

TI Precision Designs: Reference Design Noise Measurement Post-Amp



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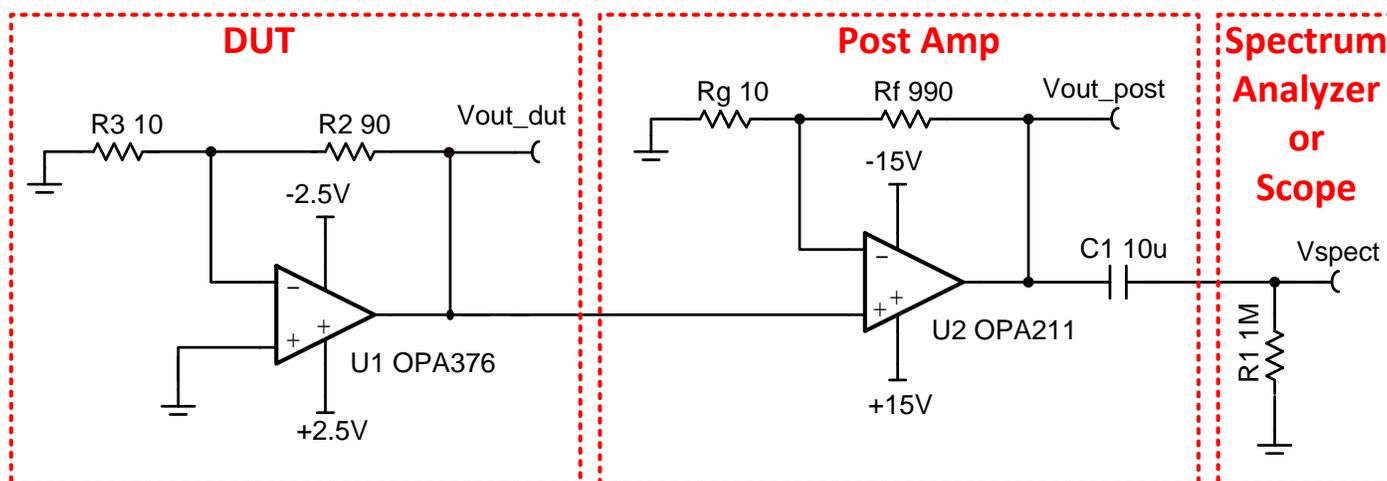
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Circuit Description

In some cases a scope or spectrum analyzer does not have the range required to measure very small noise levels. This noise measurement post-amp boosts the output noise of the device under test (DUT) to allow for measurement with standard test equipment. The key requirements of this circuit is that it has a low noise floor and sufficient bandwidth for characterization of most devices.



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1 Design Summary

The design requirements are as follows:

- Supply Voltage: ± 15 V, and ± 2.5 V
- Input: 0V (GND)
- Output: ac Noise Signal

The design goals and performance are summarized in Table 1. Figure 1 depicts the output noise spectral density.

Table 1. Comparison of Design Goals, Simulation, and Measured Performance

	Goal	Simulated
Gain (V/V)	1000	1000
Gain Error (%)	2%	1.2%
f_L	$f_L < 0.1\text{Hz}$	0.016Hz
f_H	$f_H > 100\text{kHz}$	443kHz
Noise Floor (post amp input)	1nV/rtHz	1nV/rtHz

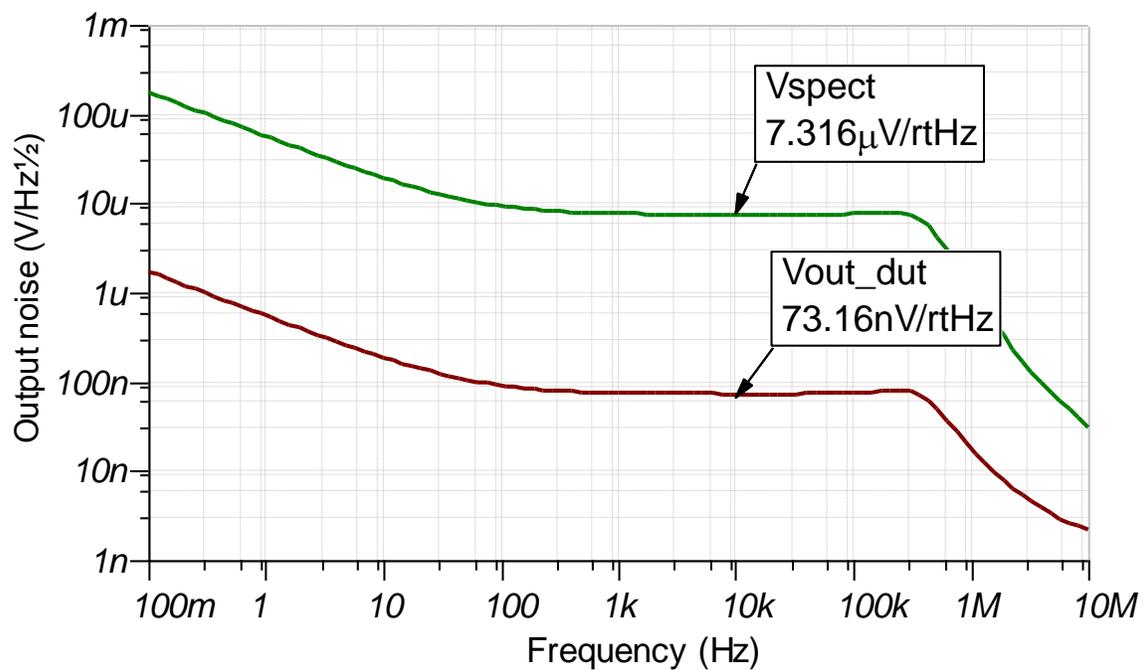


Figure 1: Output Noise Spectral Density

2 Theory of Operation

Figure 2 illustrates a common limitation of test equipment. The intent of this circuit is to measure the input referred noise of the device under test (DUT). However, the spectrum analyzer noise floor is too large compared to the DUT output noise to get an accurate result. For best results the DUT noise should be at least 3x greater than the spectrum analyzers noise floor. Equation (1) (3) shows how the DUT output noise adds with the spectrum analyzer noise floor and Equation (2) gives the calculate results for this example. Note that the error from equipment limitations is significant. The equipment limitation can be overcome using a low noise post amplifier.

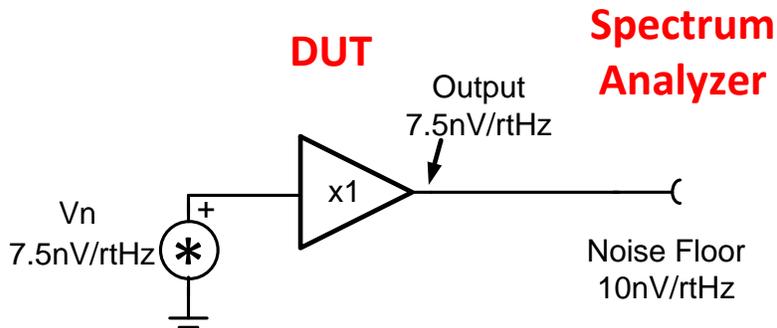


Figure 2: Noise Floor Issue with Standard Test Equipment

$$e_{n_spect} = \sqrt{(e_{n_DUT_out})^2 + (e_{n_Post_floor})^2} \quad (1)$$

Where

e_{n_post} = noise referred to the input of post amplifier

$e_{n_DUT_out}$ = noise output from DUT

$e_{n_post_floor}$ = noise floor of post amp

$$e_{n_post} = \sqrt{(7.5nV/\sqrt{Hz})^2 + (10.0nV/\sqrt{Hz})^2} = 12.5nV/\sqrt{Hz} \quad (2)$$

Figure 3 gives a simple block diagram for a noise measurement post amplifier. In this example, the post amplifier noise floor is significantly lower than the noise from the DUT stage. Equation (3) shows how the DUT output noise adds with the post amplifier noise floor and Equation (4) gives the calculated results for this example. In this case the noise floor does not introduce a significant error. The same procedure can be used to add the post amplifier output noise with the spectrum analyzer noise floor as shown in Equations (5) and (6).

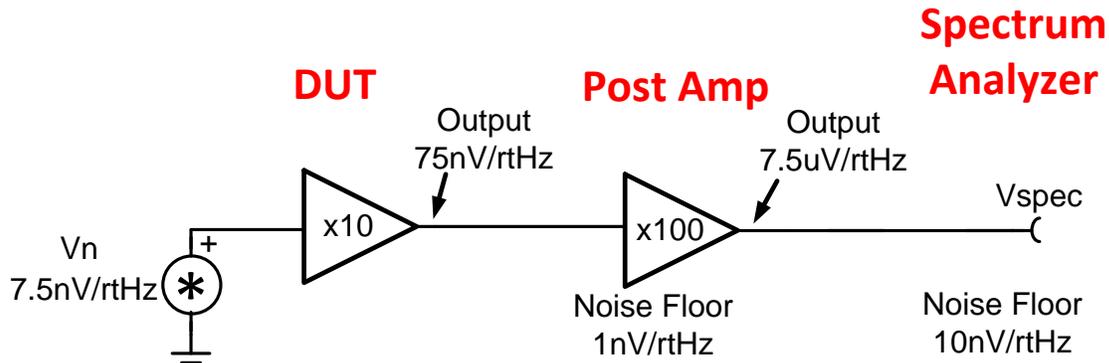


Figure 3: Using a Post Amp to Boost Noise Signal

$$e_{n_post} = \sqrt{(e_{n_DUT_out})^2 + (e_{n_Post_floor})^2} \quad (3)$$

Where

e_{n_post} = noise referred to the input of post amplifier

$e_{n_DUT_out}$ = noise output from DUT

$e_{n_post_floor}$ = noise floor of post amp

$$e_{n_post} = \sqrt{(75.0nV/\sqrt{Hz})^2 + (1.0nV/\sqrt{Hz})^2} = 75.0nV/\sqrt{Hz} \quad (4)$$

$$e_{n_spec} = \sqrt{(e_{n_post_out})^2 + (e_{n_spect_floor})^2} \quad (5)$$

Where

e_{n_spec} = noise measured by spectrum analyser

e_{n_DUT} = noise from DUT

$e_{n_post_floor}$ = noise floor of post amp

$$e_{n_spect} = \sqrt{(7.50\mu V/\sqrt{Hz})^2 + (10.0nV/\sqrt{Hz})^2} = 7.50\mu V/\sqrt{Hz} \quad (6)$$

Figure 4 shows the full schematic for the design. The first stage (U1) is the device under test (DUT). In this example a low noise device with $\pm 2.5V$ supplies is being tested; however, this circuit could be to test a wide range of devices including devices with $\pm 15V$ supplies. The DUT gain is set to 10V/V. The DUT gain is selected for maximum gain while maintaining a bandwidth of greater than 100kHz. The bandwidth of 100kHz was selected because it is a common bandwidth used in characterization of noise spectral density. The gain of the DUT can be adjusted to accommodate different bandwidth requirements. The DUT gain setting resistors are selected for low resistance to minimize the addition of thermal noise. Notice that the input of the DUT is grounded so that only its noise signal and input offset voltage is amplified.

The gain of the post amplifier is also set to maximize gain while maintaining bandwidth of greater than 100kHz. The post amplifier needs to have wide bandwidth and low noise. The goal of the post amplifier is to further amplify the DUT output without adding any significant additional noise. The post amplifier uses $\pm 15V$ supplies to allow for DUT voltages up to $\pm 15V$.

The capacitor C1 is used to ac couple the output of the post amp to the spectrum analyzer or scope. In this case we are assuming that the instrument has a 1M Ω input impedance. The noise signal is ac coupled to eliminate the dc offset from the post amplifier. Without ac coupling, the dc offset would necessitate the use of poor range for noise measurement because the magnitude of the offset is large compared to the noise signal. For example, a typical noise signal may be microvolts whereas the offset may be millivolts. This is effectively the same as using ac coupling on the instrument except that the built in ac coupling has a lower cutoff frequency of about 60Hz whereas the R1xC1 filter has a cutoff frequency of 0.016Hz. The low cutoff frequency of the R1xC1 filter is important in measuring 1/f noise.

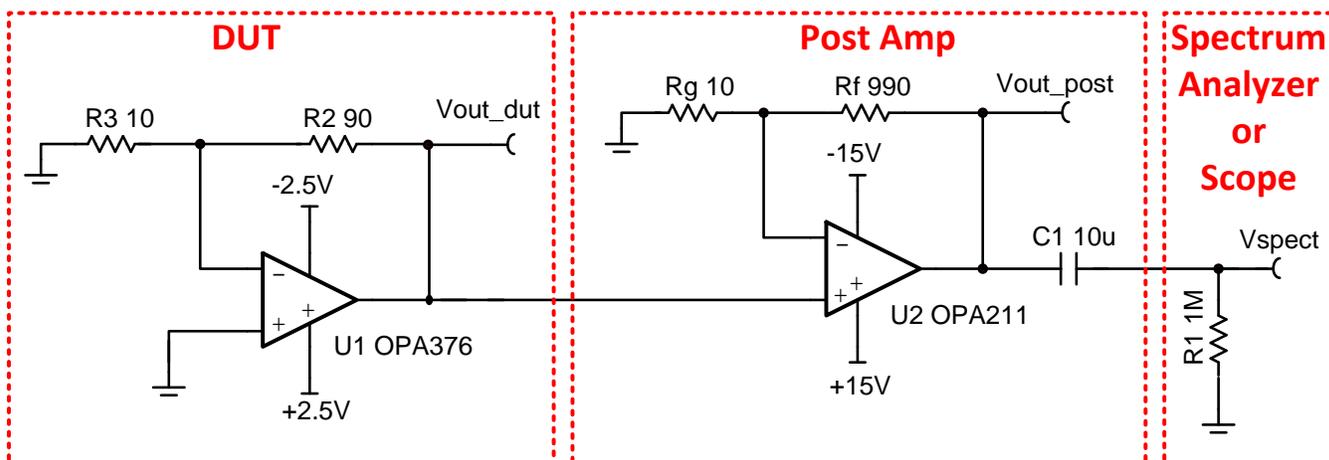


Figure 4: Complete Circuit Schematic

2.1 Design of DUT Amplifier

The objective of this design is that different DUT amplifiers can be tested without modification. However, before testing the amplifier you will have to confirm the different design requirements outlined in this section are not violated. The approach taken in this section is fairly conservative so this design will work for many amplifiers without modification.

The resistors R2 and R3 set the gain for the DUT amplifier U1. The gain of the DUT stage will amplify the noise to a level where it is dominant and other noise sources are insignificant. The maximum gain of the DUT stage determines the minimum bandwidth. In this case we want the minimum bandwidth to be 100kHz so the maximum gain is 55V/V (see Equation (7) and Table 2). It is recommended that you include a minimum of 20% margin to allow for process variation. Thus, the maximum gain should be less 44V/V (i.e. 55V/V x 80%). Furthermore, using factors of 10 allow for easy interpretation of test results, so gain was selected to be 10V/V in this case. Using the selected gain the upper cutoff frequency is 550kHz (see Equation (9)).

Table 2: Gain Bandwidth Specification from OPA376 Data Sheet

PARAMETERS	CONDITIONS	OPA376, OPA2376, OPA4376			UNIT
		MIN	TYP	MAX	
Gain Bandwidth Product (GBW)	$C_L = 100\text{pF}$, $V_S = 5.5\text{V}$		5.5		MHz

$$G_{CL_max} = \frac{GBW}{f_H} = \frac{5.5\text{MHz}}{100\text{kHz}} = 55 \text{ V/V} \quad (7)$$

Where

G_{CL_max} = Closed loop gain

GBW = Gain Bandwidth

f_H = Upper Cutoff frequency (Bandwidth Limit)

$$G_{CL_selected} = 10 \text{ V/V} \quad (\text{Less than } G_{CL_max} \text{ and simple factor}) \quad (8)$$

$$f_H = \frac{GBW}{G_{CL_selected}} = \frac{5.5\text{MHz}}{10\text{V/V}} = 550\text{kHz} \quad (9)$$

The gain set resistors in the DUT stage will add thermal noise. The objective is to select resistor values that have a noise spectral density that is small compared with the DUT amplifier. The parallel combination of R2 and R3 generate an input referred noise that can be compared with the amplifiers noise spectral density. Figure (5) can be used to compute the noise spectral density for R2 || R3 (R2 || R3 is approximately 10Ω which produces 0.4nV/rtHz of noise for this example).

In general, using small resistors will reduce the resistor noise to the point where it is no longer significant. However, be careful that the amplifier is not forced to drive excessive current. In this example the output current can be calculated by dividing the input offset voltage by R3 ($25\mu\text{V} / 10\Omega = 2.5\mu\text{A}$). In most noise test configurations, the output current will be small because the only signal is the offset voltage. However, be careful if an input signal is applied, large currents will develop when using the small feedback elements. For example if a 10mV signal is applied 1mA of current will be generated ($10\text{mV}/10\Omega = 1\text{mA}$).

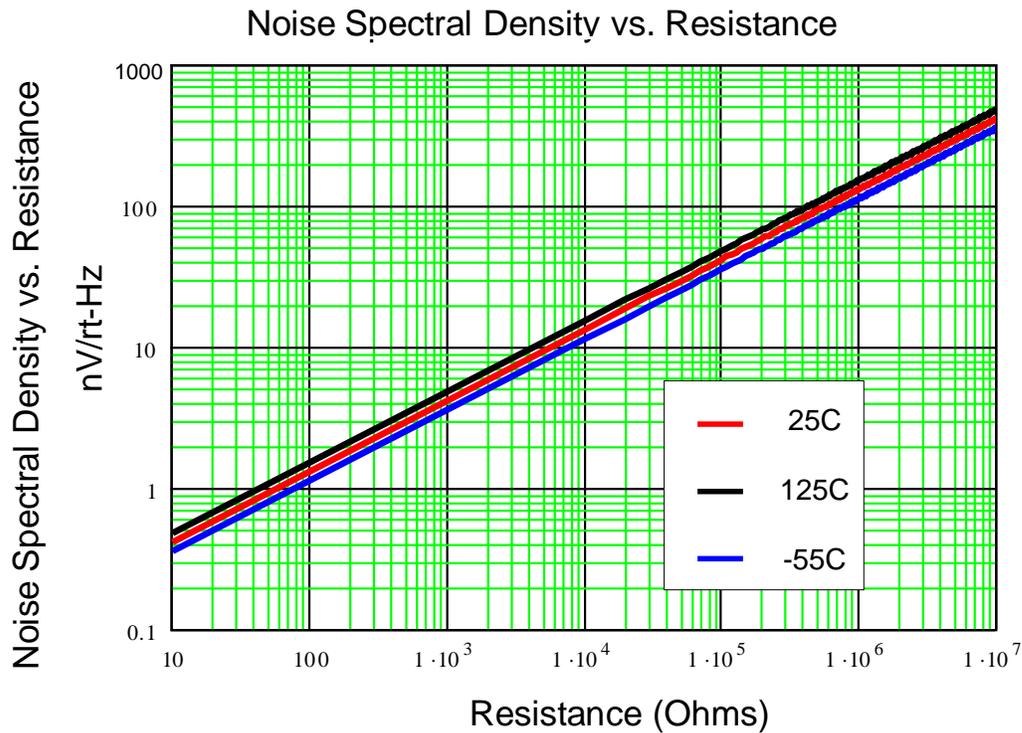


Figure 5: Noise Spectral Density vs. Resistance

2.2 Design of Post Amplifier

The post amplifier design will amplify the input noise for a wide range of different DUT amplifiers. The gain of the post amplifier is set to 100V/V and the bandwidth is 800kHz. The OPA211 was selected because it has a wide bandwidth and low noise spectral density. The noise floor of the post amplifier is approximately 1.1nV/rtHz. Select an amplifier that has an output noise at least 3x lower than the DUT noise floor to minimize noise.

The design procedure for the post amplifier is similar to the DUT. The resistors Rf and Rg set the gain for the post amplifier U2. The gain of the post amplifier stage will amplify the noise to a level where it is easily measured by the spectrum analyzer or oscilloscope. In this example, the gain is set to 100V/V for simple scaling. Equation (10) and Table 3 show the bandwidth calculation.

The resistors were selected using the same procedure given in Section 2.1. The total contribution of the resistor noise is about 0.4nV/rtHz which is small compared with the OPA211's voltage noise spectral density.

Table 3: Gain Bandwidth Specification from OPA211 Data Sheet

PARAMETERS	CONDITIONS	OPA211			UNIT
		MIN	TYP	MAX	
Gain Bandwidth Product (GBW)	G=100		80MHz		MHz

$$f_H = \frac{GBW}{G_{CL_selected}} = \frac{80MHz}{100V/V} = 800kHz \quad (10)$$

2.3 Design of ac Coupling Circuit

The purpose of the ac coupling circuit is to eliminate the dc offset at the output of the post amplifier. The ac coupling circuit is composed of the coupling capacitor (C1) and the input impedance of the instrument (R1). The cutoff frequency of the circuit needs to be lower than 0.1Hz to allow for characterization of flicker noise. A 10μF coupling capacitor gives a 0.016Hz cutoff frequency which is lower than the required 0.1Hz. Increasing the capacitor further could move the cutoff frequency even lower if you need to measure ultra low frequency noise; however, keep in mind that the capacitor needs to charge during the amplifier's initial power up. With the selected ac coupling circuit the capacitor will be 99.3% charged in 50s (see Equation (13)).

$$f_L = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi(1M\Omega)(10\mu F)} = 0.016Hz \quad (11)$$

$$\tau = R_1 C_1 = (1M\Omega)(10\mu F) = 10s \quad (12)$$

$$5\tau = 5(10s) = 50s \text{ for } 99.3\% \text{ charged.} \quad (13)$$

3 Component Selection

3.1 DUT Selection

A wide range of DUT can be used with this circuit. For amplifiers with a gain bandwidth product less than 1MHz, the gain will have to be scaled to achieve the 100kHz bandwidth. Also pay attention to the DUT output noise as it needs to be at least three times greater than the noise floor of the post amplifier (DUT Noise > 3.3nV/rtHz).

3.2 Post Amp Selection

The post amplifier (U2) was selected low noise, and bandwidth. For this configuration the DUT input noise must be at least 0.33nV/rtHz (i.e. Post_Amp_Noise x 3 / DUT_GAIN = 1.1nV/rtHz x 3 / 10). Other options are given in the modifications section (Section 5).

3.3 Passive Component Selection

Standard metal film 1% resistors is sufficient for this design. A ceramic X7R capacitor is sufficient for the coupling capacitor.

4 Simulation

The TINA-TI™ schematic shown in Figure 6 includes the circuit values obtained in the design process.

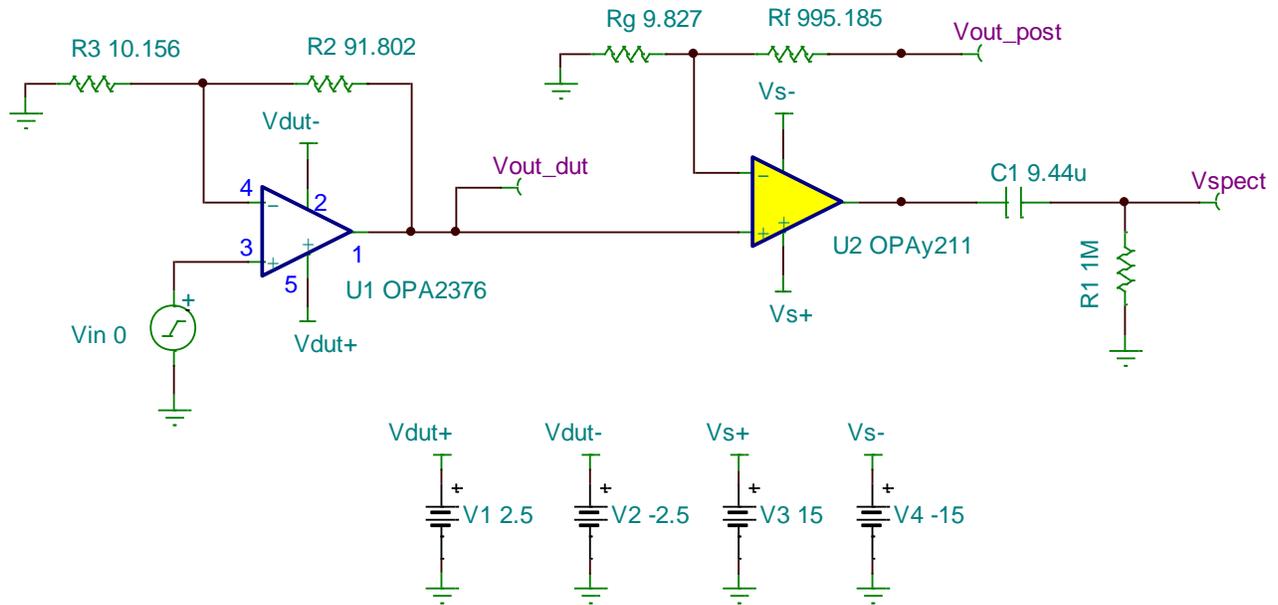


Figure 6: TINA-TI™ Schematic

4.1 Noise Spectral Density

The simulated noise spectral density for the post amplifier is given in Figure 7. The main goal of the circuit is to facilitate the measurement of the DUT's voltage spectral density curve. The DUT spectral density curve can be generated by taking the output spectral density measured by the spectrum analyzer (V_{spect}) and dividing it by the total gain (1000V/V in this case). The data sheet specified spectral density (bottom of Figure 7) to the spectrum analyzer reading divided by the total gain ($V_{spect}/1000$ at the top of Figure 7) agrees closely.

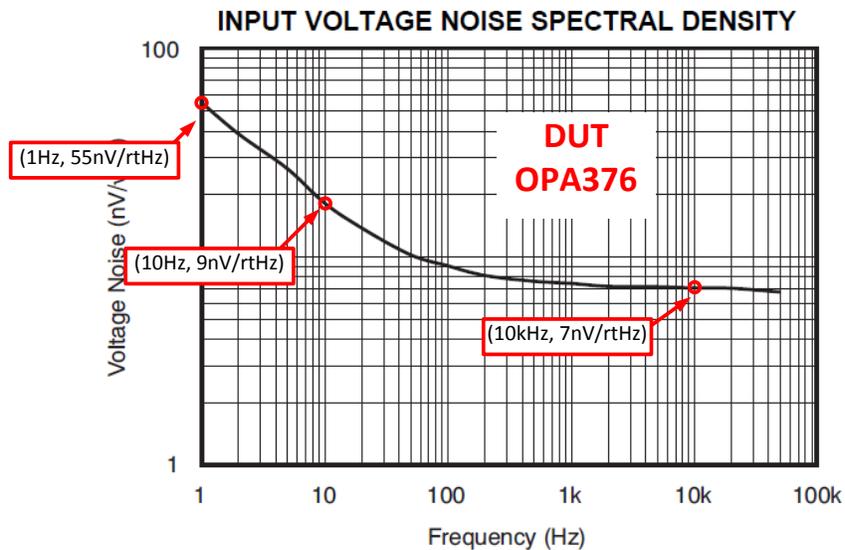
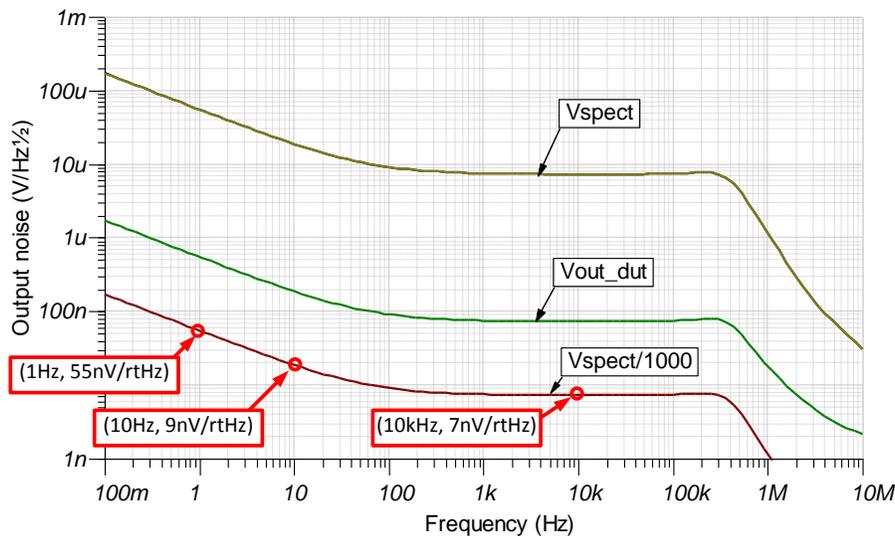


Figure 7: Simulated Noise Spectral Density vs. Specified

4.2 DC Offset

Figure 8 shows the dc offset at the output of the DUT and post amplifier stages. Depending on the offset of the DUT the offset can be different. With the given gain selection it is unlikely that offset will cause any issues; however, if higher gains were used you may need to take care to avoid output saturation. For example, in a gain of 10,000V/V a 2mV DUT offset can generate a 20V output which could drive the post amplifier into the supply rail. Note that the ac coupling network C1xR1 eliminates the offset as expected.

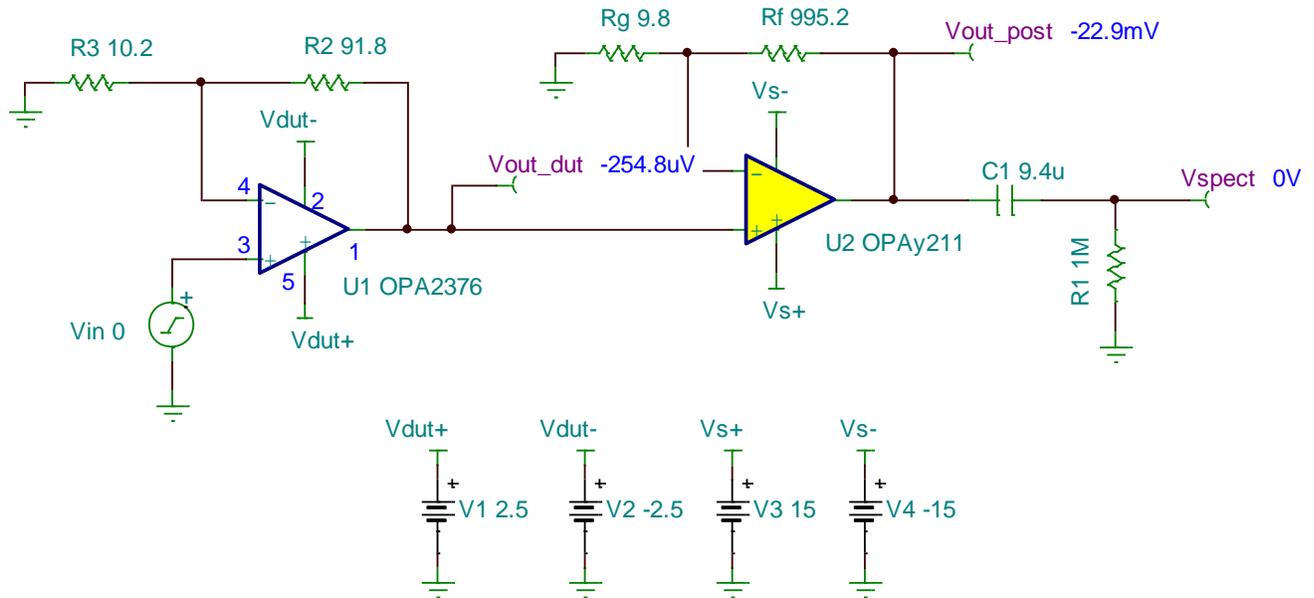


Figure 8: DC Offset for the Noise Post Amplifier Design

4.3 Bandwidth & Gain

Figure 9 illustrates the bandwidth and gain performance of the noise post amp circuit. The bandwidth is flat across the range 0.1Hz to 100kHz.

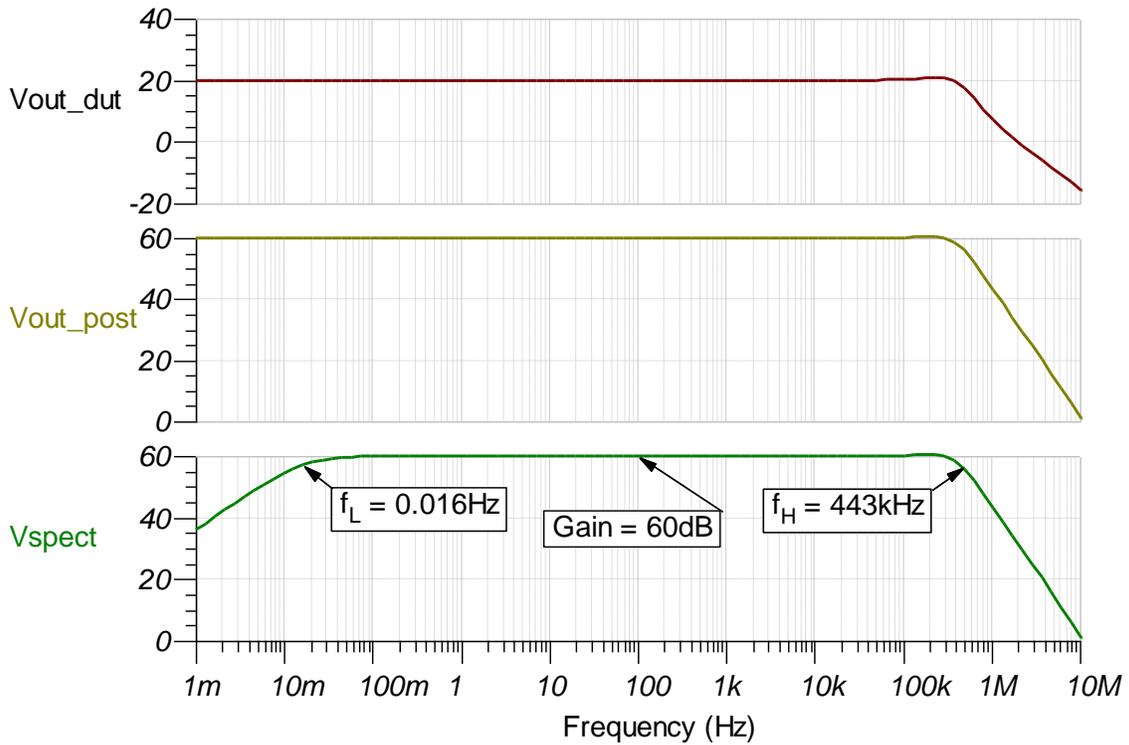


Figure 9: Bandwidth of Noise Post Amplifier

Figure 10 shows the expected gain variation for 1% resistors from a Monte Carlo analysis simulation. Equation (14) expresses the worst case error as a percent. Precise gain is normally not critical for noise analysis because the normal process variation of devices can be significant (i.e. ±10%). Nevertheless, using 0.1% resistors would reduce the overall gain by a factor of ten.

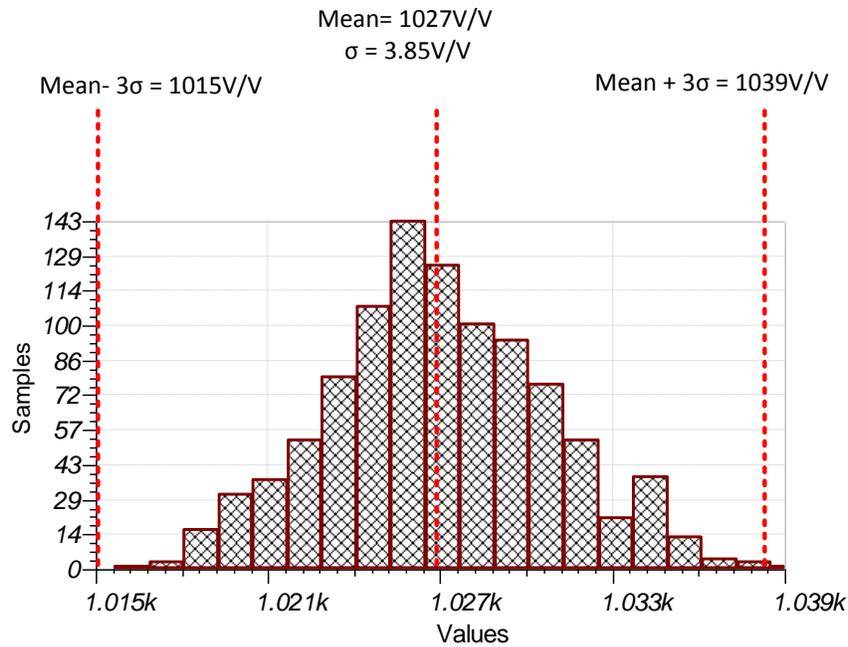


Figure 10: Distribution of Gain at 10kHz (from Monte Carlo Analysis, 1% resistors)

$$G_{\text{error}} = \left(\frac{\pm 3\sigma}{G_{\text{nominal}}} \right) 100\% = \left(\frac{\pm 3(3.853V/V)}{1000V/V} \right) 100\% = \pm 1.2\% \tag{14}$$

4.4 Noise Floor (Post Amp)

The DUT output noise must be at least three times greater than the post amp noise floor. In this design the noise floor is simulated to be 1nV/rtHz, so the DUT noise must be at least 3nV/rtHz for accurate measurements. The post amplifier noise floor is dominated by the noise spectral density of the OPA211 (See Figure 12).

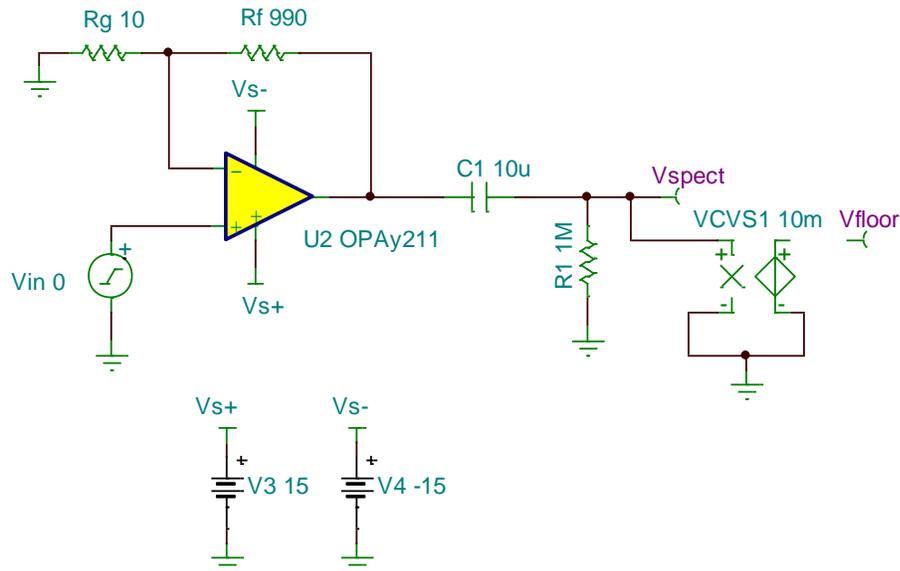


Figure 11: Post Amp Noise Floor Simulation

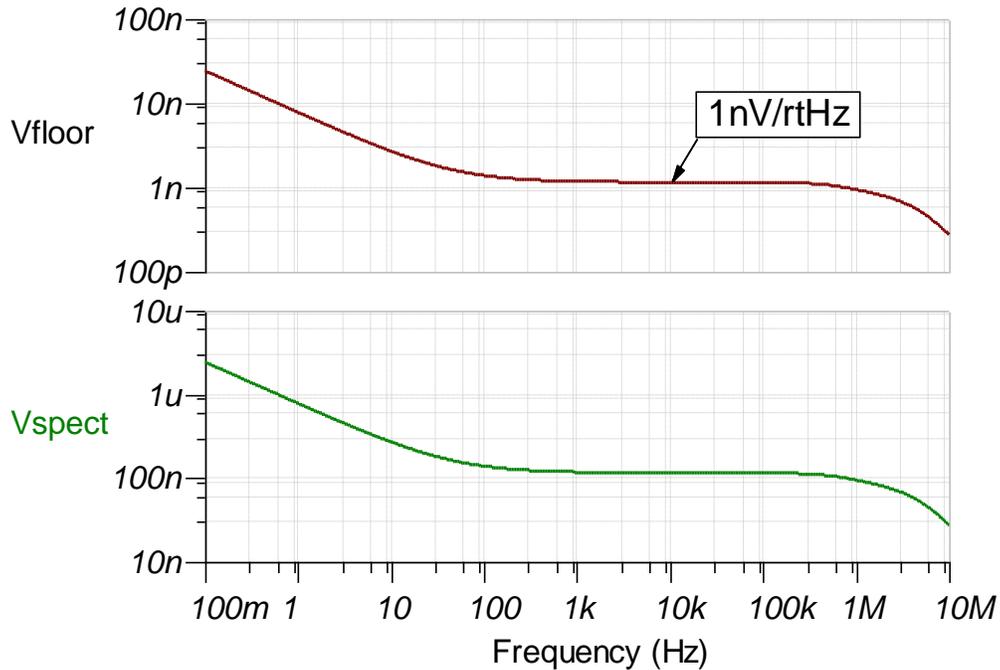


Figure 12: Noise Floor for OPA211 Post Amplifier

4.5 Simulated Results Summary

Table 4 summarizes the simulated performance of the design.

Table 4: Summary of Simulated Results

	Goal	Simulated
Gain (V/V)	1000	1000
Gain Error (%)	2%	1.2%
f_L	$f_L < 0.1\text{Hz}$	0.016Hz
f_H	$f_H > 100\text{kHz}$	443kHz
Noise Floor (post amp input)	1nV/rtHz	1nV/rtHz

5 Modifications

The method described Section 3.2 can be used to select a different post amplifier. Table 5 provides examples of different amplifiers that can be used to achieve different design objectives. Low noise high speed amplifiers offer some advantages, but care must be taken to avoid stability issues. The circuit recommended in this design is robust and will work effectively for most applications.

Table 5. Recommended Post Amplifiers

Output Amplifier	Design Objective	Vs	Vos uV	Vos Drift uV/degC	Iq mA	Voltage Noise nV/ $\sqrt{\text{Hz}}$	GBW MHz	SR V/uS	Approx. Price US\$ / 1ku
OPA211	Wide Band, Low Noise, DC Precision	$\pm 18\text{V}$	30	0.35	3.6	1.1	80	27	3.45
OPA209	DC Precision, Low Noise, Low Iq	$\pm 18\text{V}$	35	1.0	2.2	2.2	18	6.4	1.10
OPA847	Wide Band, Low Noise, DC Precision	$\pm 5\text{V}$	100	0.25	18.0	0.85	3900	950	2.00

6 About the Author

Arthur Kay is an applications engineering manager at TI where he specializes in the support of amplifiers, references, and mixed signal devices. Arthur focuses a good deal on industrial applications such as bridge sensor signal conditioning. Arthur has published a book and an article series on amplifier noise. Arthur received his MSEE from Georgia Institute of Technology, and BSEE from Cleveland State University.

7 Acknowledgements & References

7.1 Acknowledgements

The author wishes to acknowledge Collin Wells, Tim Green, and Marek Lis for technical contributions to this design.

7.2 References

1. Kay, A., *Operational Amplifier Noise*, Newnes, 2012, Chapter 1 & 5

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