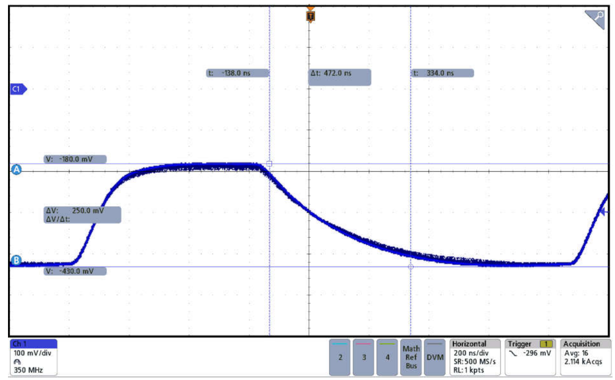

Figure 4-4. Oscilloscope Capture of a 200nA-20nA Current Step

Figure 4-5 and Figure 4-6 show the oscilloscope captures of the 200µA to 2mA current-step. The LOG200 measured a 26ns rise time and a fall time of approximately 31ns.

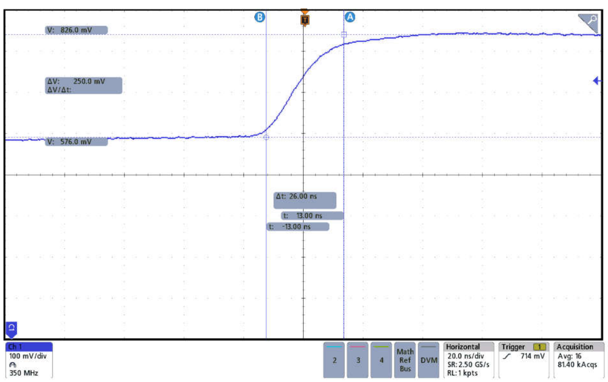

Figure 4-5. Oscilloscope Capture of a 200µA-2mA Current Step

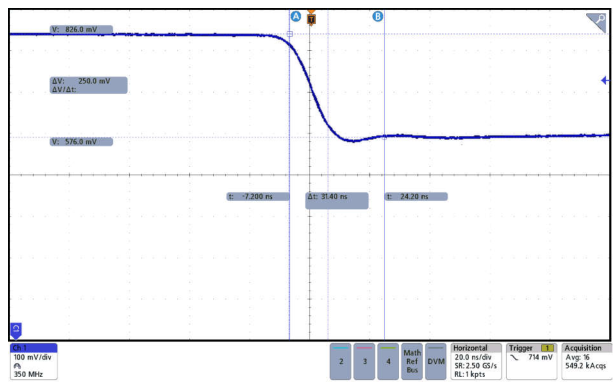

Figure 4-6. Oscilloscope Capture of a 2mA-200µA Current Step

5 Optical Power Measurements with the LOG200

A photodiode detector is a p-n junction semiconductor that can generate current if the energy of incident photons exceeds the material's bandgap. The sensitivity or responsivity of a photodiode (R) can be defined as the ratio of the generated photocurrent (I_{PD}) to the incident light power (P_{PD}) at a given wavelength (ƛ). Equation 5 show the relation of the photodiode responsivity:

$$R(ƛ) = \frac{I_{PD}}{P_{PD}} \quad (5)$$

Therefore, the optical power is equal to the ratio of the of the diode generated photocurrent and the responsivity of the photosensor, as shown on Equation 6.

$$P_{PD} = \frac{I_{PD}}{R(ƛ)} \quad (6)$$

In a default configuration, with the photodiode connected to input I1, and the LOG200 reference current output pin (I_{REF}) connected to input I2, the voltage output is defined by the transfer function shown in Equation 7:

$$V_{LOG} = 0.250 \times log_{10}\left(\frac{I_{PD}}{I_{REF}}\right) + V_{REF} \quad (7)$$

On this LOG200 circuit, I_{REF} of 1µA corresponds to an equivalent effective reference power P_{REF} of 1.25µW for a photodiode having a responsivity of 0.8A/W. Therefore, the LOG200 output transfer function can be expressed as Equation 8:

$$V_{LOG} = 0.250 \times log_{10}\left(\frac{P_{PD}}{P_{REF}}\right) + V_{REF} \quad (8)$$

The V_{LOG} voltage output can be used to calculate the optical power, where the slope for calculation is 250mV/decade for optical power or photodiode current.

6 Error Sources and Uncalibrated Error Analysis

This section shows an example of the LOG200 circuit estimated DC error analysis. These calculations use the typical LOG200 data sheet specifications to calculate the device's uncalibrated DC accuracy. This error estimate only includes the errors of the LOG200 device stand-alone.

This example assumes a photosensor application requiring a current range of 20nA to 2.5mA, where the LOG200 connects to a 12-Bit pseudo-differential input ADC powered with a 3V supply. Figure 6-1 shows the LOG200 circuit connections to the ADC.

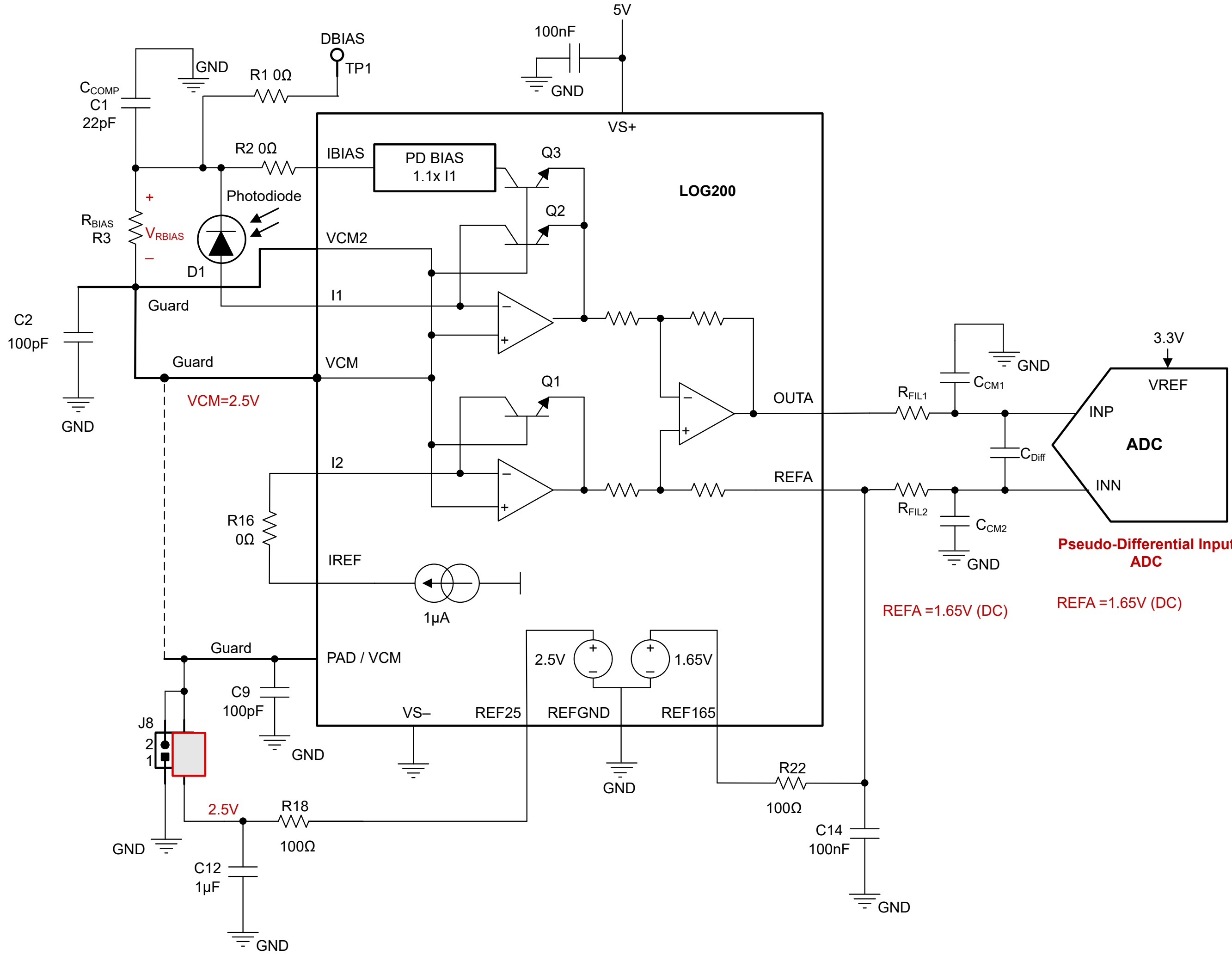

Figure 6-1. LOG200 Circuit connected to Pseudo-Differential Input ADC

Table 6-1 show the typical LOG200 specifications for error calculation:

Table 6-1. LOG200 Specifications for Error Calculation

Parameter	Description/Comment	Error Typical	UNIT
K_{Error}	Scaling factor error 100pA to 1mA	±0.15	%
LCE_{Error}	Logarithmic conformity error 10nA to 1mA	±0.050	%
I_{REF_Error}	Reference current error ±0.3% of I_{REF} = 1µA	±0.003	µA
V_{OSO}	Output offset error of logarithmic amplifier	±1.300	mV

Equation 9 shows the LOG200 designed for transfer function:

$$V_{LOG\_Ideal} = K \times \log_{10}\left(\frac{I_{PD}}{I_{REF}}\right) + V_{REF} \tag{9}$$

Equation 10 uses the designed for LOG200 transfer function to calculate the logarithmic amplifier output while adding the typical data sheet error parameters:

$$V_{LOGOUT\_Actual} = (K + \Delta K) \times \log_{10}\left(\frac{I_{PD}}{(I_{REF} - \Delta I_{REF})}\right) + (V_{REF} \pm \Delta V_{REF}) \pm LCE_{Er} \pm V_{OSO} \tag{10}$$

On a typical photodiode measurement application, where the photosensor connects to I1, V_{OS} does not contribute a significant error on the log amplifier transfer function. When the photodiode is biased with a proper reverse voltage, the sensor produces an input current virtually independent of the small input offset voltage V_{OS}. Therefore, in this photodiode measurement, VLOG_Actual is only dependent on the output offset error (V_{OSO}) of the logarithmic amplifier.

In this example, the REF165 1.65V reference connects to the negative input of a pseudo-differential input ADC, where the ADC converts only the difference between the ADC positive and negative inputs (AINP-AINN). Therefore, the accuracy of the voltage reference does not contribute to an error in the overall ADC conversionEquation 11 provides an estimate the total uncalibrated output error for a given photodiode current in this example:

$$V_{LOGOUT\_Actual} = (K + \Delta K) \times \log_{10}\left(\frac{I_{PD}}{(I_{REF} - \Delta I_{REF})}\right) + V_{REF} \pm LCE_{Er} \pm V_{OSO} \tag{11}$$

Table 6-2 summarizes the primary error sources in the LOG200 application. The calculations assume a photosensor application requiring a current range from I_{min} = 20nA to I_{max} = 2mA.

Table 6-2. Estimated V_{LOG} Uncalibrated Error Calculations From Typical Spec

Parameter	Equation	Result
Uncalibrated DC accuracy at I_{min} = 20nA, at 25 °C		
Nominal log amp output at I_{min} V_{LOG_Imin}	$V_{LOG\_Imin} = K \times \log_{10}\left(\frac{I_{min}}{I_{REF}}\right) + V_{REF}$	1.2253V
Log conformity error at I_{min} LCE_{Error_Imin}	$\Delta LCE_{Er\_Imin} = LCE_{Error} \times (V_{LOG\_Imin} - V_{REF})$	-0.212mV
Actual log amp output at I_{min} $V_{LOG\_Actual\_Imin}$	$V_{LOG\_Actual\_Imin} = (K + \Delta K) \times \log_{10}\left(\frac{I_{PD}}{(I_{REF} - \Delta I_{REF})}\right) + V_{REF} - \Delta LCE_{Er\_Imin} - V_{OSO}$	1.223V
Log amp error at at I_{min} $V_{LOG\_Error\_Imin}$	$V_{LOG\_Er\_Imin} = V_{LOG\_Imin} - V_{LOG\_Actual\_Imin}$	-2.598mV
Uncalibrated DC accuracy at I_{max} = 2.5mA, at 25 °C		
Nominal log amp output at I_{max} V_{LOG_Imax}	$V_{LOG\_Imax} = K \times \log_{10}\left(\frac{I_{max}}{I_{REF}}\right) + V_{REF}$	2.4995V
Log conformity error at I_{max} LCE_{Error_Imax}	$\Delta LCE_{Er\_Imax} = LCE_{Error} \times (V_{LOG\_Imax} - V_{REF})$	0.425mV
Actual log amp output at I_{max} $V_{LOG\_Actual\_Imax}$	$V_{LOG\_Actual\_Imax} = (K + \Delta K) \times \log_{10}\left(\frac{I_{max}}{(I_{REF} - \Delta I_{REF})}\right) + V_{REF} + \Delta LCE_{Er\_Imax} + V_{OSO}$	2.504V
Log amp error at at I_{max} $V_{LOG\_Error\_Imax}$	$V_{LOG\_Er\_Imax} = V_{LOG\_Imax} - V_{LOG\_Actual\_Imax}$	4.526mV
Total uncalibrated error as % of full-scale		
% Full-scale error at I_{min} $V_{LOG\_Error\_Imin\_FS}$	$V_{LOG\_Er\_Imin\_FS} = \frac{V_{LOG\_Er\_Imin}}{V_{LOG\_Imax} - V_{LOG\_Imin}} \times 100\%$	-0.204%
% Full-scale error at I_{max} $V_{LOG\_Error\_Imax\_FS}$	$V_{LOG\_Er\_Imax\_FS} = \frac{V_{LOG\_Er\_Imax}}{V_{LOG\_Imax} - V_{LOG\_Imin}} \times 100\%$	0.355%

The typical error specifications are added into the LOG200 transfer function to calculate a total compounded error. Since the absolute values are added together to calculate the total error, calculations using these typical values can yield a conservative error analysis, as the summation of uncorrelated errors tends to result in a larger compounded total predicted error than the actual total error observed on a real system. In many applications, the circuit designer can perform a two point linear calibration to reduce the errors due to offset and scale factor, resulting in a smaller DC error.

7 Auxiliary Op Amp Circuits

The LOG200 features an additional wide-bandwidth auxiliary amplifier. The amplifier can be used to perform scaling gain functions, filtering functions and single-ended to differential conversion circuts. This section contains an example for single-ended to differential conversion, and a low-pass Sallen-Key filtering application.

Do not use the auxiliary amplifier as a comparator, as the input pins of the auxiliary op-amp are protected from excessive differential voltage with an internal clamp built with back-to-back diodes. The op-amp is not intended to withstand a continuous differential voltage. For more information, refer to the auxiliary amplifier input voltage specifications on the Absolute Maximum Ratings table of the LOG200 data sheet.

7.1 Single-Ended to Differential Conversion Circuit

Figure 7-1 shows a circuit example of the LOG200 driving a fully-differential input ADC. This circuit uses the auxiliary op amp in the inverting configuration to perform a single-ended to differential conversion for driving the ADS7954 fully-differential, SAR ADC.

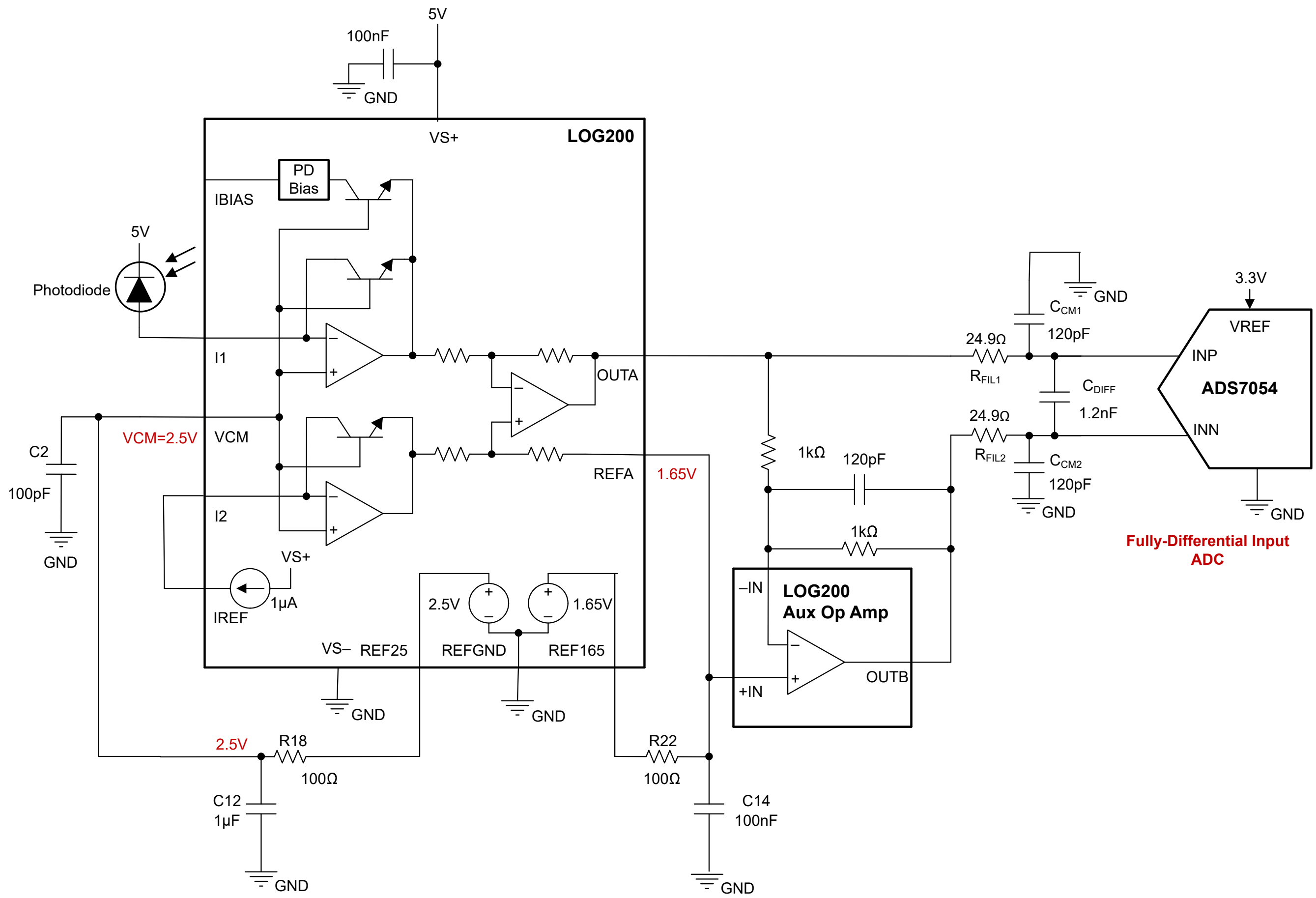

Figure 7-1. LOG200 Driving a Fully-Differential Input ADC

Table 6-1 show the typical LOG200 specifications for error calculation:

Design Notes:

1. Select high-grade C0G (NP0) capacitors for C_{DIFF}, C_{CM1}, C_{CM2} and C_{FB} to minimize distortion.
2. Use 0.1% resistors for R_{IN} and R_{FB} to minimize gain error and drift on the inverting amplifier circuit.
3. The R-C-R filter placed at the ADS7054 inputs drives the SAR as a charge kickback filter. The filter component values depend on the data converter sampling rate, the ADC sample-and-hold structure, and the data converter requirements. The filter combination (R_{FIL} and C_{FIL}) is tuned for ADC sample-and-hold settling performance while maintaining amplifier stability. The component value selection is dependent on the data converter sampling rate, the ADC sample-and-hold structure.

4. The values shown in this example provide good settling performance for the LOG200 and ADS7054 14-Bit, 1-MSPS, differential input, SAR ADC. If the circuit is modified, the circuit designer can need to select a different R-C-R filter depending on the ADC selection and application needs. See the Introduction to SAR ADC Front-End Component Selection training video for an explanation of how to select the RC filter for best settling performance.

7.2 Sallen-Key Low-Pass Filter

A typical application use case for the auxiliary amplifier is implementing an active low-pass filter and delivering a low-noise signal free of high-frequency aliasing signals into an ADC. Figure 7-2 shows an example of the LOG200 with the auxiliary amplifier on a second-order low-pass Sallen-Key filter. The LOG200EVM provides footprint components to implement this filter in the hardware. This example presents a second-order Sallen-Key filter configuration to provide a Butterworth filter response, giving a 40dB/decade roll-off with a –3dB frequency of 50kHz.

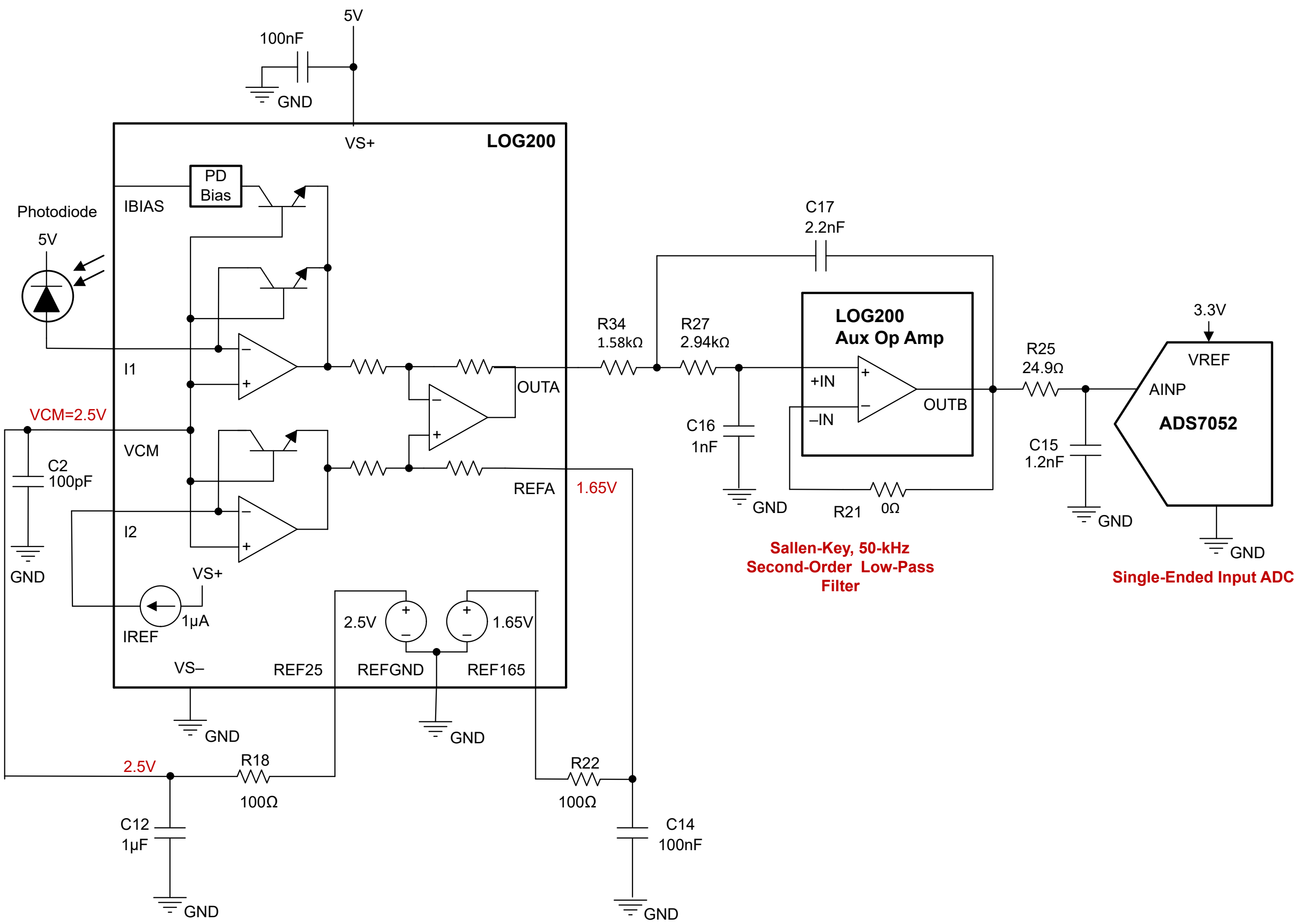

Figure 7-2. LOG200 with Sallen-Key Low-Pass Filter

Design Notes:

The design is implemented using TI's *Filter Design -Tool*. The steps to design the filter are as follows:

1. Use TI's *Filter Design -Tool* selecting a low-pass second-order filter with Gain 0dB, a passband frequency of 50kHz, and Butterworth filter response.
2. Using TI's Analog Filter Tool, select the Sallen-Key topology for the filter and create the design.
3. Scale the resistor values carefully to not meaningfully contribute to the output noise produced by the LOG200. Choose E94 (5%) or better accuracy capacitors and E198 (0.1%) resistors for accurate filter frequency response. Select high-grade C0G (NP0) capacitors on the filter and signal path to minimize distortion.

4. Set the output resistor to 24.9Ω with a 1.2nF capacitor. The values shown in this example provide good settling performance for the LOG200 and ADS7052 14-Bit, 1-MSPS, single-ended input, SAR data converter. If the circuit is modified, the designer can need to select a different R-C charge reservoir filter depending on the ADC selection and application needs. See the *Introduction to SAR ADC Front-end Component Selection* training video for more information.

Figure 7-2 shows the filter's gain and phase frequency response plots. The Sallen-Key filter features a Butterworth response with a maximally flat passband gain, and a second-order roll-off at 50kHz. The filter greatly attenuates any unwanted higher-frequency signals and keeps noise from aliasing back into the photosensor signal frequency range.

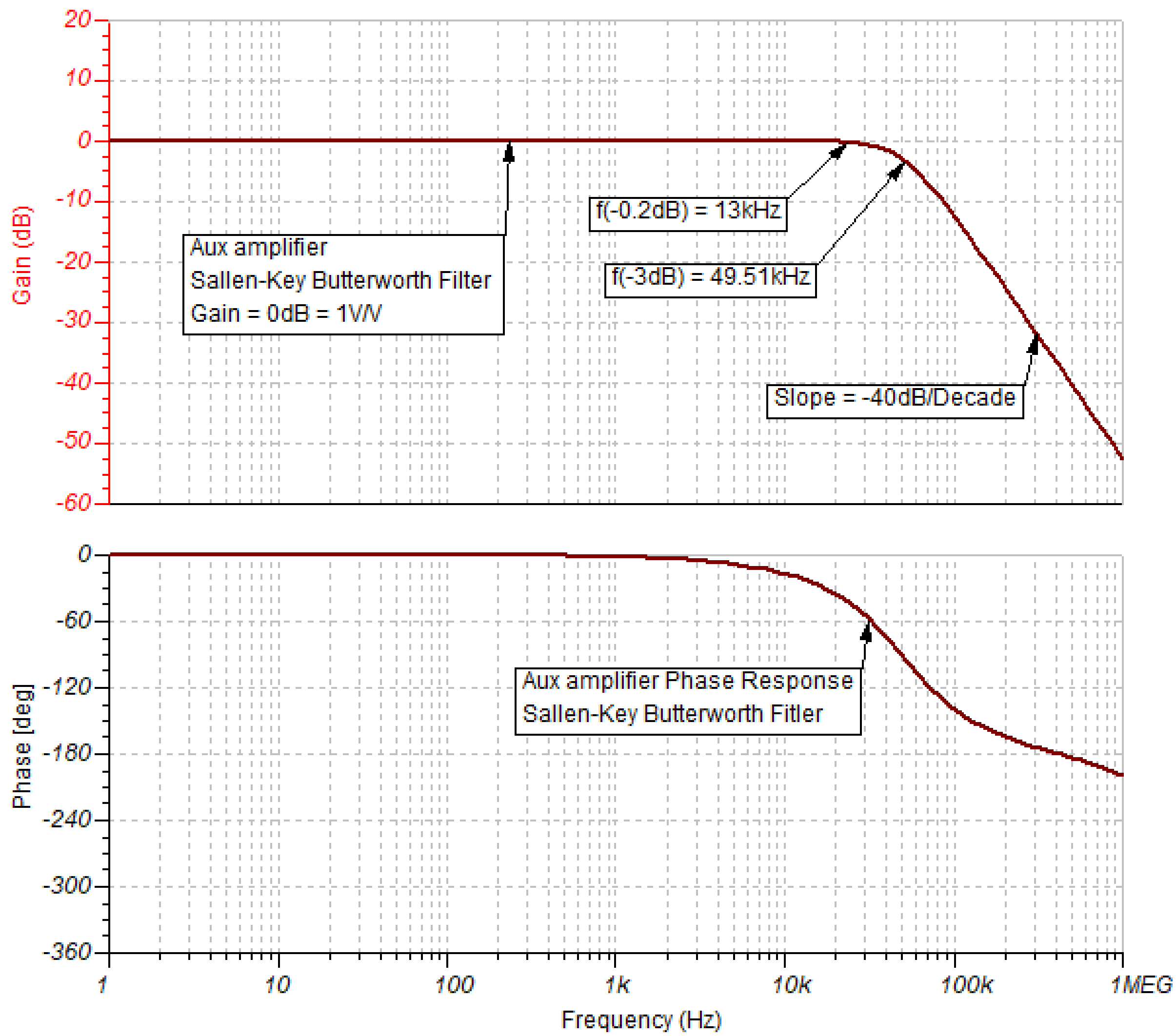

Figure 7-3. Aux Amplifier Sallen-Key Filter Frequency Response Simulation

8 Summary

The preceding discussion provides information and examples on how to interface the LOG200 to facilitate the design of the logarithmic amplifier on optical current sense measurement applications.

9 References

1. Texas Instruments, *LOG200 Precision, High-Speed Logarithmic Amplifier With Integrated Photodiode Bias*, data sheet.
2. Texas Instruments, *LOG200 Evaluation Module User's Guide*
3. Texas Instruments, *Introduction to SAR ADC Front-end Component Selection*, training video.
4. Texas Instruments, *Filter Design -Tool.*

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265