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Working Headline: Accurate Simulation of Noise Figure for an RF ASIC Design

Deck: SPICE linearizes a circuit and ends with a linear time invariant representation. But what is critical for accurate noise simulation of RF circuits is to linearize the circuit so that you end up with a linear periodically varying representation.

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Traditional RF design utilizes SPICE-based simulation, and that's acceptable for about 75 percent of the design. The problem is SPICE simulation cannot predict the noise of large signal RF circuits such as mixers and oscillators. Instead, designer's must make due with estimates that stem from experience and manual calculation. Even if you achieve acceptable test lab results, they are often troublesome to correlate to an RF integrated circuit (IC) because the "single transistor, bond-wires-on-a-test fixture" is a very different environment.

Accurate simulation of the noise is crucial to achieving first-pass success for RFICs that contain such blocks as low-noise amplifiers (LNAs), voltage controlled oscillators (VCOs), and mixers. The design and simulation of the VCO and down converting mixer functions of a 1 GHz RF transceiver ASIC show how you can overcome these problematic areas by utilizing advanced RF simulation techniques. These techniques treat the RF circuit as periodically-varying linear circuits and so accurately account for frequency-translation effects such as noise folding.

An RF LSI simulator like Cadence's SpectreRF allows the simulation of frequency translation effects through its unique algorithms (see box: What's Behind PSS, PAC, PXF, P-Noise?). It allows you to expeditiously simulate noise figures versus all parameters such as temperature, process, power levels, and others. This advanced simulation also plays a major role in the VCO design. Here, you still need advanced noise analysis capabilities, but you also need phase noise simulation, which is slightly different from the mixer noise figure simulation. Thus, you need the extra ability to measure phase noise of an oscillator and/or a frequency multiplier. When your simulation is fast and highly accurate like this, you can optimize the device with considerably more confidence.

RF Chip Design

Fig. 1 shows the block diagram of a bipolar RF chip, consisting of an LNA, down converting mixer, intermediate frequency (IF) amplifier, I/Q demodulator, VCO, I/Q modulator, and transmit driver amplifier. On the receive side, the incoming signal is usually at a very low level, hence you need the LNA that has good power gain (about 15 dB), but a low noise figure (less than 2 dB). The down converter mixer then converts the signal from its high (≈900 MHz) frequency to a lower (≈250 MHz) frequency so that a considerable amount of gain can be inexpensively added with low current. This operation is performed by mixing the incoming signal with the local oscillator frequency. This local oscillator frequency is generated by phase locking the VCO with a crystal reference.

The local oscillator is offset in frequency from the RF carrier by the ≈250 MHz intermediate frequency. Those two signals go into a nonlinear device (the mixer) to produce the IF at 250 MHz. The signal can then be amplified considerably because the designer has established the receiver's noise floor through the LNA and mixer.

In the IF strip, which is an automatic gain controlled (AGC) amplifier, the signal is amplified by as much as 90 dB depending on the power level of the incoming signal. Afterward, it goes into the I/Q demodulator stage, which converts it to baseband and splits it into real and imaginary components for processing. The processor expects two orthogonal channels, an I channel and a Q channel. The I and Q signals are then sent through and off-chip analog-to-digital converting (ADC) circuit.

PSS/PAC/PXF/P-Noise Analyses

A general characteristic of RF components along the signal path, such as mixers, filters, and amplifiers, is that they are linear by design. They must be linear so that the information signal they are processing is not distorted. Now, it is widely known that mixers must be nonlinear to function, and that best performance is usually achieved with switching mixers, which are strongly nonlinear. However, mixers have two inputs, one for information signal and the other is a local oscillator (LO). The LO signal contains no information, rather it is only used as a frequency reference. The mixer takes the RF information signal and translates it in frequency by an amount equal to the frequency of the LO. The LO signal is very large and causes the circuit to behave in a strongly nonlinear fashion. However, the mixer is designed to respond linearly to the information signal on the RF input. Thus, mixers are accurately modeled as near linear periodically varying circuits, where the periodic variation is induced by the LO.

SpectreRF accurately and efficiently handles this type of behavior by applying two analyses in sequence. Periodic steady state (PSS) is applied first to compute the response of the circuit to the LO alone. This is the periodic operating point. PSS is followed by either periodic AC analysis (PAC), periodic transfer function analysis (PXF), or a periodic noise analysis, depending on the type of information that is needed. While these analyses each perform a small-signal analysis about a periodic operating point, each is slightly different from the others. Collectively, PAC, PXF, and P-Noise are referred to as periodic small-signal analyses because they treat the input signal as a small perturbation to signals that are already present and computed by the PSS analysis.

PAC and P-Noise are similar to the SPICE AC and noise analyses. However, SPICE linearizes about a quiescent, or constant, operating point and so generates a linear time-invariant representation that cannot exhibit frequency conversion. Whereas SpectreRF linearizes about a periodic operating point and so generates a linear periodically-varying representation that accurately models frequency conversion.

PAC calculates the small-signal transfer function through the circuit. Since PAC accurately accounts for frequency translation, it can be applied to compute the conversion gain of mixers.

PXF is similar to PAC in that it computes transfer functions, however it's different. In PAC analysis, you specify the input, and it computes the transfer functions to all possible outputs. With PXF, you specify the output, and it computes the transfer function from all possible inputs. PXF is particularly valuable for mixers. Take for example in a receiver, you specify the output as the output of a circuit at baseband. PXF then directly computes the conversion gain from the RF input, the various images of it, and the transfer function from undesired inputs such as the power supplies.

P-Noise is somewhat different from the other analyses in the sense it is not computing transfer functions. Rather, it computes the output of the circuit as it responds to various noise sources, i.e., noise generated by the electrical device inside the circuit, itself. P-Noise is similar to SPICE noise analysis. But because it is operating about a periodically varying operating point, it takes into account the frequency translation of the noise by the LO. This is often referred to as "noise folding." Moreover, since noise sources are bias dependent, P-Noise analysis also takes into account the fact that the noise sources, themselves, are periodically varying because the operating point is periodically varying.

SPICE linearizes a circuit and ends with a linear time and variant representation of the circuit. On the other hand, SpectreRF linearizes the circuit and comes up with a linear periodically varying representation. This is a key distinction. The fact the linear circuit is periodically varying means it is capable of implementing frequency translation, which is the essence of the complete RF circuit. It is there to translate input signals down to baseband and from baseband up to the transmission band.

Design Examples

P-Noise provides a summary of the contribution to the overall noise from all components within the circuit. From that, you can now find what can best be described as "hidden noise sources" in different designs. Other tools only provide an estimated noise figure and that's all. Often, you estimate the noise of the standard components and the resulting noise figure is higher than anticipated. Usually, in these instances, there are hidden noise sources in these components. P-Noise gives you a listing of these noise sources ranked in percentage of overall noise.

LNA Optimization Using P-Noise Analysis

Fig. 2 shows the chosen topology for a 900 MHz Low Noise Amplifier (LNA). Q26 and Q15 make up a standard cascade stage. This stage is biased to a quiescent current by the combination of a pnp current mirror (QP1,QP2,QP3) and an npn current mirror (Q27,Q25). The reference current for the current mirror is developed by applying a bandgap voltage (~1.25v) to the base of Q2. The reference current developed is:

Problem: Q26 is not labeled in the schematic

Problem: QP1 is not shown in schematic, and QP3 is shown twice

$$\mathrm{Iref} = \frac{\mathrm{Vbg-Vbe(on)}}{R_{REF}}$$

$$= \frac{1.25 - 0.75}{2.5K}$$

$$= 200\mu A$$

This value is amplified by the current mirrors by a factor of 10, giving a cascade current of 2mA. The input of the cascade is matched to 50 ohm using lossless series feedback. This feedback is generated by the current through L3. The resultant input impedance is:

$$Z_{in} \approx r_b + \frac{g_m L3}{c_{in}} + \frac{1}{sc_{in}} + s\mathrm{Lin}$$

Where c_{in} is the equivalent input capacitance of Q26, r_b is the base resistance of Q26, and L_{in} is an external series matching inductor used to tune c_{in}. The $g_m L3/c_{in}$ term represents the lossless feedback. With the proper choice of L3 and Lin, matching the 50 ohm is accomplished. The RF noise figure of the cascade structure, in a 50 ohm system, is typically dominated by thermal noise generated by the base resistance of Q26. Collector and base shot noise can also contribute. When designing an ultra low noise amplifier, however, all noise sources must be considered and minimized.

After the initial hand calculation, the LNA was simulated using the P-Noise analysis of SpectreRF. A noise summary (Table 1) shows, as expected, the main noise contribution coming from Q26 base resistance and collector current. In addition, current mirror resistors R39 and R40 have significant contributions.

With these initial results, circuit modifications are made. R39 was increased from 2K to 4K, and R40 was increased from 20K to 40K. In addition, Q26 and Q27 were doubled in area. The cascade current was held constant. Table 2 shows the Noise Summary of the optimized design. The total noise has been reduced significantly due to the reduction in contributions from R_b to Q26 and the current mirror resistors. Fig. 3 shows the before and after LNA noise figures. This simple example demonstrates some of the capability of the PSS P-Noise function in analyzing and optimizing LNA functions.

Question: Was it really Q26 and Q27 that were doubled in area?

PAC Analysis For Simulating IP3

Third-order intercept point (IP3) is a key specification when designing RF circuits. The IP3 is a measure of the linearity of the circuit in question. Typically, this simulation has been done with a transient time domain simulator such as SPICE. In this case, two in-band input tones, spaced closely in frequency and having the same magnitude, are applied to the input of the circuit. The output spectrum will consist of both first- and third-order products. The ratio of third-order to first-order output powers is used to calculate the IP3. In order to accomplish the measurement, the simulator time step control parameters are set so that the internal time step is small enough to resolve the second or third harmonic of the highest frequency of interest. The time span is set to one period of the frequency spacing (with a little extra time to account for initial start up transients). In addition, all tones and spacings should be co-periodic. This allows the use of a Discrete Fourier transform to resolve the output spectrum of the circuit under test. The problem with this approach comes when the input tone spacing is small and the tone frequencies are high. This makes for a very long duration with many time steps, which translates into long simulation times and heavy memory requirements even for modest circuits. This effect is further exacerbated when simulating frequency-translating circuits.

Using the PAC analysis feature of SpectreRF, the simulation times and memory requirements can be greatly reduced. To illustrate this point, the LNA from Fig. 2 was simulated using both techniques. In standard transient analysis, two -40dBm tones at 900 MHz were applied to the circuit. The resulting simulation took 188 seconds. Using the PAC analysis, and the same input conditions, the simulation took only eight seconds. In both cases, an input intercept point of -19.5 dBm was observed. Fig. 4 shows the results of a swept PSS/PAC analysis. In this case, the input power was swept to observe the 1:1 and 3:1 slopes of the output first- and third-order terms, respectively. This simulation took considerably less time than a single power SPICE simulation.

The vast improvement in simulation time is even more apparent for larger circuits, especially those with frequency translation. It's normal for a two-tone test of a 50-100 transistor receiver to require six to eight hours of simulation time using the standard technique. A PAC analysis on the same circuit could take less than one hour. This translates into reduced design and cycle time and faster time to market. These are significant advantages in today's marketplace.

PXF Analysis

PXF is used to optimize mixer and image rejection mixer performance and design. The most notable feature is that PXF uses only one large tone to simulate a mixer's performance. When performing this analysis with SPICE, both the LO and receive signal tone must be large signal tones, which are more difficult to analyze than small signal sources.

If a standard analysis without PXF is performed, the two large tones must be harmonically related. If one is at one gigahertz, for example, the other has to be a multiple of one gigahertz, i.e., two, three gigahertz. So, this approach doesn't offer much analysis flexibility.

PXF smoothes all that away. It permits the use of only one large tone, most often used on the LO, and then it injects a small tone of any frequency into the receiver signal. PXF then performs the conversion gain and noise figure measurements. Today, there is no other way to efficiently perform this gain and noise figure versus frequency for a mixer analysis. **[NOTE TO GEOFF: Did you want to include a PXF design example here??)**

# # #

Box -- What's Behind PSS, PAC, PXF, AND P-Noise?

A method called shooting methods is used for periodic steady state (PSS) analysis. A shooting method is an iterative process layered on top of transient analysis that is designed to solve boundary-value problems. Shooting methods simulate the circuit in the time domain over one cycle or one period. They adjust the initial condition and re-simulate over that one period until the initial condition and the final condition are the same, which is the condition for steady state. Once that is true, then you know the circuit is in periodic steady state.

Shooting analysis are also used for the periodic small-signal analysis of PAC, PXF, and P-Noise. This basic algorithm is very similar to the one used in PSS, but to a degree is it easier in the sense it is a linear problem that does not require iteration. Here, it is possible to find the solution in one step. The difference in the periodic small-signal analyses is that the circuit is not periodic, but rather it is quasi-periodic. This is because the small signal is applied at a frequency that is unrelated to the frequency of the

LO. Quasiperiodic signals require special boundary conditions In this case, we are no longer looking for the initial point to be the same as the final point. Instead, we're looking for the final point to be related to the initial point, but which is not necessarily equal to the initial point. The relationship between initial and final point is a function of the frequency of the analysis.

# # #

Fig. 1. RF IC Transceiver Block Diagram

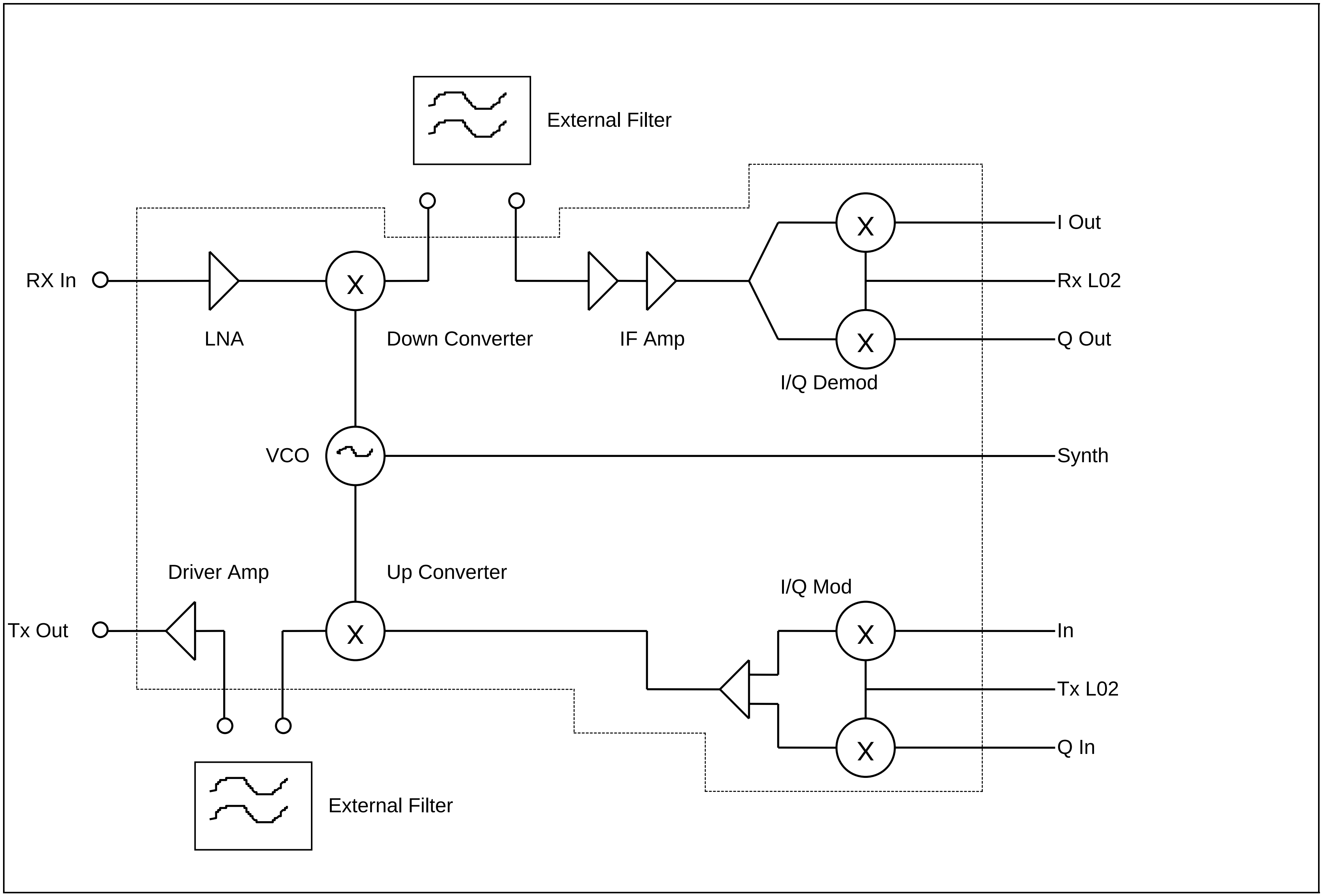

Fig. 2

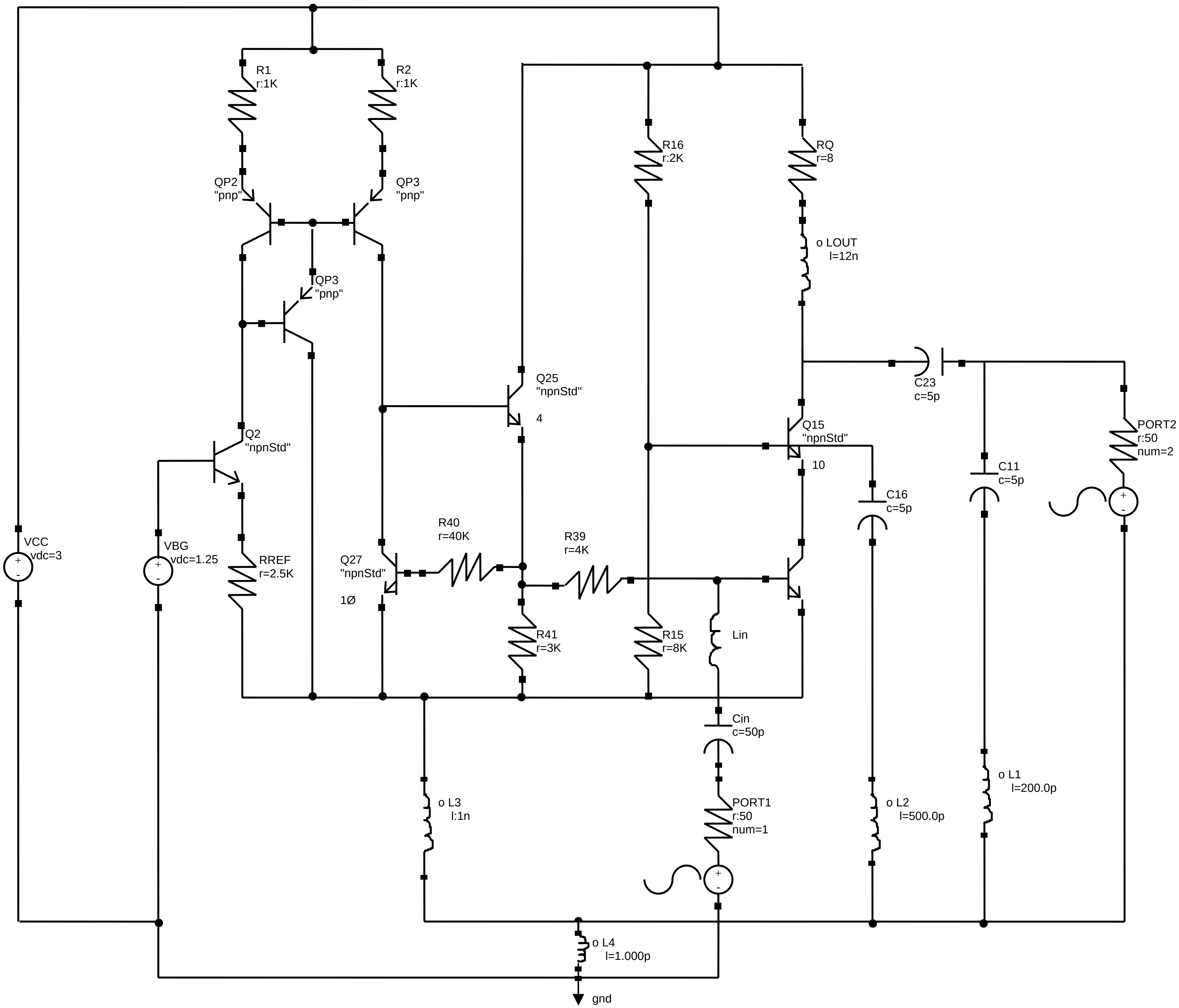
R1
r:1K
R2
r:1K
QP2
"pnp"
QP3
"pnp"
QP3
"pnp"
R16
r:2K
RQ
r=8
o LOUT
l=12n
Q25
"npnStd"
4
C23
c=5p
Q2
"npnStd"
Q15
"npnStd"
10
PORT2
r:50
num=2
C11
c=5p
C16
c=5p
VCC
vdc=3
VBG
vdc=1.25
RREF
r=2.5K
R40
r=40K
R39
r=4K
Q27
"npnStd"
1Ø
R41
r=3K
R15
r=8K
Lin
Cin
c=50p
o L3
l:1n
PORT1
r:50
num=1
o L2
l=500.0p
o L1
l=200.0p
o L4
l=1.000p
gnd

Table 1. Spot Noise Summary (in V^2/Hz) Sorted By Noise Contributors

Device	Param	Noise Contribution	Percent of Total
/Q26	rb	2.71195e-18	11.17
/Q26	ic	2.42331e-18	9.98
/R39	rn	3.70809e-19	1.53
/R40	rn	3.2372e-19	1.33
/Q26	re	2.12814e-19	0.88
/Q26	ib	2.11235e-19	0.87
/RQ	rn	1.56671e-19	0.65
/Q27	ib	1.31768e-19	0.54
/Q27	ic	1.070643-19	0.44
/R2	rn	3.44209e-20	0.14

Total Output Noise = 2.42858e-17
Total Input Referred Noise = 2.96441e-19

Table 2. Spot Noise Summary (in V^2/Hz) Sorted By Noise Contributors

Device	Param	Noise Contribution	Percent of Total
/Q26	ic	2.29476e-18	11.24
/Q26	rb	1.23425e-18	6.05
/R39	rn	1.82621e-19	0.89
/Q26	ib	1.64038e-19	0.80
/RQ	rn	1.56554e-19	0.77
/Q26	re	9.50399e-20	0.47
/Q15	rb	8.58967e-20	0.42
/Q15	ic	4.11859e-20	0.20
/Q15	ib	2.60947e-20	0.13
/Q27	ic	1.32746e-20	0.07

Total Output Noise = 2.04097e-17
Total Input Referred Noise = 2.7129e-19

Fig. 3   Low Noise Amplifier Design

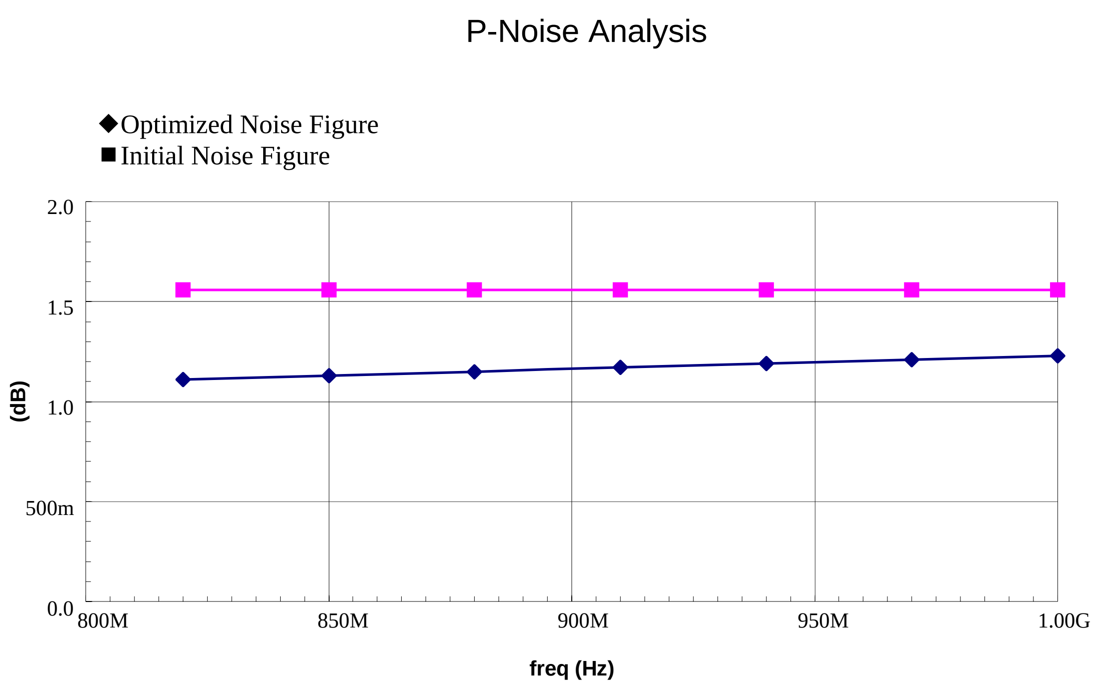

Fig. 4 Low Noise Amplifier Design