Source resistance and noise considerations in amplifiers

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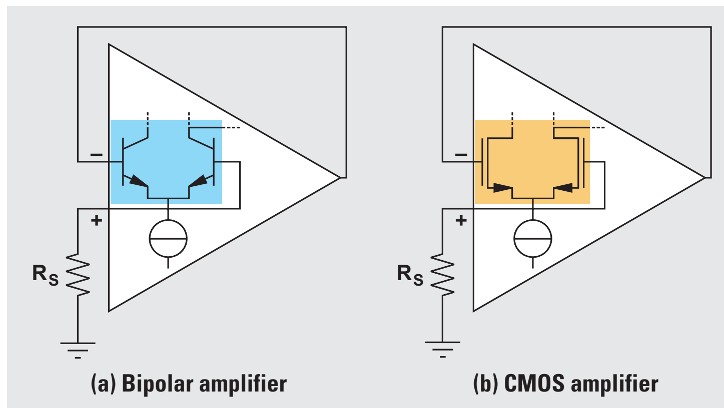
Introduction

In many applications it is critical to design for low noise. Different types of sensors, filters, and audio designs are common examples where low noise is critical. These applications can be modeled as a source resistance in series with a signal source. The source resistance has thermal noise and also converts current noise into voltage noise, increasing the amplifier's total output-voltage noise.

A common question is how to choose an amplifier that minimizes total output-voltage noise, even when a source resistance is modeled. This question is relevant because amplifiers can be fabricated in either bipolar or CMOS technology. Bipolar amplifiers have significant current noise but often have lower voltage noise than CMOS amplifiers for a given quiescent current. Current noise is most problematic when the source resistance is high. This article demonstrates how a CMOS amplifier is the best choice when a high source resistance is used and noise is the only concern. Knowing these facts along with the voltage-noise specifications of the amplifier is instrumental in making the right choice. For this analysis, it is assumed that the bipolar and CMOS amplifiers have comparable bandwidth, power, and intrinsic voltage noise. The trade-offs between the two amplifiers are also examined.

Figure 1 shows each amplifier in a buffer configuration with a modeled source resistance connected to the positive input and ground. The different noise contributions from the modeled source resistance, input-referred voltage noise, and input-referred current noise are taken into account. These models serve as reference examples for analyzing and comparing amplifier noise performance in a low-noise application where noise is the only parameter in play.

Figure 1. Buffer-configured amplifiers with source resistance attached to positive input and ground



Total voltage-noise contributions

The key to choosing the best amplifier is to understand how the amplifier's current noise, voltage noise, and resistor thermal noise combine to form the total output-voltage noise. Depending on the magnitude of the source resistance, sometimes low-current noise is the key specification. In other cases, low-voltage noise may be the key specification. To better understand this, the designer needs to have a grasp of the amplifier's total voltage-noise density, which is given by a root-mean-square (RMS) operation:[1]

$$E_O = \sqrt{(e_N)^2 + (i_N \times R_S)^2 + (4K_B T R_S)} \quad (1)$$

In Equation 1, E_O is the total voltage-noise density at the output of the amplifier. e_N and i_N are the voltage- and current-noise densities of the amplifier, respectively. R_S is the source resistance connected to the positive input. K_B is Boltzmann's constant, equal to 1.38×10^{-23} J/K, and T is absolute temperature in Kelvin units. At room temperature, T is equal to 300 K. For all the calculations in this article, it is assumed that T is at room temperature.

The three terms in Equation 1 account for the noise-density contributors at the output of the amplifier. The first term, e_N, is the intrinsic voltage-noise density of the amplifier, which is independent of the source resistance. The second term, $i_N \times R_S$, shows the voltage contribution from the current-noise density multiplied by the source resistance. The third term, $\sqrt{4K_B TR_S}$, corresponds to the thermal-noise density of the source resistance. The RMS sum of these three terms yields the total voltage-noise density of the amplifier in volts per square root of hertz.

In Equation 1, note that $i_N \times R_S$ increases faster than $\sqrt{4K_B TR_S}$ as the source resistance increases. This is significant because, for low source resistance, the thermal-noise density of the source resistance dominates. But there comes a point when the contribution from $i_N \times R_S$ becomes significant and is thus the dominating noise source. Figure 2 presents a plot of these two noise contributors in a linear-linear scale.

Bipolar amplifiers have significant current-noise density, which the source resistance converts into voltage-noise density. CMOS amplifiers have a major advantage in this regard over bipolar amplifiers because their components have extremely low current-noise density. Even though both bipolar and CMOS amplifiers have all three noise contributors, the total noise density in a CMOS amplifier is primarily from only two noise contributors, e_N and $\sqrt{4K_BTR_S}$. This is because the current-noise density of $i_N \times R_S$ is very small and its impact on the total noise density can be neglected.

Datasheets for low-noise amplifiers present a typical graph showing the voltage- and current-noise densities versus frequency traces. Figure 3a shows this graph for a bipolar amplifier, and Figure 3b for a CMOS amplifier. Note that the trace for current-noise density is not shown in Figure 3b because it is extremely low, well into the femtoamperes range. This is in contrast to the bipolar amplifier's current-noise density, which is in the picoamperes range, or 1000 times greater than that of the CMOS amplifier.

To compare the noise contributors on both amplifiers, the voltage and current noise at 1 kHz can be used as the reference. This facilitates the explanation, since the thermal-noise region, not the flicker region, of the graphs is being examined. In Figure 3a,[2] the bipolar amplifier has a voltage-noise density of 3.3 nV/$\sqrt{\text{Hz}}$ and a current-noise density of 1 pA/$\sqrt{\text{Hz}}$. In Figure 3b,[3] the CMOS amplifier has a voltage-noise density of 4.5 nV/$\sqrt{\text{Hz}}$. With these values for intrinsic-noise density identified, the noise-density contributors can be quantified by using all three terms of Equation 1 for the bipolar

Figure 2. Voltage-noise density versus source resistance

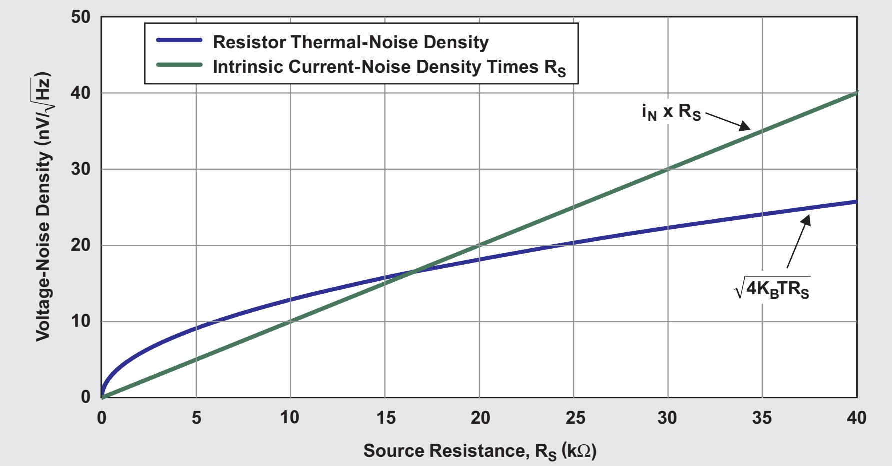
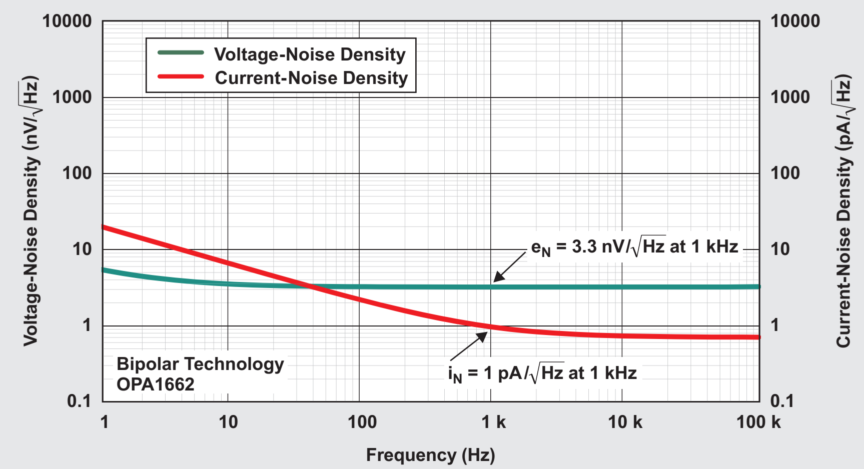
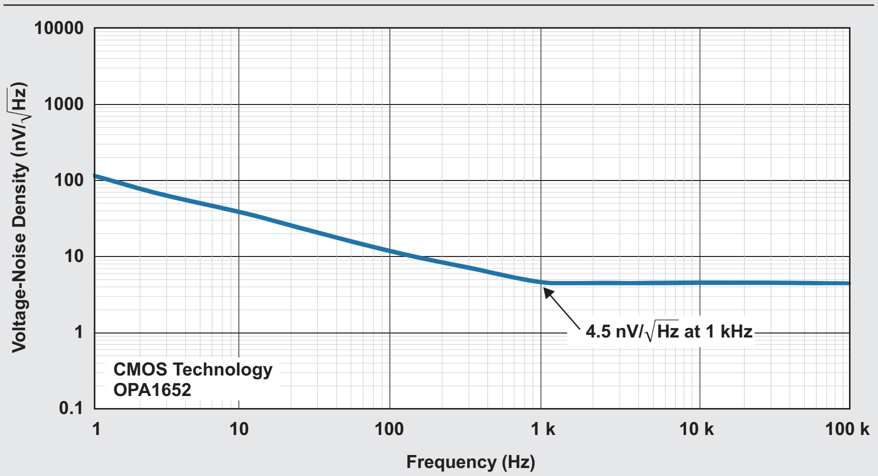


Figure 3. Noise density versus frequency on bipolar and CMOS amplifiers



(a) Voltage- and current-noise density for a bipolar amplifier



(b) Voltage-noise density for a CMOS amplifier

amplifier, and the first and third terms for the CMOS amplifier. The sweeping variable in Equation 1 is the source resistance. In other words, the voltage-noise density is calculated as a function of source resistance with voltage- and current-noise densities taken at 1 kHz. This is shown in Example 1 for a bipolar amplifier.

Example 1: Bipolar amplifier's noise contributors

$$e_N = 3.3\ \text{nV}/\sqrt{\text{Hz}}$$

$$i_N \times R_S = 1\ \text{pA}/\sqrt{\text{Hz}} \times R_S$$

$$\sqrt{4K_BTR_S} = \sqrt{4 \times \left(1.38 \times 10^{-23}\ \text{J/K}\right) \times \left(300\ \text{K}\right) \times \left(R_S\right)}$$

The second term of Equation 1 is not used for the CMOS amplifier because current-noise density is negligible in a CMOS amplifier. The calculation for the CMOS amplifier is shown in Example 2.

Example 2: CMOS amplifier's noise contributors

$$e_N = 4.5\ \text{nV}/\sqrt{\text{Hz}}$$

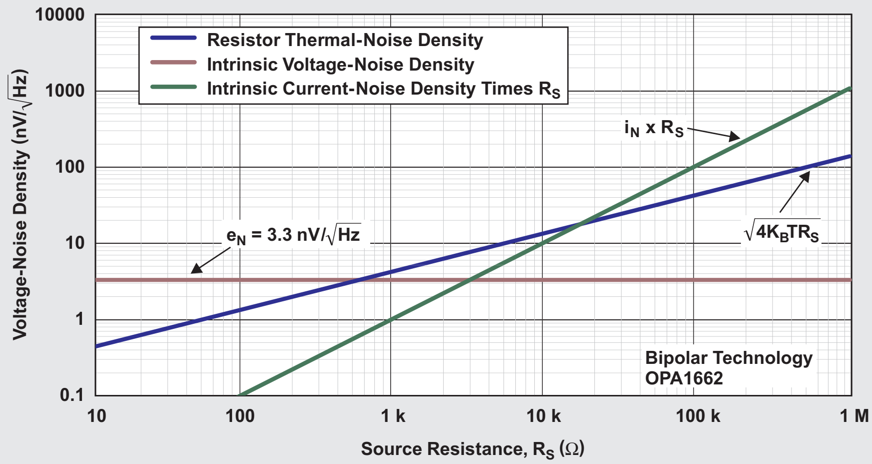
$$\sqrt{4K_BTR_S} = \sqrt{4 \times \left(1.38 \times 10^{-23}\ \text{J/K}\right) \times \left(300\ \text{K}\right) \times \left(R_S\right)}$$

Figure 4a plots the three noise-density contributors for the bipolar amplifier. The trace for intrinsic voltage-noise density (e_N) is constant and independent of the source resistance. As the source resistance increases, the value of $i_N \times R_S$, although small for low source resistance, increases faster than that of $\sqrt{4K_BTR_S}$, becoming the dominating noise source.

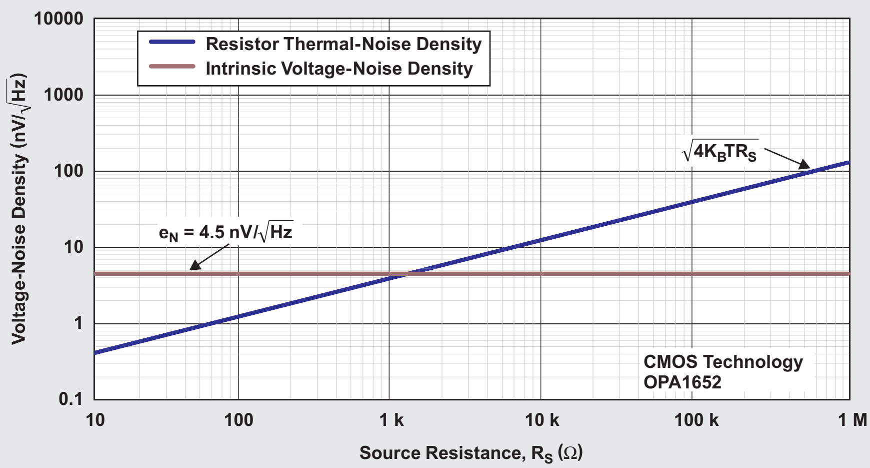
The noise-density contributors for the CMOS amplifier are plotted in Figure 4b.

For the bipolar amplifier, the total voltage-noise density (E_O) at 1 kHz can be obtained by using Equation 1. The

Figure 4. Voltage-noise density versus source resistance



(a) In a bipolar amplifier



(b) In a CMOS amplifier

total noise density for the CMOS amplifier is given by Equation 2:

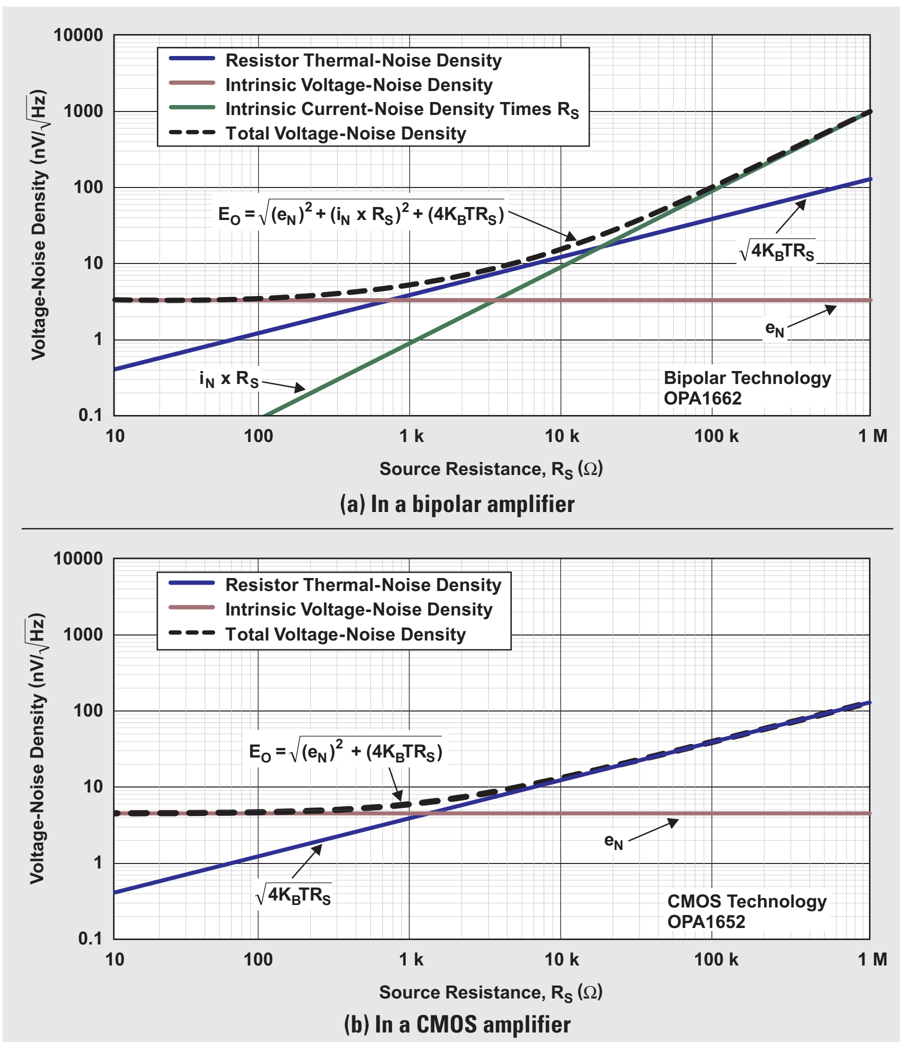
$$E_O = \sqrt{(e_N)^2 + (4K_BTR_S)} \qquad \textbf{(2)}$$

Figures 5a and 5b respectively plot the total voltage-noise density for the bipolar amplifier and the CMOS amplifier.

Figure 5a shows that, on a bipolar amplifier using low source-resistance values, the total voltage-noise density (E_O) converges with the intrinsic voltage-noise density (e_N) of the amplifier. For midrange source-resistance values, E_O approaches the thermal-noise density of the source resistance $\left(\sqrt{4K_BTR_S}\right)$. For large source-resistance values, E_O converges with the product of the current-noise density and the source resistance $(i_N \times R_S)$. The current-noise density becomes a significant contributor towards the amplifier's total output-voltage-noise density as source resistance increases.

Figure 5b shows that, for low source resistance, the E_O of the CMOS amplifier, like that of the bipolar amplifier, converges with the amplifier's intrinsic voltage-noise density (e_N). The difference between the bipolar and the CMOS amplifier lies where the noise density converges for high source resistance. As already noted, the bipolar amplifier's E_O converges with $i_N \times R_S$ for large source resistance. However, as shown in Figure 5b, the CMOS amplifier's E_O converges with the thermal-noise density of the source resistance $\left(\sqrt{4K_BTR_S}\right)$.

Figure 5. Total voltage-noise density versus source resistance



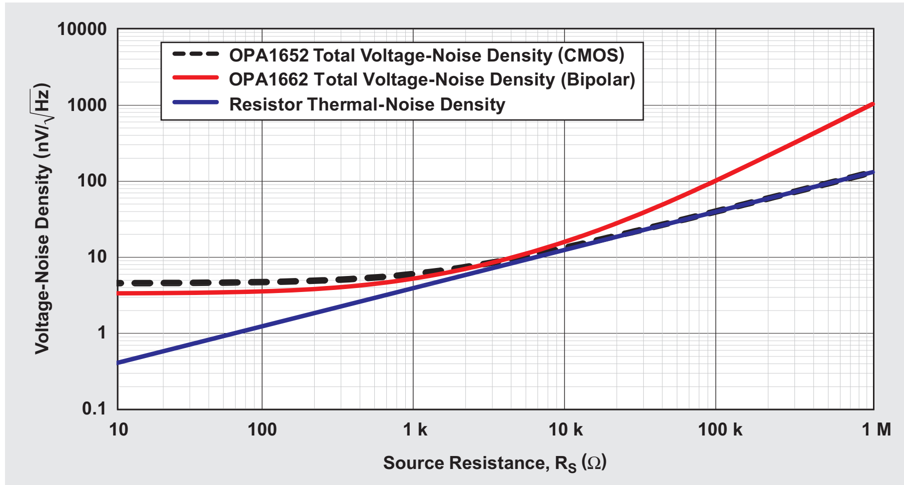
(a) In a bipolar amplifier

(b) In a CMOS amplifier

Noise analysis using different R_S values

Figure 6 shows the total voltage-noise density as a function of source resistance at 1 kHz for the bipolar and CMOS amplifiers. The thermal noise of the source resistance is included to serve as a reference. This graph may be found in the datasheets of low-noise amplifiers such as the Texas Instruments OPA1662[2] and OPA1652.[3] It helps the system engineer decide which type of amplifier is best to use, depending on the source resistance modeled. If the source-resistance curve is not available, the engineer can make point calculations by plugging values from the voltage-noise-density curves into Equations 1 and 2 to get an idea of what type of amplifier will yield the best noise characteristic.

Figure 6. Total voltage-noise density of bipolar and CMOS amplifiers compared to thermal-noise density of R_S



In Example 3, the bipolar amplifier (Figure 3a) has a voltage noise (e_N) of 3.3 nV/$\sqrt{\text{Hz}}$ at 1 kHz. The equivalent resistor value that generates this same amount of noise can be calculated by rearranging $e_N = \sqrt{4K_BTR_S}$ to solve for R_S.

Example 3: Calculations with $i_N \times R_S << \sqrt{4K_BTR_S}$ and a small R_S value

$$R_S = \frac{e_N^2}{4K_BT},$$

where e_N = 3.3 nV/$\sqrt{\text{Hz}}$, $K_B = 1.38 \times 10^{-23}$ J/K, and T = 300 K.

$$R_S = \frac{\left(3.3\ \text{nV}/\sqrt{\text{Hz}}\right)^2}{4\times\left(1.38\times10^{-23}\ \text{J/K}\right)\times\left(300\ \text{K}\right)} \approx 660\ \Omega$$

Substituting 660 Ω for R_S yields the noise-density contributors:

$$e_N = 3.3\ \text{nV}/\sqrt{\text{Hz}}$$

$$i_N \times R_S = \left(1\ \text{pA}/\sqrt{\text{Hz}}\right)\times\left(660\ \Omega\right) = 0.66\ \text{nV}/\sqrt{\text{Hz}}$$

$$\sqrt{4K_BTR_S} = \sqrt{4\times\left(1.38\times10^{-23}\ \text{J/K}\right)\times\left(300\ \text{K}\right)\times\left(660\ \Omega\right)} = 3.3\ \text{nV}/\sqrt{\text{Hz}}$$

The total noise is

$$E_O = \sqrt{\left(3.3\ \text{nV}/\sqrt{\text{Hz}}\right)^2 + \left(0.66\ \text{nV}/\sqrt{\text{Hz}}\right)^2 + \left(3.3\ \text{nV}/\sqrt{\text{Hz}}\right)^2} = 4.71\ \text{nV}/\sqrt{\text{Hz}}.$$

Note that if the current-noise density is ignored, the following is obtained:

$$E_O = \sqrt{\left(3.3\ \text{nV}/\sqrt{\text{Hz}}\right)^2 + \left(3.3\ \text{nV}/\sqrt{\text{Hz}}\right)^2} = 4.66\ \text{nV}/\sqrt{\text{Hz}}$$

Thus, ignoring this term for a source resistance of 660 Ω has little impact on the total voltage-noise density. Factoring yields a term of $\sqrt{2}$, or 3 dB:

$$E_O = \sqrt{2}\times\left(3.3\ \text{nV}/\sqrt{\text{Hz}}\right) \approx 4.7\ \text{nV}/\sqrt{\text{Hz}}$$

Thus, if a source resistance of 660 Ω is used, the increase in noise is approximately 4.7 nV/$\sqrt{\text{Hz}}$, or 3 dB. Beyond 660 Ω, the total noise starts to converge with the thermal noise of the source resistance.

Example 4: Calculations with $i_N \times R_S = \sqrt{4K_BTR_S}$ and a larger R_S value

Just like in Example 3, the current-noise density begins to become a major factor when $\sqrt{4K_BTR_S}$ becomes approximately equal to $i_N \times R_S$:

$$i_N \times R_S = \sqrt{4K_BTR_S}$$

$$R_S = \frac{4K_BT}{\left(i_N\right)^2},$$

where i_N = 1 pA/$\sqrt{\text{Hz}}$, $K_B = 1.38 \times 10^{-23}$ J/K, and T = 300 K.

$$R_S = \frac{4\times\left(1.38\times10^{-23}\ \text{J/K}\right)\times\left(300\ \text{K}\right)}{\left(1\ \text{pA}/\sqrt{\text{Hz}}\right)^2} \approx 16\ \text{k}\Omega$$

Substituting 16 kΩ for R_S yields the noise-density contributors:

$$e_N = 3.3\ \text{nV}/\sqrt{\text{Hz}}$$

$$i_N \times R_S = \left(1\ \text{pA}/\sqrt{\text{Hz}}\right) \times \left(16\ \text{k}\Omega\right) = 16\ \text{nV}/\sqrt{\text{Hz}}$$

$$\sqrt{4K_B T R_S} = \sqrt{4 \times \left(1.38 \times 10^{-23}\ \text{J/K}\right) \times \left(300\ \text{K}\right) \times \left(16\ \text{k}\Omega\right)}$$
$$= 16\ \text{nV}/\sqrt{\text{Hz}}$$

The total noise is

$$E_O = \sqrt{\left(3.3\ \text{nV}/\sqrt{\text{Hz}}\right)^2 + \left(16\ \text{nV}/\sqrt{\text{Hz}}\right)^2 + \left(16\ \text{nV}/\sqrt{\text{Hz}}\right)^2}$$
$$= 23.06\ \text{nV}/\sqrt{\text{Hz}}.$$

If the intrinsic voltage-noise density is ignored, the following is obtained:

$$E_O = \sqrt{\left(16\ \text{nV}/\sqrt{\text{Hz}}\right)^2 + \left(16\ \text{nV}/\sqrt{\text{Hz}}\right)^2} = \sqrt{2} \times \left(16\ \text{nV}/\sqrt{\text{Hz}}\right)$$
$$= 22.82\ \text{nV}/\sqrt{\text{Hz}}$$

Ignoring the intrinsic voltage-noise density for a source resistance of 16 kΩ has little impact on the total noise density because the amplifier is starting to be affected only by the current-noise density and the thermal-noise density of the source resistance. Beyond 16 kΩ, the total voltage-noise density begins to converge with $i_N \times R_S$. The bipolar amplifier provides the least noise of the two amplifiers at low source impedance, from approximately 660 Ω and below.

The CMOS amplifier shows the least amount of noise at high source resistance. The 3-dB point is when the thermal noise of the source resistance is equal to 4.5 nV/$\sqrt{\text{Hz}}$, which corresponds to 1.2 kΩ. Beyond this point, the output noise starts to converge with the thermal noise of the source resistance because the CMOS amplifier has negligible current noise.

Choosing the right amplifier

A quick rule of thumb can be used to decide if a bipolar or a CMOS amplifier is best: If e_N is larger than or equal to $i_N \times R_S$, a bipolar amplifier should be used; otherwise a CMOS amplifier should be used. For example, if data for the OPA1662 were used and R_S equaled 100 Ω, then e_N would be 3.3 nV/$\sqrt{\text{Hz}}$, and $i_N \times R_S$ would be 1 pA/$\sqrt{\text{Hz}}$ × 100 Ω, or 0.1 nV/$\sqrt{\text{Hz}}$. Since 3.3 nV/$\sqrt{\text{Hz}}$ > 0.1 nV/$\sqrt{\text{Hz}}$, using a bipolar amplifier would be best. If R_S equaled 100 kΩ, then $i_N \times R_S$ would be 1 pA/$\sqrt{\text{Hz}}$ × 100 kΩ, or 100 nV/$\sqrt{\text{Hz}}$. Since 3.3 nV/$\sqrt{\text{Hz}}$ < 100 nV/$\sqrt{\text{Hz}}$, the right choice would be a CMOS amplifier. This rule of thumb ignores the thermal noise of the source resistance, which will be present regardless of the amplifier chosen. Figure 6 validates this rule of thumb.

If the application calls for a midrange source resistance of about 4 kΩ, what amplifier should be used according to Figure 6? When the gain bandwidth, power, and DC specifications are comparable, a bipolar amplifier can be almost twice the price of a CMOS amplifier. So the choice would be the CMOS amplifier because it yields noise characteristics that are approximately equal to those of the bipolar amplifier for this source resistance.

The choice of source resistance also plays a role in the amplifier's total harmonic distortion plus noise (THD+N). The THD+N in bipolar amplifiers gets worse with increasing source resistance, whereas the CMOS amplifier has negligible current noise to increase the total distortion.[4] In a low-noise, low-distortion application with a large source resistance, a CMOS amplifier would be a better choice.

Coincidentally, the measurement of current noise in bipolar amplifiers is done with the choice of a source resistance whose value for thermal noise is lower than $i_N \times R_S$. The voltage noise due to $i_N \times R_S$ is intentionally made bigger than the thermal voltage noise of the source resistance so it can be easily measured.

Conclusion

Low-noise applications that demand the use of source resistance require an amplifier that minimizes the total output-voltage noise. This article has discussed the different voltage-noise contributors on a bipolar and a CMOS amplifier that have comparable bandwidth, power, and intrinsic voltage noise. It has been shown that the bipolar amplifier is a poor choice for use with high source resistance because the voltage-noise contribution from $i_N \times R_S$ becomes increasingly dominant. The CMOS amplifier is a better choice since its current noise is negligible. With this information in hand, the system designer is better equipped when choosing between a bipolar or a CMOS amplifier for a low-noise application when noise is the only concern.

References

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