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SOLVING THE NOISE PUZZLE WITH LOW-NOISE MATCHED BIPOLAR TRANSISTOR PAIRS

LS310 & LS350

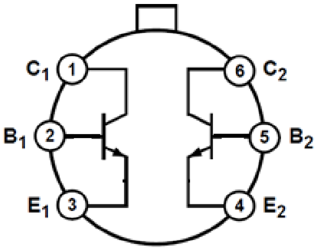
Noise is one of the more important aspects of circuit design. Lower noise in audio amplifier design means better quality audio. Low-noise in instrument design means more reliable and accurate measurements at lower voltage and current levels. And low-noise in current source designs means less noise injected into the electronic system.

One of the most basic approaches to reduce noise in an amplifier is to use low-noise components. This would include low-noise bipolar transistors and low-valued resistors. Although one can use low-noise operational amplifiers in the design of low-noise circuits or low-noise current sources it is often not done. This is because lower noise can be often be obtained with a well-thought out discrete design. And that's because discrete transistors offer much more design customization capability for specific circuit applications – like optimized collector biasing. One must remember that monolithic chip designs are built for the most part for general purpose applications. It is hard to tailor a specific op amp or current source chip for a specific source resistance, specific power consumption requirement and a specific bandwidth that will lower the overall noise – that is unless you add-on more compensation components.

When to Select a Matched Low-Noise Bipolar Transistor

Bipolar transistors offer significant lower noise at lower source resistance levels and lower collector currents than JFETs. As a rule of thumb, a low-noise bipolar transistor should be chosen over a JFET when the source resistance is less than 10K ohms or when the active current (drain or collector) is less than 0.5 ma. Because the LS310 (NPN) and LS350 (PNP) Series are tightly matched low-noise bipolar pairs they are ideal for low-noise applications that have two or more transistors and for designing ultra-low-noise differential circuit topologies. In a differential arrangement common mode signal line noise is canceled out because of the architecture leaving only the ultra-low-noise of the LS310 or LS350 to stand by itself or to be further optimized.

For differential applications, these bipolar transistors include vbe matching in the order of 0.2mV, good differential current gain matching, low base current differential and low voltage and current differential change with temperature. For both single and dual ended applications the devices feature an equivalent noise voltage between 700pV and 7.5nV typical, current gain between 100 and 1000 and a current gain bandwidth product specified at 200 MHz minimum.



Note:

1. **Substrate is connected to case on TO-78 package.**
2. **Substrate is normally connected to the most negative circuit potential, but can be floated.**

Figure 1: The LS310 and LS350 NPN and PNP Matched Bipolar Transistors are often used for low-noise amplifier design and as a replacement part for low-noise aftermarket and legacy bipolar transistor products. The LS310 comes as tested bare die and in several different package types: PDIP 8L RoHS, TO-71 6L RoHS, TO-78 6L RoHS, SOIC 8L RoHS, SOT-23 6L RoHS and DFN 8L RoHS.

Design for Noise Checklist

Low-noise components and the lowest possible resistor values are often at the top of a Design for Noise checklist. However, there are several other Design-for-Noise items that need to be checked if you want to ensure a noise-free success. This includes a noise optimized collector bias level and the overall layout of the design (avoid long leads). Other check list items include noise coming through the power lines or that being picked up over the airways. There is also temperature. Noise, random fluctuation of electrons, increases with temperature. Also remember there is bandwidth to consider. Circuits with lower bandwidth will have less noise. So, it is prudent to have narrowband input filters and to design amplifiers to have precisely defined low and high cutoff frequencies. Add to this list the source resistance, the input noise current and noise voltage specification of the bipolar transistor and for the most part you should be on your way.

Noise and Resistance

Because noise increases with increased resistance values, Design for Noise means using resistors that are as low in value as possible, especially if they are in a noise gain signal path. The thermal noise (Johnson Noise) equation for a resistor, below, indicates that noise voltage increases with temperature, the resistor value and the bandwidth of the circuit design. Specifically, this equation gives the root mean square voltage in volts across a resistor as a function of temperature (Degrees Kelvin) bandwidth(delta f), and resistance (R). K is Boltzmann's constant.

Equation 1: Thermal Noise Voltage of a Resistor, Johnson Noise

$$e_N = \sqrt{4kTR_s\Delta f}\ \ V$$

One will see the Johnson noise equation in various forms in the study of thermal noise. It is sometimes expressed in terms of Volts squared, at room temperature=300 K, and with the numerical value of the Boltzmann constant, k, factored in to simplify noise calculations.

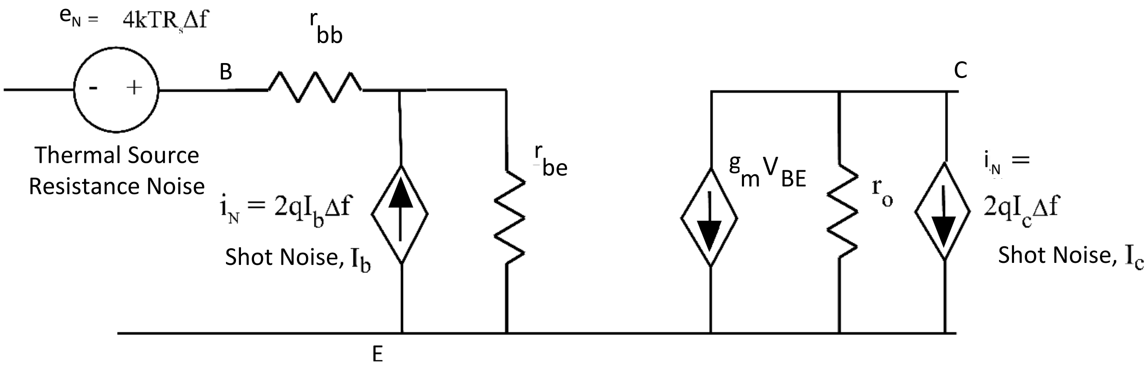
Equation 2: Root Mean Square Thermal Noise Voltage of a Resistor at Room Temperature

$$(e_n)^2 = 1.66X10^{-20}(R_s\Delta f)\ \ V^2$$

It is the above two equations along with the fundamental noise equation, equation 3, discussed later, that are most dominant in bipolar circuit noise calculations. Other equations can be used to factor in flicker noise, combination and recombination noise and burst noise. These basic equations indicate that circuits that have a lower bandwidth and lower resistor values will inherently have lower noise.

Shown below is one common bipolar noise model. It includes the thermal noise from the source resistance (of which the base spreading resistance can be added). It also includes the base current shot noise and the collector current shot noise dependent current sources. This model is often used for a quick analysis of noise in bipolar circuits (Fronczak).

Figure 2: Bipolar Noise Model

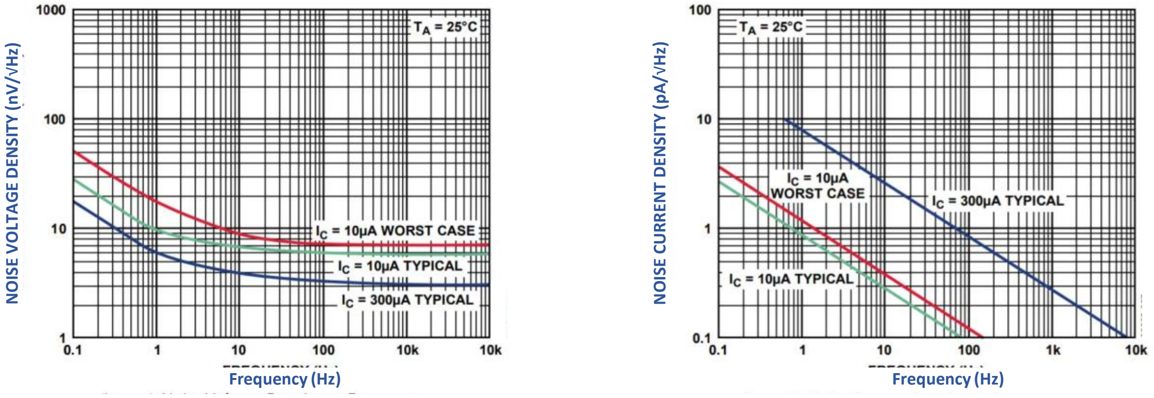


Often the bandwidth, delta f, is taken out of the equation. This results in the term often seen in data sheets, where input voltage noise has units of Volts per square root Hertz. These equations represent the noise voltage density and not the root mean square noise voltage. They give the noise per 1 Hz bandwidth. Although these equations are useful, they do not directly give the noise voltage as a function of bandwidth.

Bipolar Noise Specifications

In the realm of the bipolar transistor itself, the main consideration is the equivalent input noise voltage and equivalent input noise current – the lower the better. These two specifications are often given on data sheets as min typ or max specifications or graphed on a chart of noise voltage versus frequency versus collector current. The specifications and charts in themselves imply design guidelines. Noise in bipolar transistors is highest at low frequencies and drops dramatically with increased frequency. As well, voltage noise decreases with higher collector currents and current noise increases with higher collector currents. Because the input current noise flows through the source resistor and the base spreading resistor, the effect of increasing the collector current to reduce current noise is offset with an increase in noise voltage from the higher noise current flowing through the source and base spreading resistor.

Figure 3: Noise Voltage and Noise Current Density as a Function of Frequency and Collector Current



Noise Voltage Density vs. Frequency

Noise Current Density vs. Frequency

Source Resistance and Noise

Source resistance is one of the major factors that affect noise. Because input current noise flows through the source resistance driving the circuit, input current noise is multiplied by the source resistor to obtain the input voltage noise. As collector current rises, input current or base current must rise since collector current and base current are related through beta.

The fundamental noise equation for a bipolar transistor, equation 3 below, illustrates the effect of the value of source resistance on equivalent input voltage noise. The source resistance is in the base shot noise and the thermal noise terms of the equation. The equation also indicates that temperature and collector current play a role in noise. This equation is expressed in units of Volts squared per Hertz (the bandwidth, delta f, would have to be multiplied by the equation to give the noise in Volts squared. The he square root would then have to be taken to give the noise voltage in Volts).

Equation 3: Fundamental Bipolar Voltage Noise Density, Volts Squared Per Hertz

$$e_N^2 = \frac{2k^2T^2}{qI_c} + \frac{2qI_c r_s^2}{h_{FE}} + 4kTr_s$$

Equation 4: Fundamental Bipolar Voltage Noise Density, Volts Squared Per Hertz

$$e_N^2 = \frac{2k^2T^2}{qI_c} + \frac{2qI_c r_s^2}{h_{FE}} + 4kTr_s$$

The equation suggests that to obtain the lowest possible noise there is an optimal value of collector current for a given value of source resistance. From calculus, taking the derivative of the above equation with respect to the collector current and setting the result equal to zero, gives the optimal value of collector current for a noise minimum, equation 4.

Equation 5: Optimum Collector Current for Minimum Noise and Given Source Resistor

$$I_{copt} = \frac{kT}{q}\sqrt{\frac{h_{FE}}{r_s}} = 0.025\sqrt{\frac{h_{FE}}{r_s}}$$

The above equation can be used for a specific temperature using degrees Kelvin. Or the simplified form can be used for room temperature of 300 degrees Kelvin. In the equation, q, is the charge of an electron, 1.6 X 10^-19 and k is Boltzmann's constant, 1.381X10^-23.

If the base spreading resistance(r_{bb}) of the bipolar transistor is significantly high enough it should be included as part of the source resistance in equation 4. For the LS31X series, rbb is in the order of 30 Ohms at a nominal bias level. At lower levels of collector bias it can increase up to 1000 ohms.

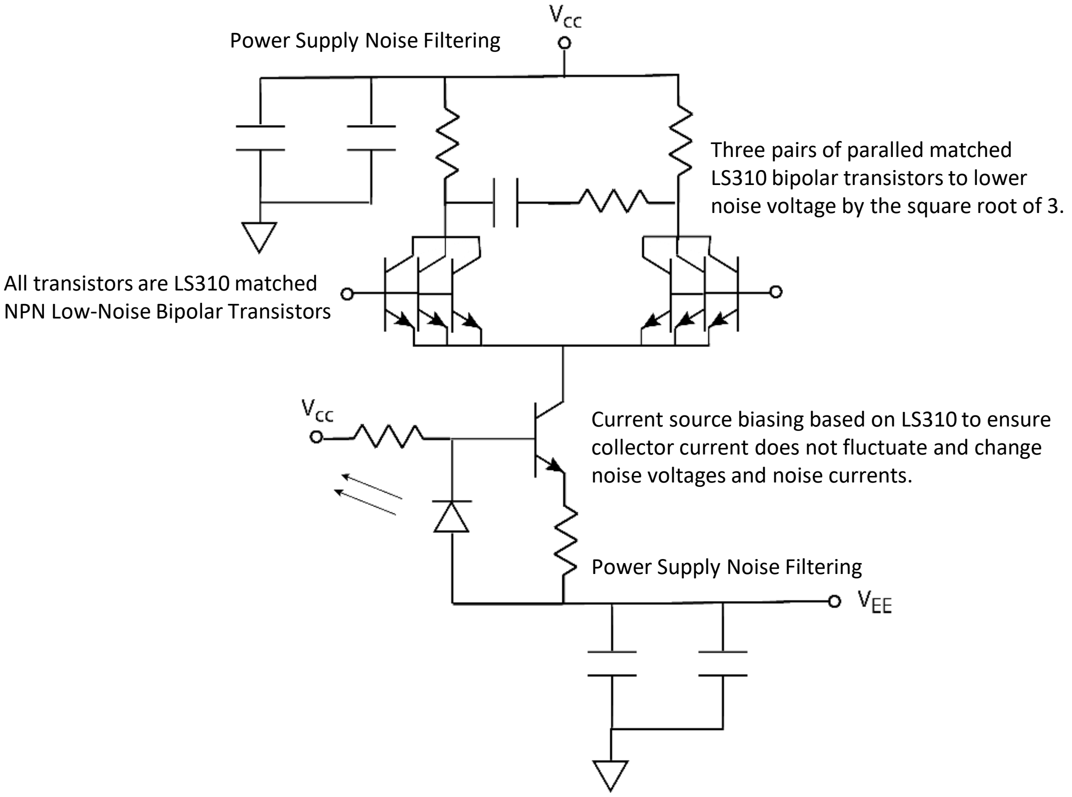
In analyzing equation 4, it should be borne in mind that hfe (or Beta) increases with both collector current(to a point) and temperature. There is a peak hfe associated with collector current, after which hfe decreases with increasing collector current. For the LS310 series, the LS310, 311, 312, and 313 nominal hfe ranges from 100 to 1000.

Building Ultra-Low-Noise Amplifiers, Current Sources, Multipliers and More

Low-noise discrete bipolar designs are commonly used to build ultra-low-noise preamplifiers, low-noise microphone preamplifiers, digitally programmed current pumps (DAC with Wilson Current Source) cascode current sources, current matching circuits, multipliers, power meters, strain gauge instrumentation amplifiers, thermocouple amplifiers and a wide range of analog mathematical circuits.

Shown below is an ultra-low-noise discrete bipolar preamplifier that can be designed for a voltage noise level below 0.5 nV per square root Hertz. The design uses paralleled LS310s to reduce the input voltage noise (paralleling bipolar transistors reduces the base spreading resistance by a factor equal to the square root of the number of transistors paralleled, in this case the square root of three). This reduces the input voltage noise as related to the shot current noise of the base. For ultra-low-noise and ultra-low power, the circuit can be biased using the optimum Ic value calculated from equation 4, given above. The current source in the schematic is based on a red LED.

Figure 4: Noise Optimized Differential Amplifier Based on LS310 Paralleled Resistors and Current Source



Conclusion

Depending on the specific parameters of the transistor used, a wide range of low-value collector bias currents can be used to obtain both low-noise and low power circuits Knowing what the source resistance is and the value of hfe lets one calculate the optimum noise collector bias current. It also allows one to optimize for the lowest power consumption.

It should be remembered that input current noise increases with higher collector current, but voltage noise decreases with higher collector current. This tradeoff is mitigated through the selection of a lower source resistance, if possible. Paralleling bipolar transistors allow for reduced noise voltage, but low source resistances should be used to compensate for an increase in input noise current. Finally, one should use characteristic curves for the voltage noise and the current noise of a specific transistor for frequency, hfe (beta), collector current and temperature. This simplifies the noise analysis task in that actual noise effects of operating points can be determined without calculation or simulation.

References

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