Electronic Pages Die Homepage der Familie Beis

Extreme Low Noise Preamplifier

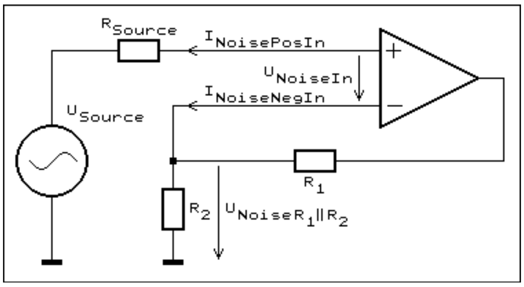
0,4 nV/Sqr(Hz) and less - isn't that low?

My original intention (but who cares about that, anyway?)

Originally I looked for a very low noise balanced preamplifier for dynamic microphones, but with a gain of 20 dB only. Very low noise was meant to be 1.5 nV/Sqr(Hz) or less. I thought this should be easy as usual ICs like the INA103 provide as low as 1.0 nV/Sqr(Hz) voltage noise. But I was wrong.

Why do low-gain amplifiers produce more noise than a high-gain ones?

This is for two reasons: The current noise of the input stage and the voltage noise of the feedback resister network. Have a look at the following circuit diagram:



The overall amplifier noise is summed up from the following sources:

- The input voltage noise of the Amplifier ($U_{NoiseIn}$)
- The positive input current noise multiplied by the impedance of the signal source (R_{Source} x $I_{NoisePosIn}$)
- The negative input current noise multiplied by the source resistance of the feedback resistor divider ((R_1 parallel to R_2) x $I_{NoiseNegIn}$)
- The resistor noise of of the feedback resistor divider (R_1 parallel to R_2)

Of course the resistance of signal source, e. g. the microphone, adds another noise, but we can't influence that with the design of the amplifier so I don't include it here. My goal is the design of a preamplifier that adds so few noise to the signal that **the noise caused by the preamplifier compared to the signal source's noise is really negligible**. You should know that summing noise physically is and mathematically must be done by summing the square of the individual noise voltages and afterwards extracting the root from this sum:

$$U_{NoiseSum} = Sqr(U_{Noise1}^2 + U_{Noise2}^2 + U_{Noise3}^2 + ... + U_{NoiseN}^2)$$

The noise of a 200 Ω resistor amounts to 1.82 nV/Sqr(Hz). Should the preamplifier produce another 1.0 nV/Sqr(Hz), the sum would become 2.08 nV/Sqr(Hz), i. e. approx. 1 dB more than the source. My goal of 1.5 nV/Sqr(Hz) was "moderate".

When you look at the INA103 you'll find the current noise specified for its signal inputs ($I_{NoisePosIn}$) there, but not for the feedback inputs ($I_{NoiseNegIn}$). In fact, as the feedback inputs are the emitters of the input transistors, the input current noise there is significantly higher that that on the signal inputs, which are the transistor's bases. The problem, particularly for low gains, occurs at these feedback inputs.

The INA103 provides feedback resistors of 3 kΩ at each side (R_1 in the circuit above). You cannot reduce them, the op-amp won't work, either because the driver capacitance is too low or the system gets instable. You have to use them. For a gain of 10 you need 2 x 333 Ω (or 1 x 333 Ω, R_2 in the circuit above) to set a gain of 10. This resistor network produces 3.15 nV/Sqr(Hz) of voltage noise and even more caused by the (unspecified) current noise of the INA103. The sum is 5 nV/Sqr(Hz) approx. - far, far away from my goal and drastically reducing the system's noise performance.

So what can be done to reduce the input noise?

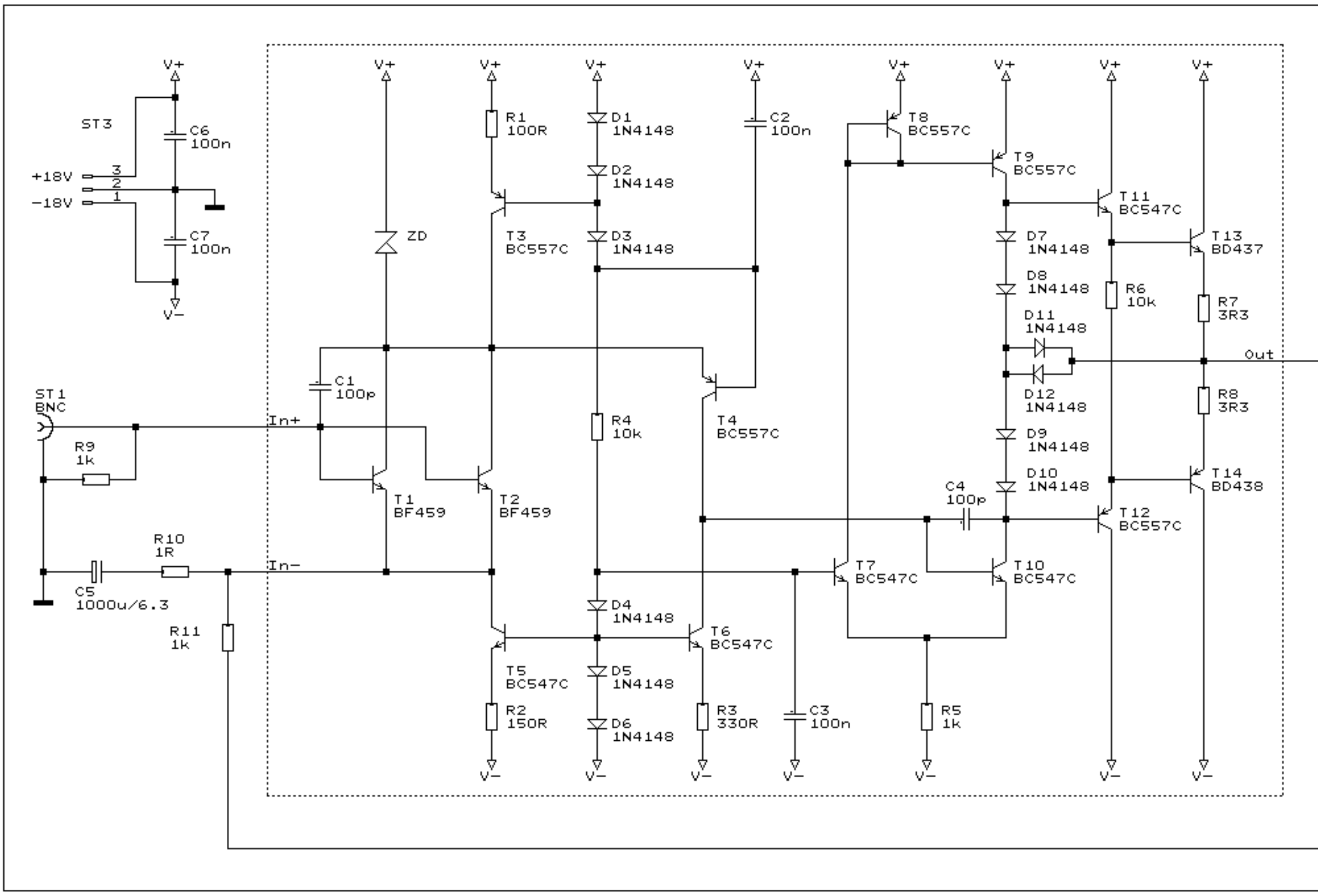
The feedback resistor divider's output resistance must drastically be reduced. It is, by the way, drastically lower when the gain is high, i. e. it is 6 Ω only in case the gain is 1000 (60 dB). But for low gains it is difficult to reduce. Just imagine a gain of 2 and a feedback resistance of 6 Ω: The divider in the circuit above ought to built from two 12 Ω resistors! The input power for this divider would be 4 W in case of an output voltage of 10 V_{rms}, which is not an unusual voltage in average amplifier stages.

I did not want to go that far, but a power output stage sufficient to drive 100 Ω dividers (90 + 10 Ω) should be aimed.

I finally ended in a fully discrete circuit with a very high open-loop gain and an appropriate power output stage. I made lots of experiments, experiences and measurements for lowest noise transistors. Particularly measuring these small voltages and currents reliably and to make these measurements reproducible is really difficult and sometimes almost drove me mad.

My ultra-low noise preamplifier circuit

The circuit diagram below shows my prototype, an unbalanced amplifier with a gain of 1000 built for experiments and for noise measurements. It is, so to speak, one half of the INA103 input stage. I was disappointed to realize that it was not possible to reduce it's gain down to 10. I had expected that I only had to increase C_4 sufficiently, but the system shows relaxation oscillations. I am convinced that the huge open loop gain has to be reduced to avoid that.



Transistor Selection

The noise performance, on the other hand is much better than I originally aimed. Currently the input voltage noise is as low as 0.45 nV/Sqr(Hz), or, for a balanced version, it would be 0.64 nV/Sqr(Hz). I tested a couple of transistors. The best ones all were high-voltage power transistors. My favorites up now are BF459 or MJE13007. BF459 is better when current noise matters, i. e. impedances like dynamic microphones and low gains. MJE13007 produces less voltage noise, but much more current noise and is better for low-impedance sources like ribbon microphones and high gains.

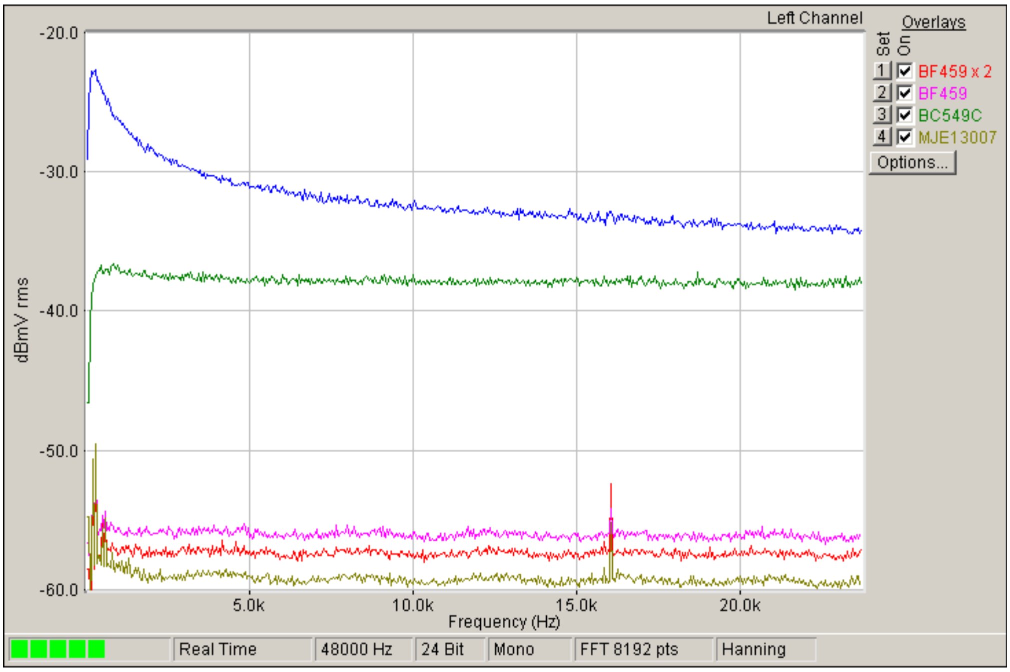
I cannot explain why these transistors are good and others not. Some say it's the base resistance that matters, but I believe this is not the whole truth. (Electronics, to my point of view, should not be a matter of believing, but I'm not a semiconductor physician and what shall I do as long as I do not know. I would highly appreciate everybody giving me an exact explanation.) Higher collector currents, up to a certain limit, reduce the input voltage noise, but increase the input current noise(s). Depending on the source resistance a specific collector current is optimal.

The voltage noises, measured at a collector current of 4 mA approx. and source and feed-back resistances of 1 Ω each are:

Single BF459	0.54 nV/Sqr(Hz)
Dual BF459	0.45 nV/Sqr(Hz)
Single MJE13007	0.38 nV/Sqr(Hz)

Theoretically an improvement of 3 dB could be expected using two transistors in parallel, each with the same collector current as the single one, but practically, if at all, it is much less. This obviously is caused by comparably high noise currents through the source and feed-back resistances. There was no improvement with two MJE13007 in parallel. Instead, at low frequencies the noise was slightly increased, a typical effect of current noise. I did not investigate that further. Instead, I would rather test several more transistors, as those few I happened to have were so different from each other that it is very likely to find significantly better ones.

As an example, here are the noise measured spectra of a few measurements:



From bottom to top:

Brown: MJE13007
Red: Two BF459 in parallel
Pink: BF459
Green: BC549C, a "low-noise", low power transistor, for comparison
Blue: Two BF459 in parallel, 1 kΩ as source resistance

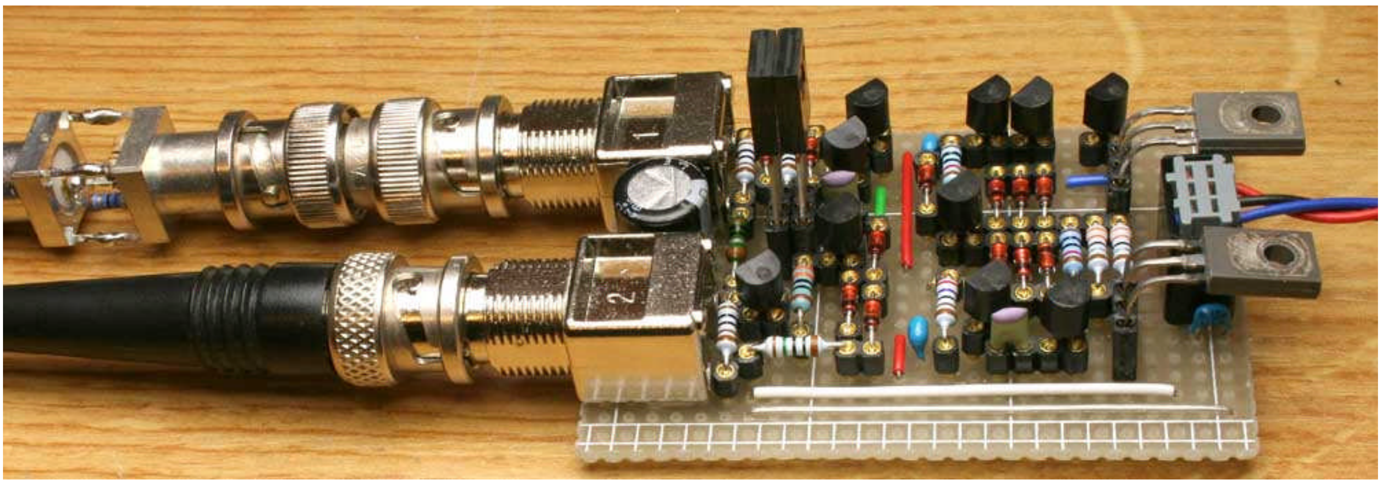
In the latter spectrum the 1/f base-current noise is obvious. It can be calculated as 1.5 pA/Sqr(Hz) approx. @ 2 mA collector current through each transistor.

Further transistors I tested:

BD237, BD437, TIP152, BF471, MJE340 and several low and medium power transistors. Next best to the BF459 is the MJE340, which was my favorite until I tested the BF459.

Better do not build this circuit...

... unless you are not able to discriminate by smell if a transistor or a resistor is about to get hot!



This is an experimental circuit. It rather should not be used in practice as it shows some problems that should not occur. E. g., small input voltages of some 10 or few 100 mV are sufficient to destroy the circuit because the input transistor's collector current can cause high reverse currents through the emitter of T_4 and destroy it. I did not test the zener diode ZD above proposed in the circuit diagram above which might help. Also, I sometimes observed the circuit falling into an oscillating state. I did not investigate this further, it did not happen often. Both problems should not occur when a source is fixed (not plugged) to the input. But as I said, the more harm- than useful huge open loop gain should be reduced anyway.

For a more precise gain and lower low frequency limit I recommend to use an OSCON 2700 µF/2.5 V from Sanyo as electrolytic capacitor C_5, which is as small as the standard one I used in my prototype but has 1/10th of its ESR (10 instead of 100 mΩ).

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This project is experimental. Should you work on something where it might be interesting, i. e. on microphones, or should it be interesting for you anyhow else, I'd appreciate your feed-back. So you are very welcome to email me!

Last update: January, 4th, 2009 Made with <NVU> Uwe Beis