

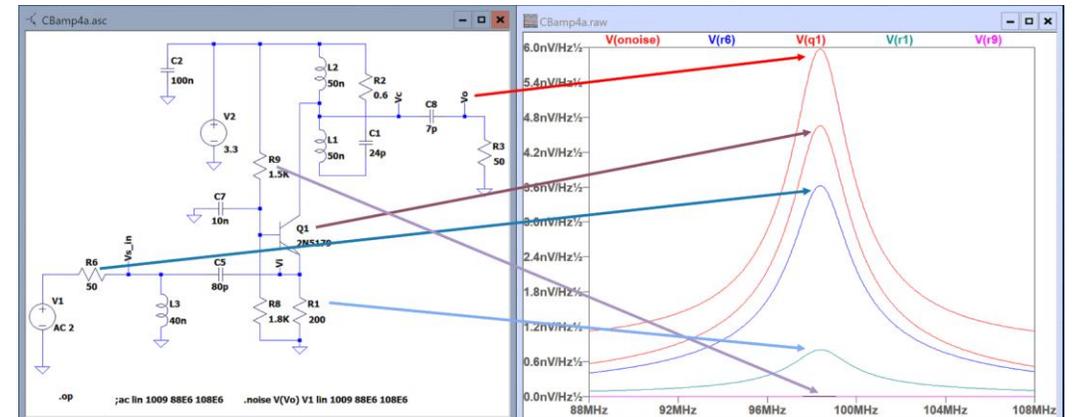
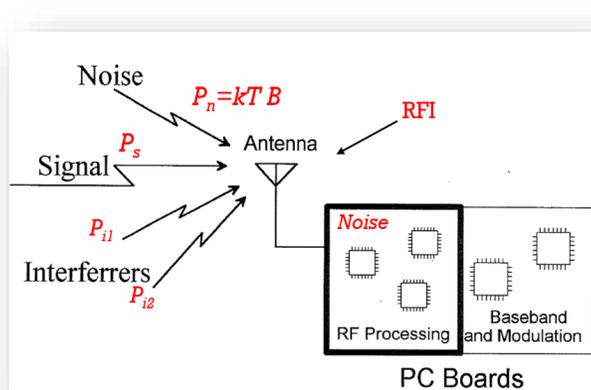
LNAs, Noise Figure, and Noise Analysis - Radio Design 401, Episode 6

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Companion videos at: <https://www.youtube.com/playlist?list=PL9Ox3wpmB0krNexW2k5JMCaewXN7LoRXd>

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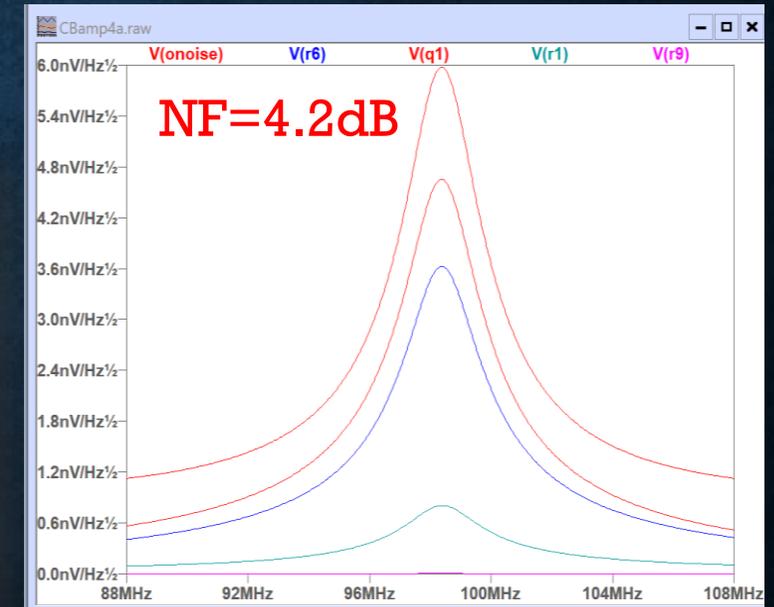
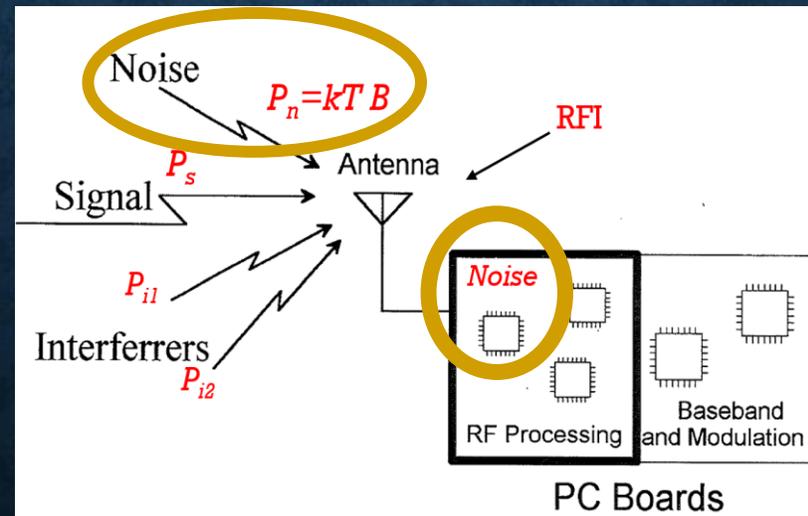
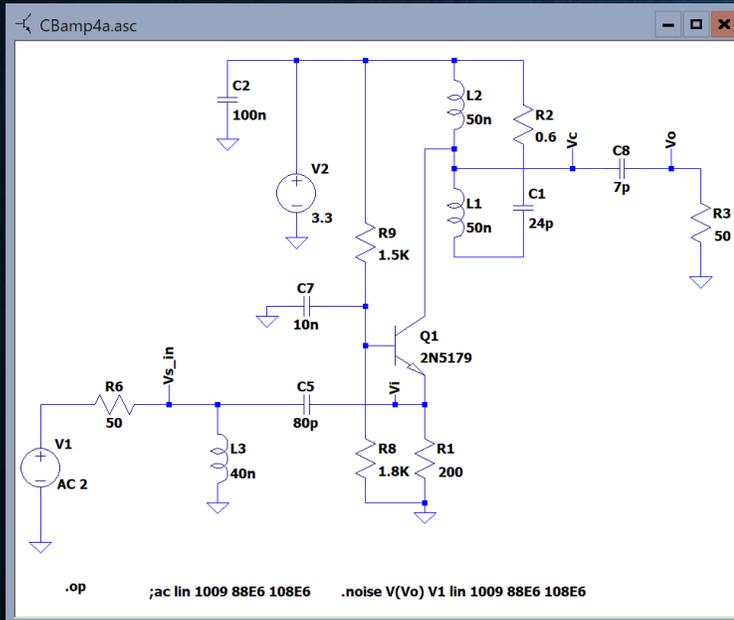
This episode in our Advanced Receiver Design series covers Low Noise Amplifiers (LNA) from both a circuits and system perspective. Part 1 illustrates two real-world scenarios before going into noise analysis in circuits. In the GPS example, we show that low noise figure is important, but it is critical to minimize losses ahead of the LNA. In an automotive receiver, the importance of NF depends on several factors, including receiver architectures used - which are discussed in some depth. Noise modeling in circuits is also discussed, and the topics of analysis, simulation, and measurement are studied further in Part 2 of this episode.



Radio Design 401 – Episode 6

Advanced Receiver Design

LNAs and Noise Analysis



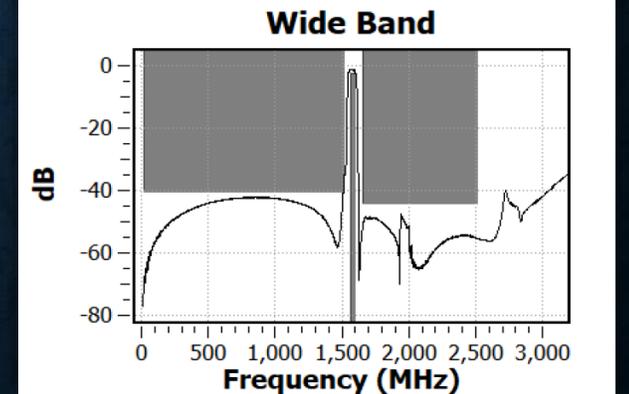
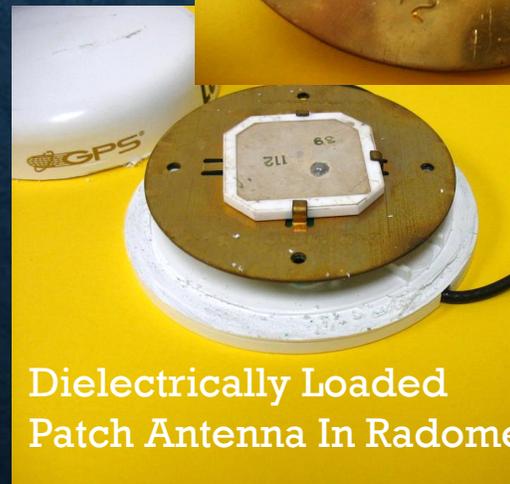
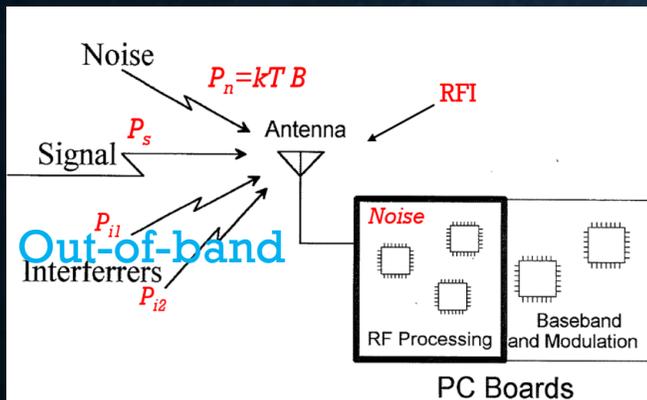
Real World Example 1

Marine GPS Antenna



Narrowband GPS filter from Qorvo website:

QPQ1060
L1 Low Loss GPS SAW Filter
<https://www.qorvo.com/products/p/QPQ1060>

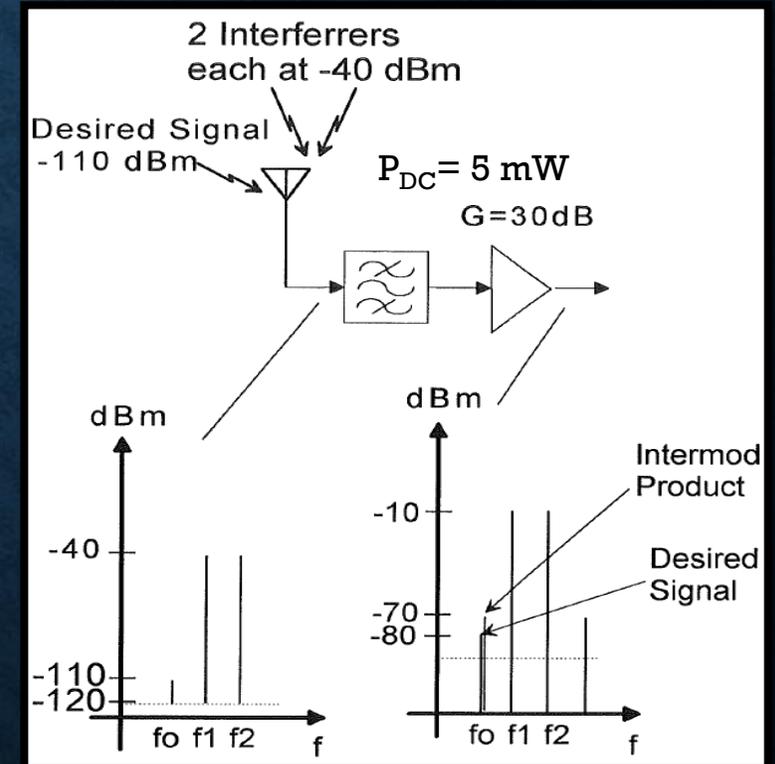
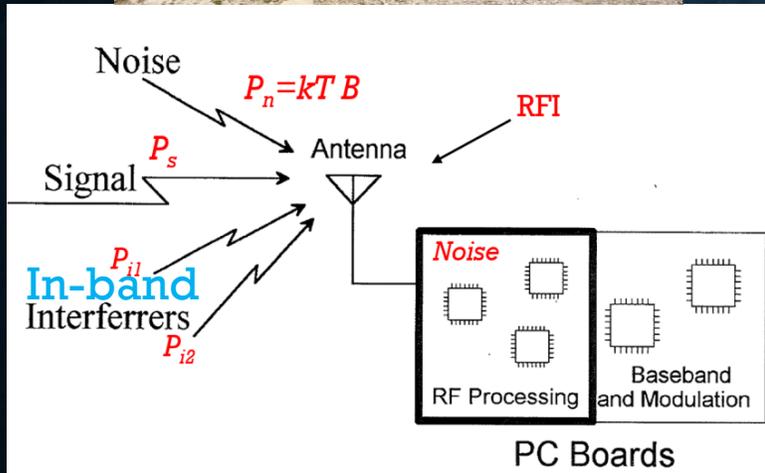
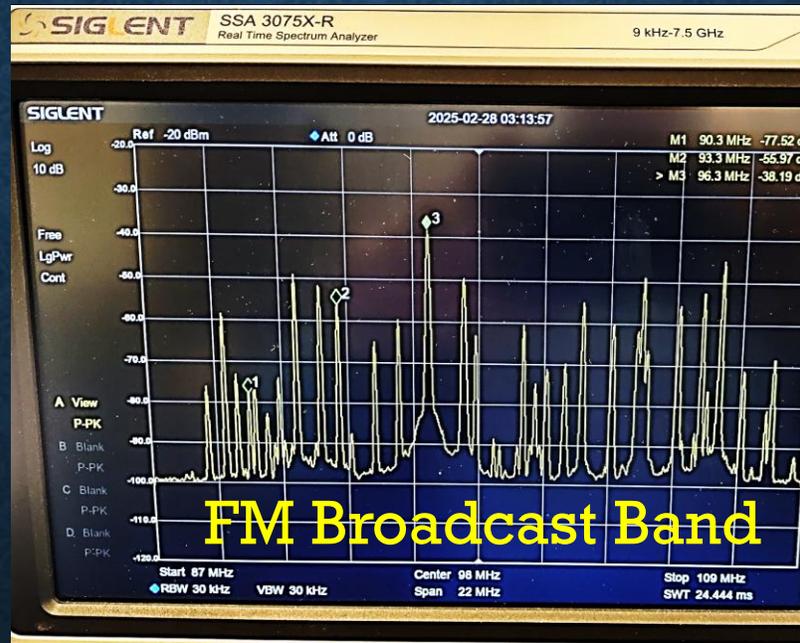


Real World Example 2

Receivers in Motor Vehicles

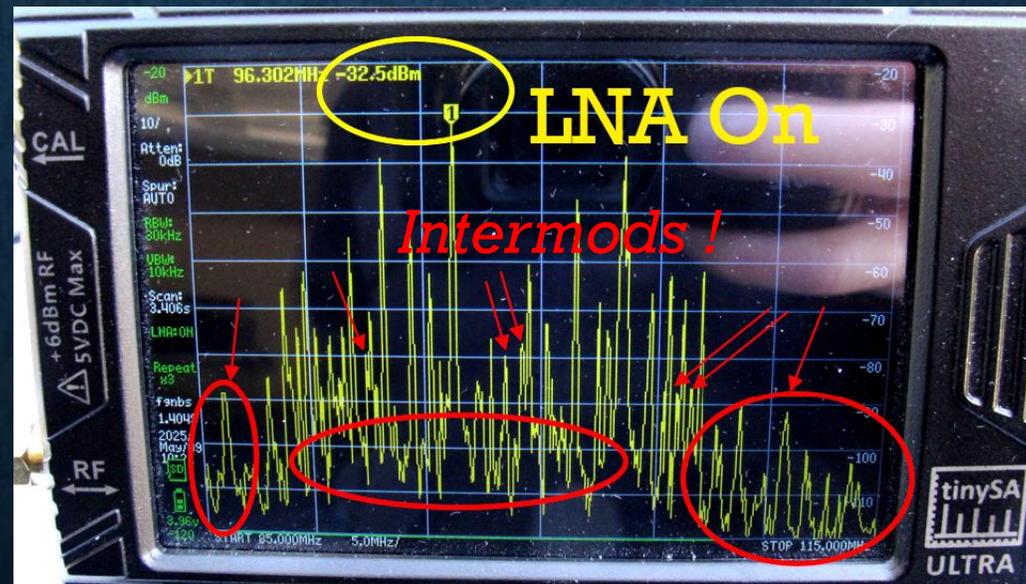


FM Broadcast Band



LNA Considerations

- High gain and low noise figure (NF) are often sought after (and sometimes needed), **but** ...
- **In crowded spectrums**, with decent antennas, amplifiers produce intermods, and **LNA noise figure may not be as important.**



Classic Solution

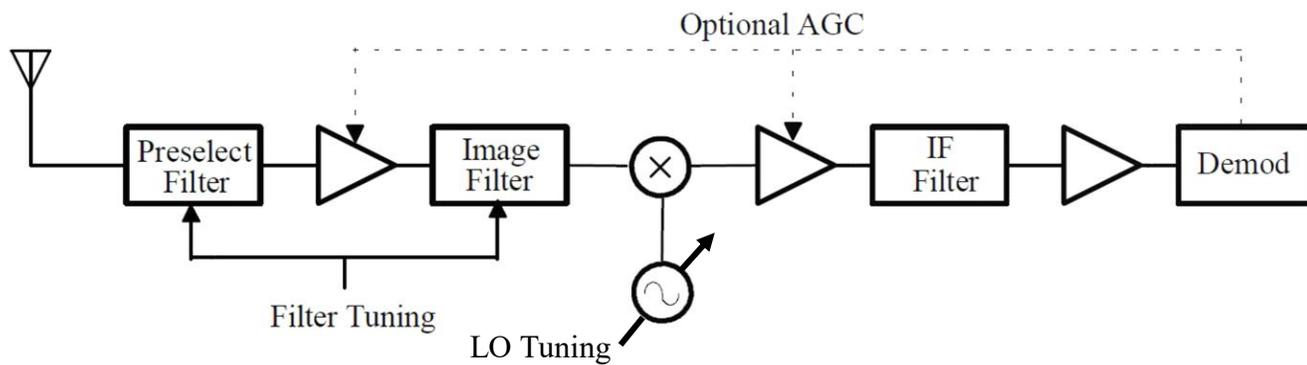
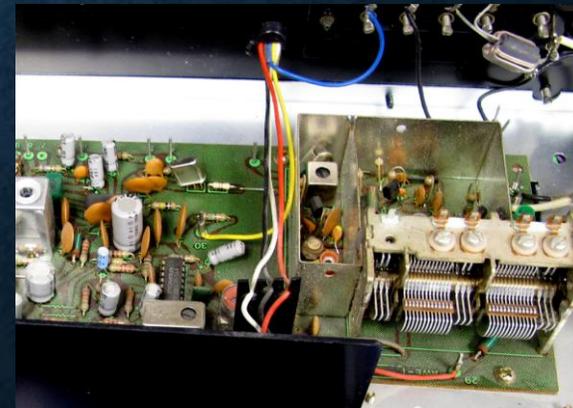


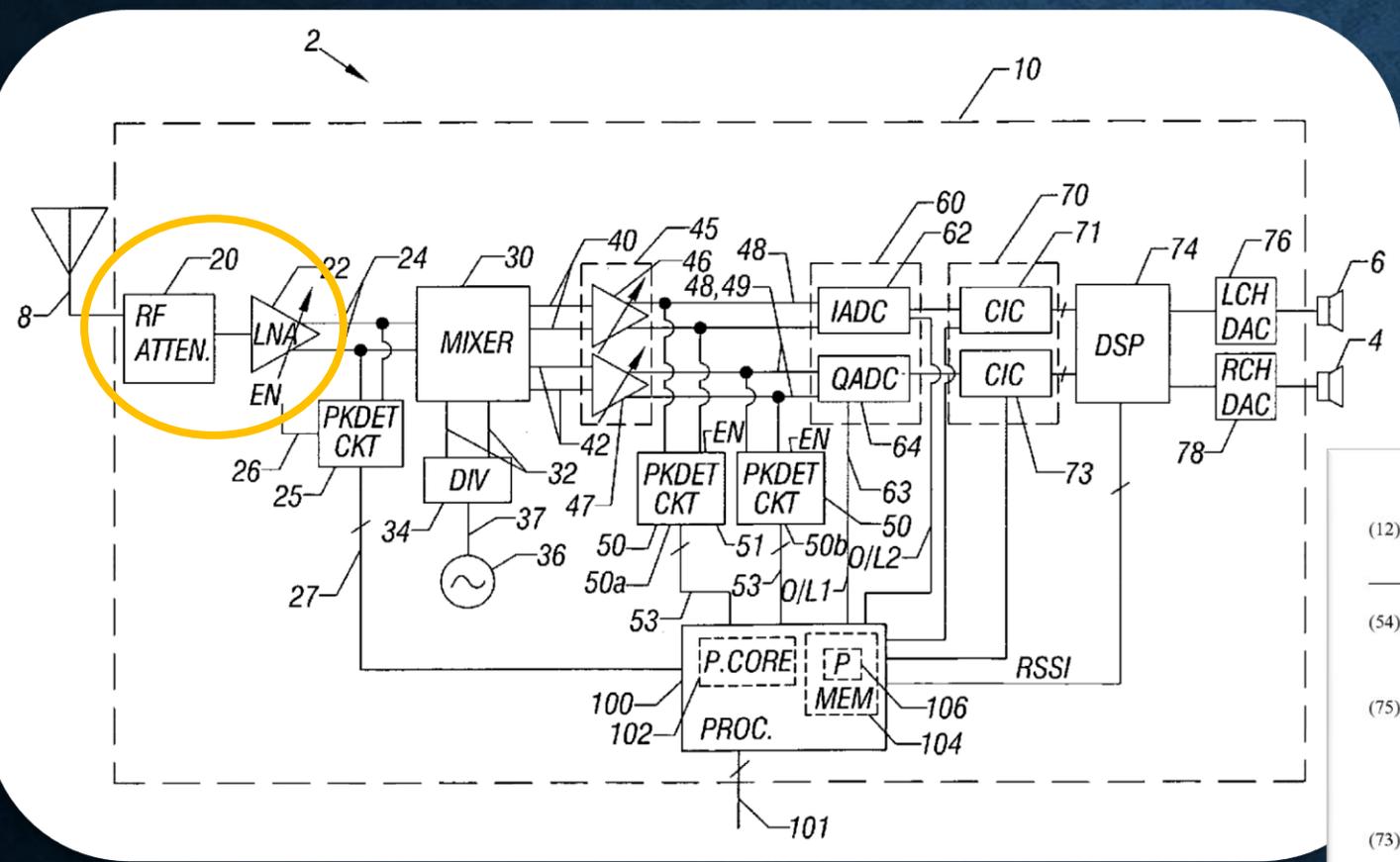
Figure 4.7: Single conversion superheterodyne with tracking preselect.

- LNA increases signal level so that noise introduced later in mixer, etc. doesn't lower received S/N
- Tracking Preselect Filter 'protects' LNA from strong off-channel signals
- Filters must be *narrow* and track with LO tuning ...

From: "Design of Integrated, Low Power, Radio Receivers in BiCMOS Technologies", PhD dissertation, Virginia Tech, 1995.



Modern 'Solutions' (fully integrated receivers)



- Narrowband filters difficult to do on-chip – so ‘punt’!
- Rely on attenuators to deal with strong interferers ☹️

(12) **United States Patent**
Srinivasan et al.

(10) **Patent No.:** US 7,426,376 B2
(45) **Date of Patent:** Sep. 16, 2008

(54) **RECEIVER HAVING DIGITAL AUTOMATIC GAIN CONTROL**

(58) **Field of Classification Search** 455/136, 455/138, 232.1, 239.1, 240.1, 250.1, 252.1, 455/234.1, 333
See application file for complete search history.

(75) **Inventors:** Vishnu S. Srinivasan, Austin, TX (US); G. Tyson Tuttle, Austin, TX (US); Dan B. Kasha, Seattle, WA (US); Alessandro Piovaccari, Austin, TX (US)

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(73) **Assignee:** Silicon Laboratories Inc., Austin, TX (US)

(*) **Notice:** Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 443 days.

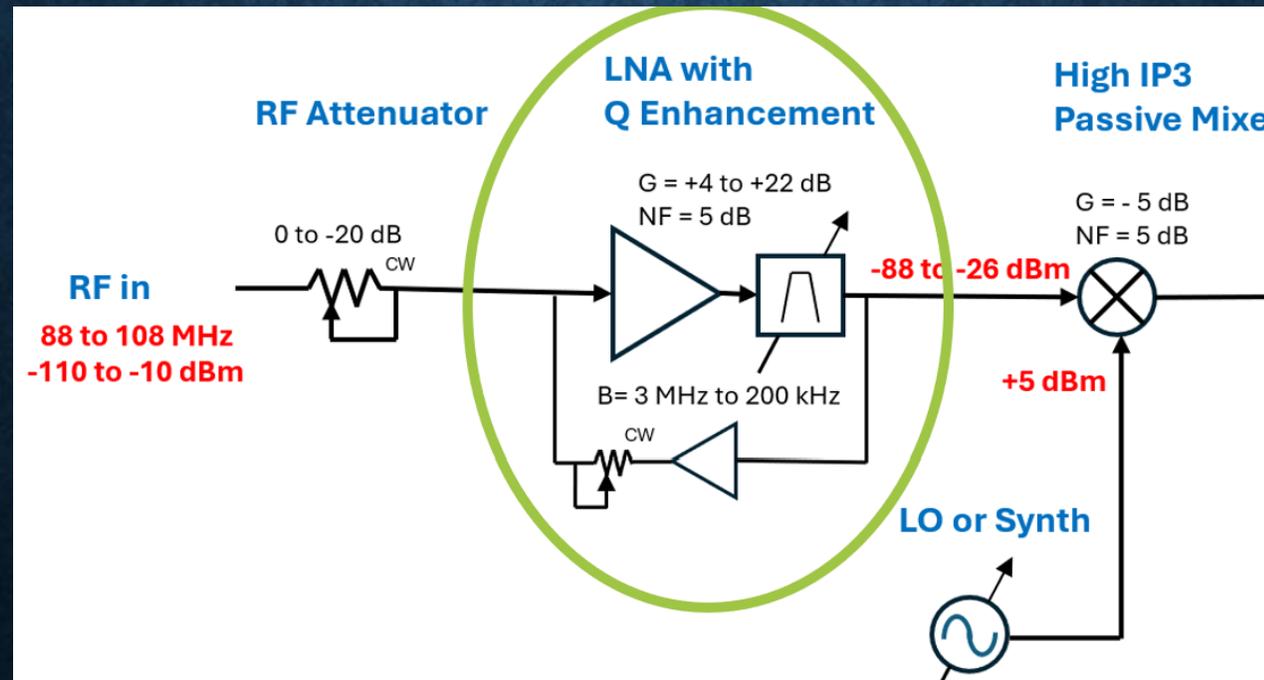
LNA / System Implications

- Modern “fully-integrated” receivers make extensive use of AGC and RF attenuators, plus high DC power consumption to combat intermods.
- Result: Not suitable for very low power applications, and **System NF** can be up to 30 dB ☹️



LNA Design Research

- Q-enhanced Front-ends may allow more sensitivity, at lower power 😊 See Episode 1
- But we need to analyze and understand their noise figure

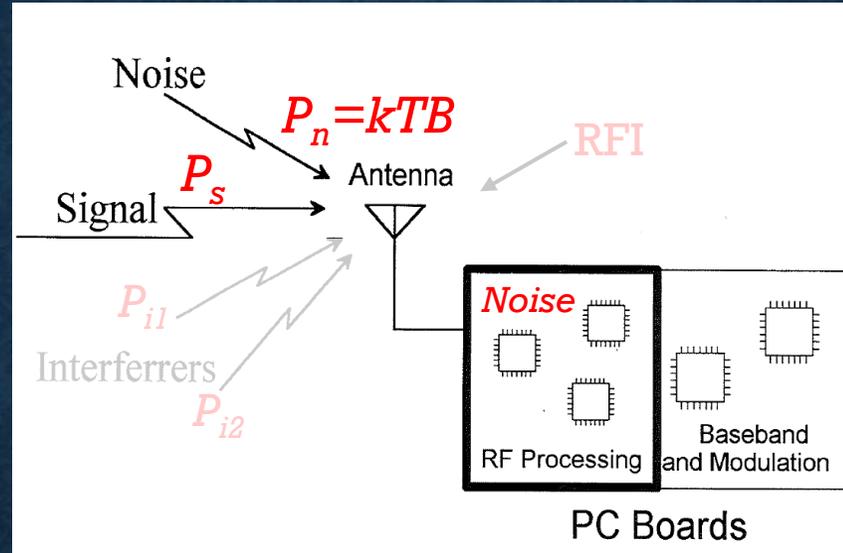


Presentation Outline



- Noise Figure Definition and Basics
- Circuit-level noise models
- Circuit noise analysis
- Simulation – with examples
- NF measurement

A Noise Figure “Implicit” Definition

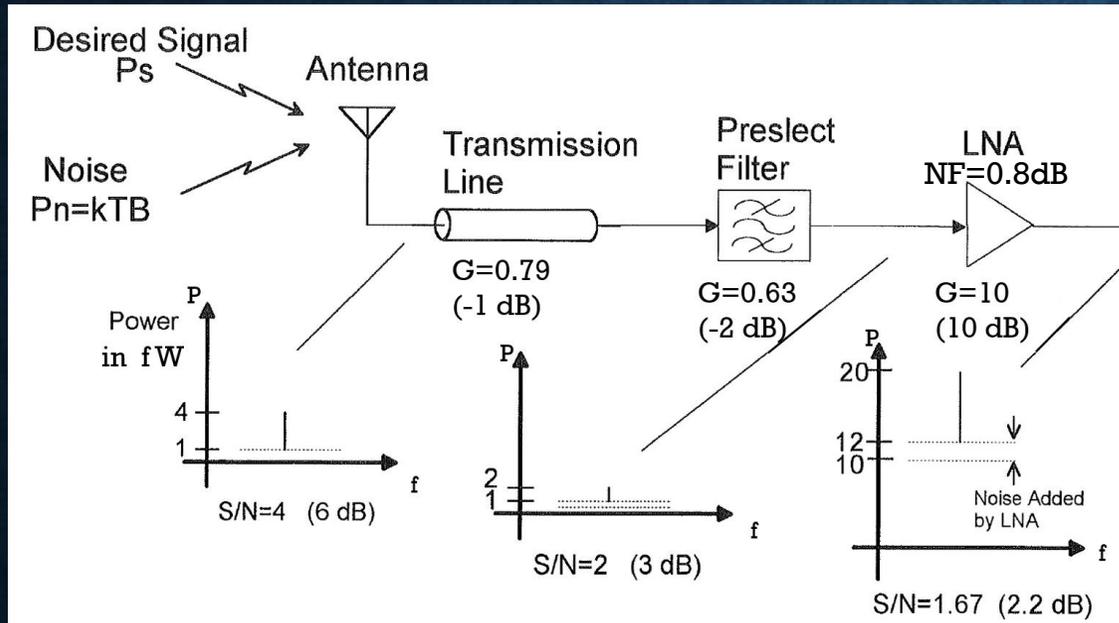


Effect on Receiver Sensitivity: See Episode 2

$$P_{s_min} = -174 \text{ dBm} + 10 \log(B) + S/N_{min} + NF_{rcvr}$$

NF is the amount by which the ideal sensitivity is degraded by circuit noise

Noise Factor and Noise Figure



Front-end “noise factor” is:

$$F = \frac{S_i/N_i}{S_o/N_o} = \frac{N_o}{(G)(N_i)} \quad \leftarrow$$

And “noise figure” is:

$$NF = 10 \log(F) \text{ dB}$$

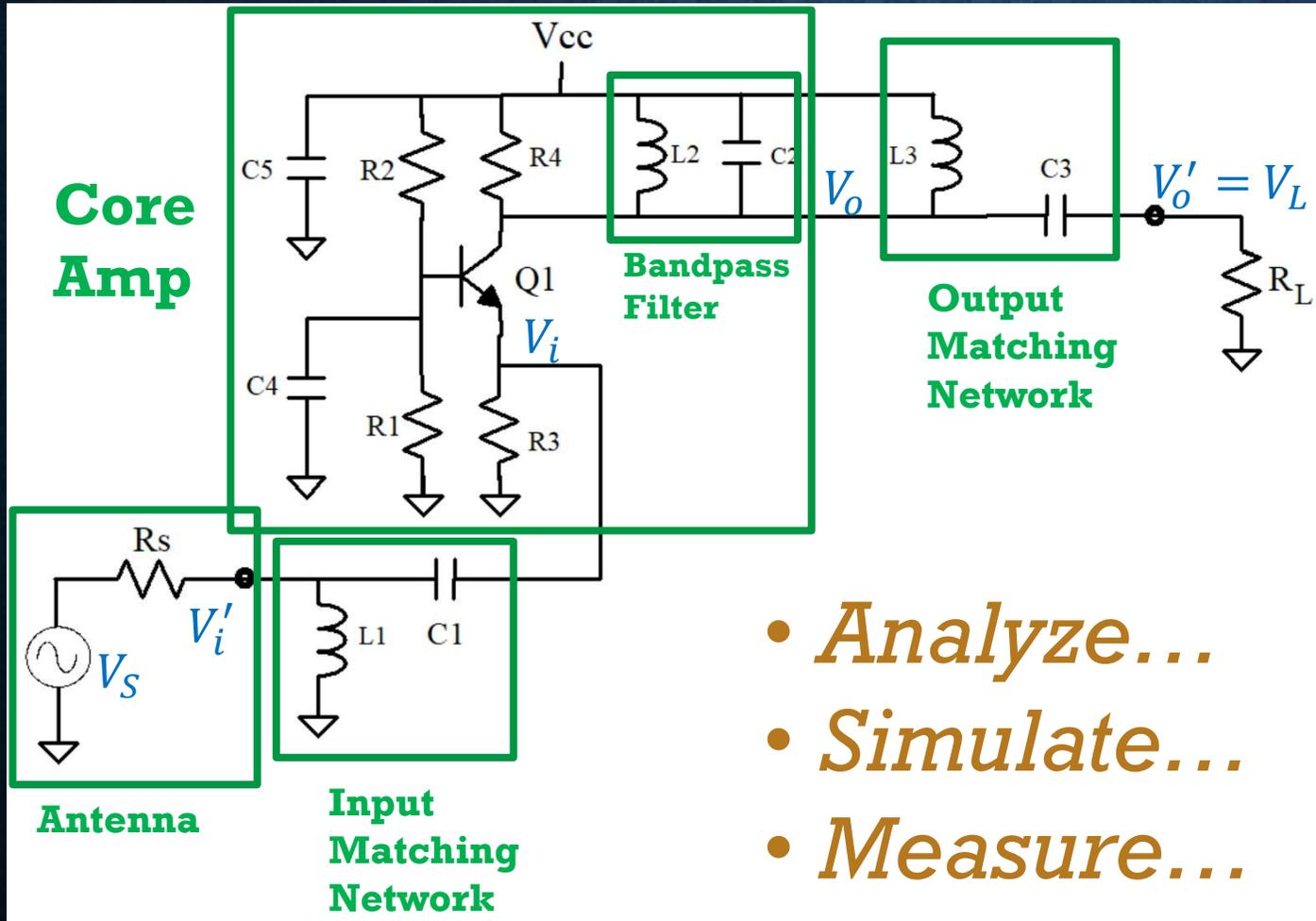
- NOTES:**
- Signal and Noise levels in graphs are shown in ‘linear’ power units here ! (not dB)
 - S/N values and gains are shown as power ratios, with their dB equivalents
 - Overall NF here is $NF = 10 \log(12 / (0.79 * 0.63 * 10 * 1)) = 3.8 \text{ dB}$
 or, directly in dB, $(S/N)_{in} - (S/N)_{out} = 6 \text{ dB} - 2.2 \text{ dB} = 3.8 \text{ dB}$
 Even though NF of LNA is 0.8 dB !!

Presentation Outline

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How Do We Find the NF of an LNA ?



- *Analyze...*
- *Simulate...*
- *Measure...*

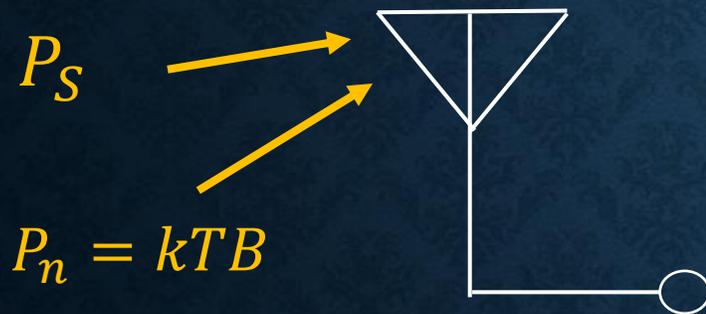
Example:

Common-base LNA
from Radio Design 101 series

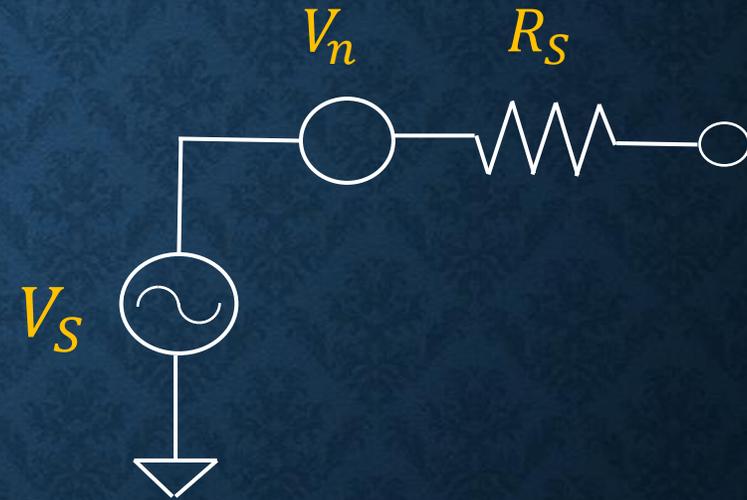
Need “noise models”
for components ...

Component Noise Models

Resonant Antenna



=

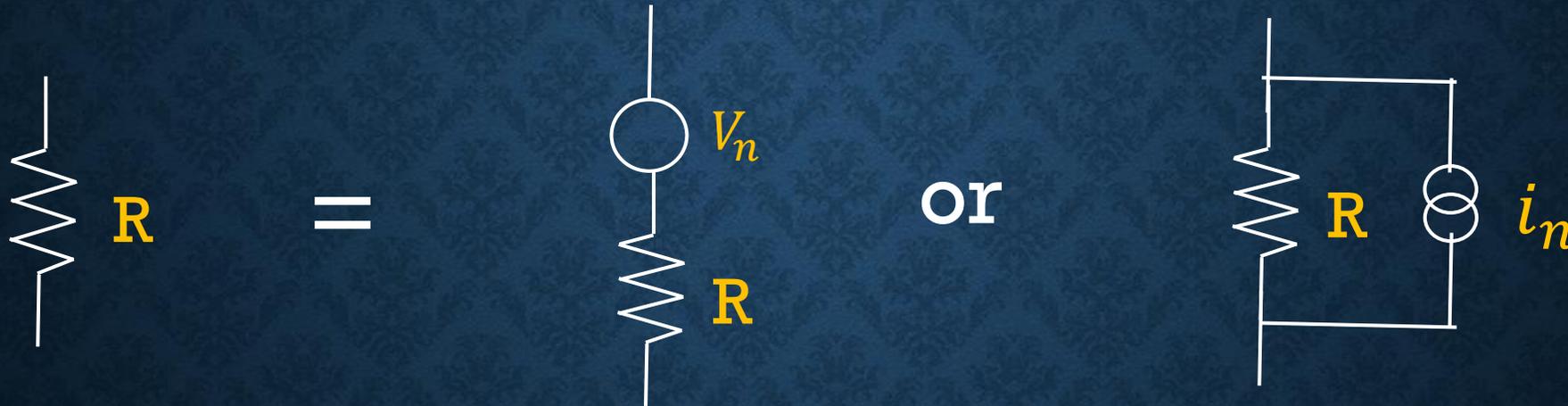


$$V_n = \sqrt{4kTR_sB}$$

Example: $T=290$ K, $B=200$ kHz, $R_s=50$ Ohms: $P_n = 0.8$ fW or -121 dBm (to matched load)

$V_n = 0.4$ μ V (open circuit value)

Component Noise Models



$$V_n = \sqrt{4kTRB}$$

$$i_n = \sqrt{4kT \frac{1}{R} B}$$

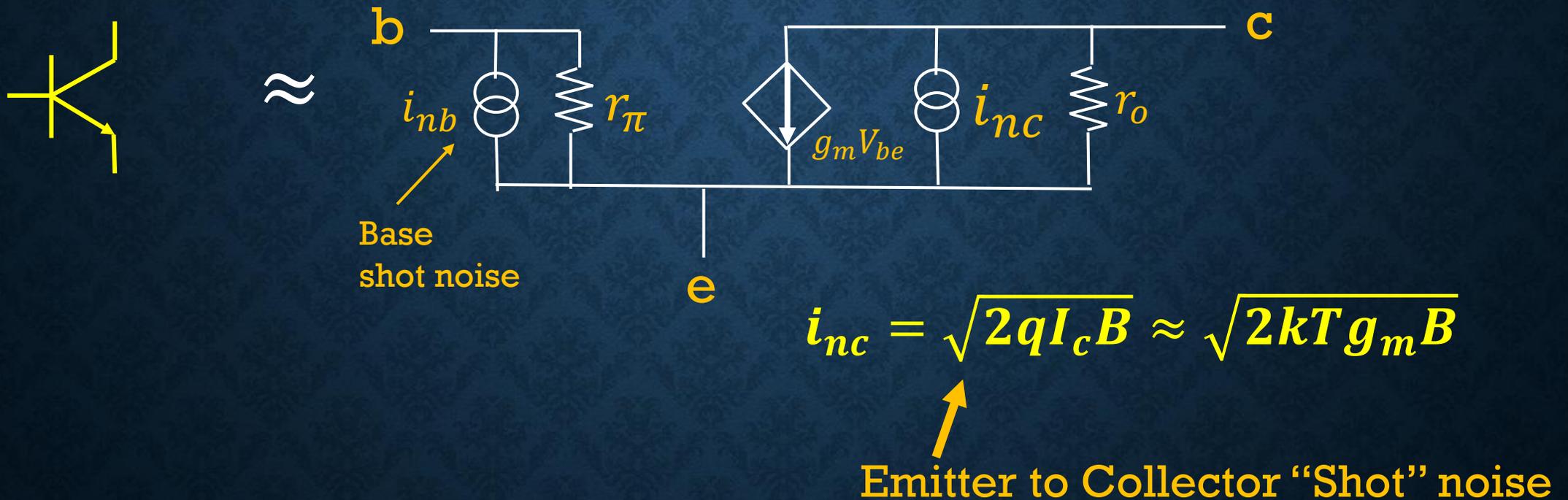
(Simplified) Component Noise Models



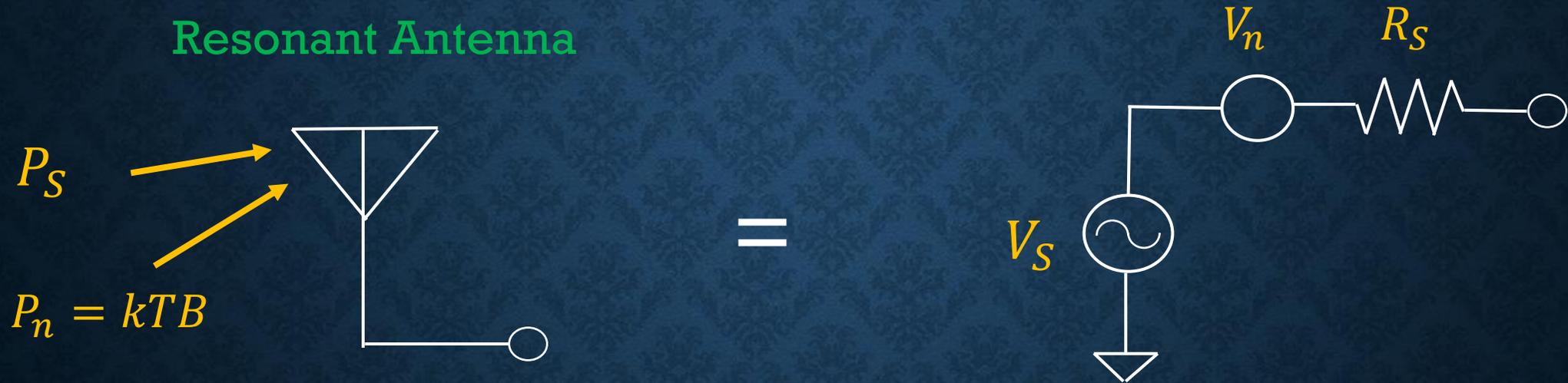
Reactive Components are approximately noiseless ***if*** Q is large

If Q is not large, add a series or parallel loss R and model its noise...

(Simplified) Component Noise Models



Normalized Noise (1 Hz Bandwidth)



$$V_n = \sqrt{4kTR_s} \quad \text{V}/\sqrt{\text{Hz}}$$

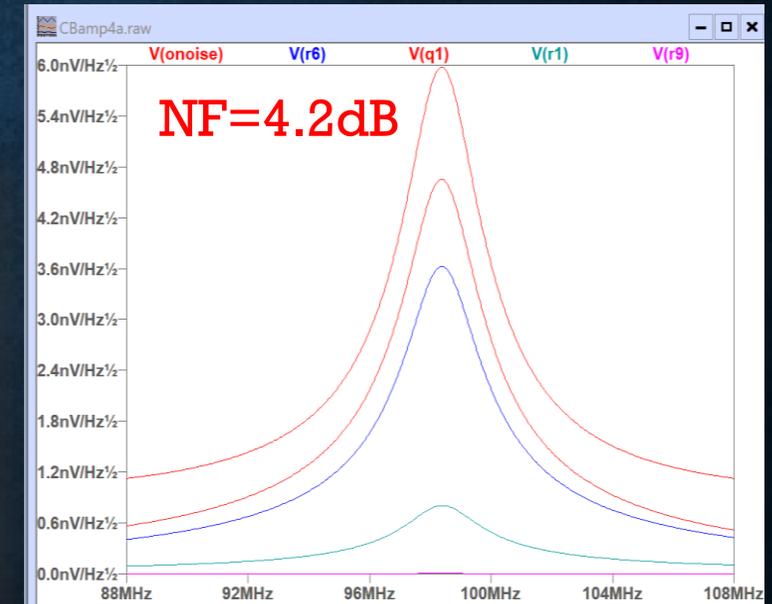
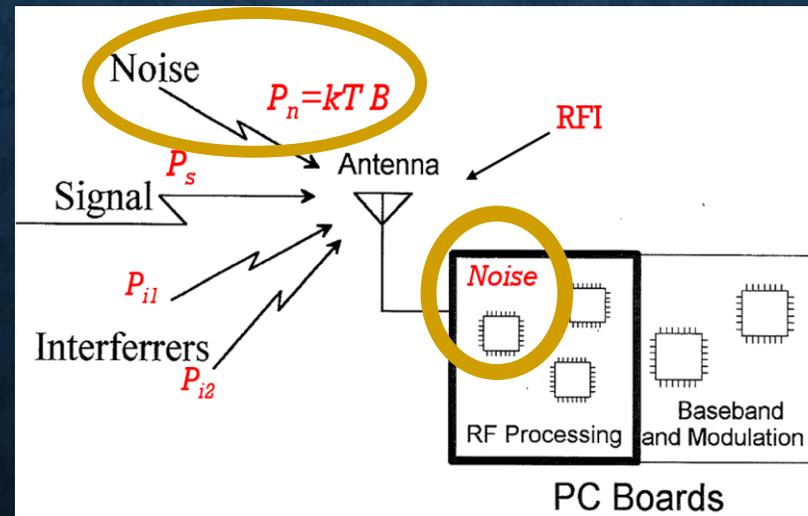
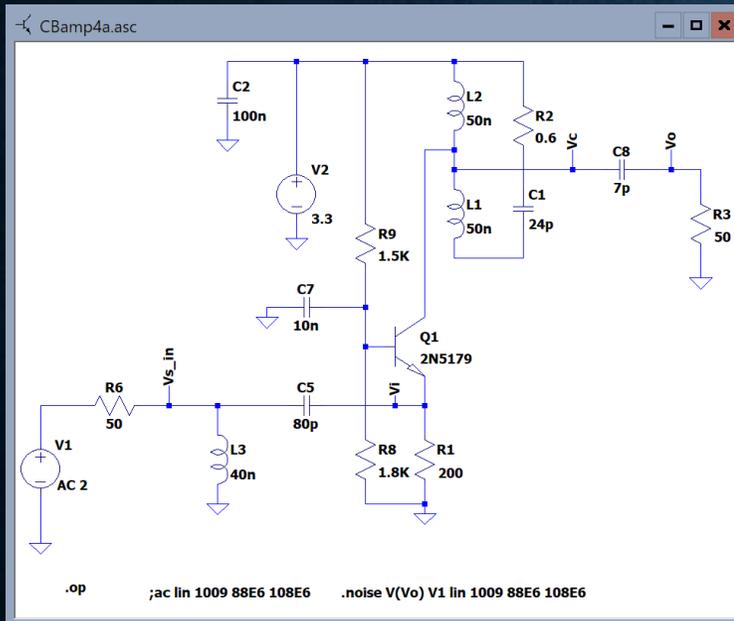
Example: $T=290 \text{ K}$, $B = 1 \text{ Hz}$, $R_s=50 \text{ Ohms}$: $P_n = (4.0)10^{-21} \text{ W}$ or -174 dBm (to matched load)
 $V_n = 0.9 \text{ nV}/\sqrt{\text{Hz}}$ (Loaded value is $0.45 \text{ nV}/\sqrt{\text{Hz}}$ at 50 Ohms)

Radio Design 401 – Episode 6

Advanced Receiver Design

LNAs and Noise Analysis

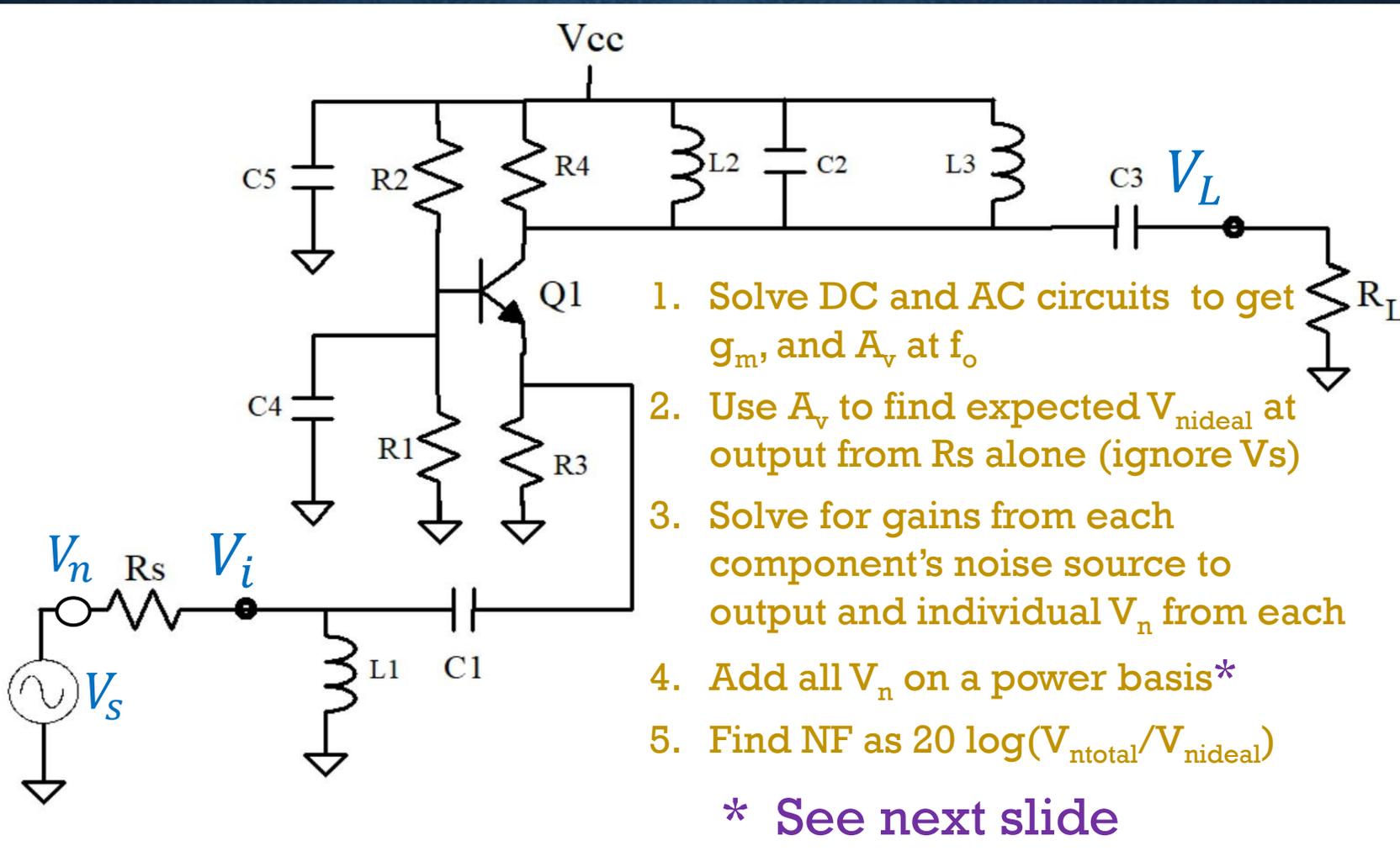
Part 2 of 2



Presentation Outline

- Noise Figure Definition and Basics
- Circuit-level noise models
- ➔ • Circuit noise analysis
- Simulation – with examples
- NF measurement

Analysis Procedure



Adding Noise Voltages on Power Basis

- Noise sources are random, and uncorrelated from each other
- Hence, we can't add noise voltages using normal superposition
- But we can add the “power” (voltage squared) associated with each, and then take the square root to get the total RMS noise ...

$$V_{n_{total}} = \sqrt{V_{n_{ideal}}^2 + V_{n_1}^2 + V_{n_2}^2 + V_{n_3}^2 + \dots}$$

Presentation Outline

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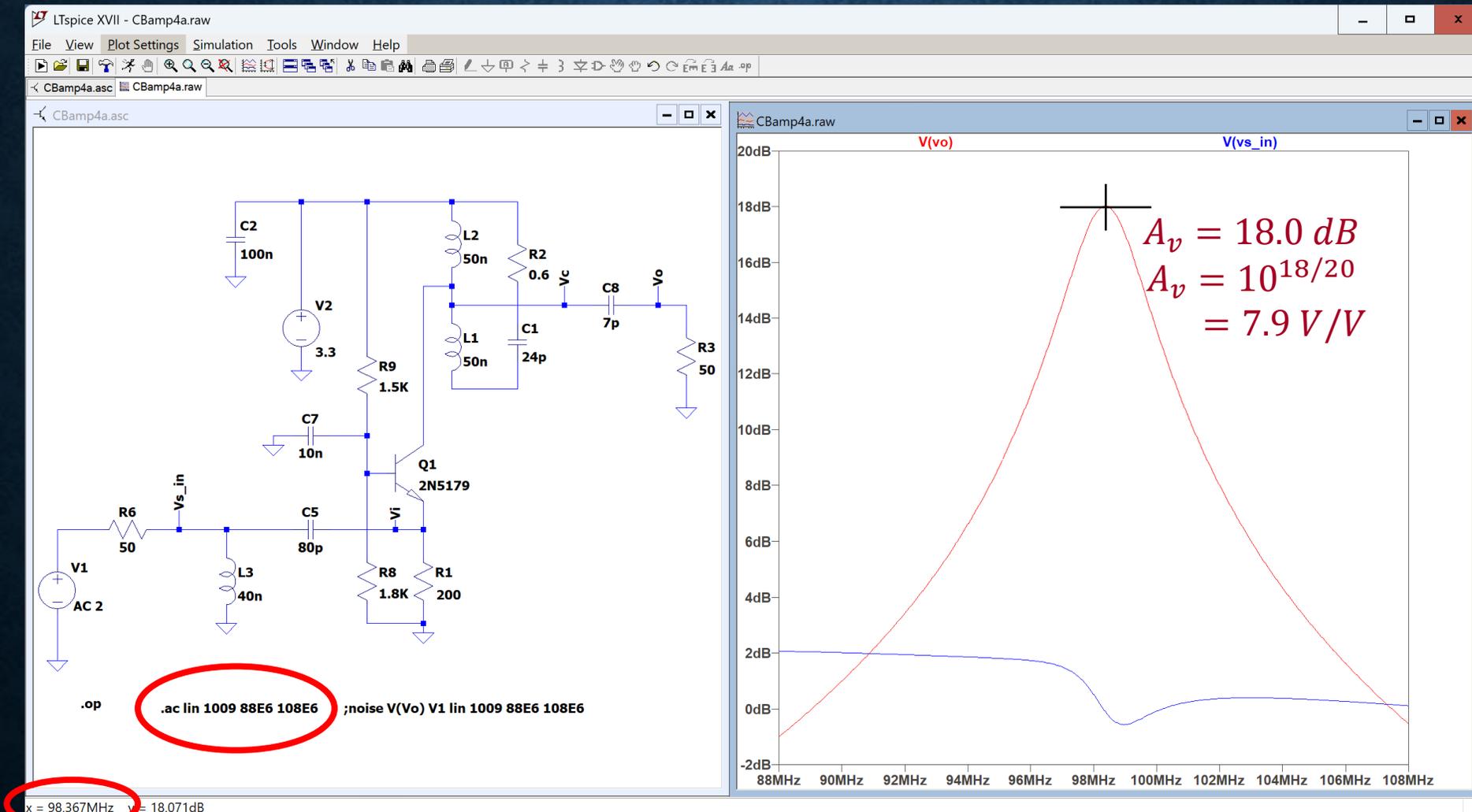


Simulators Do This For Us 😊

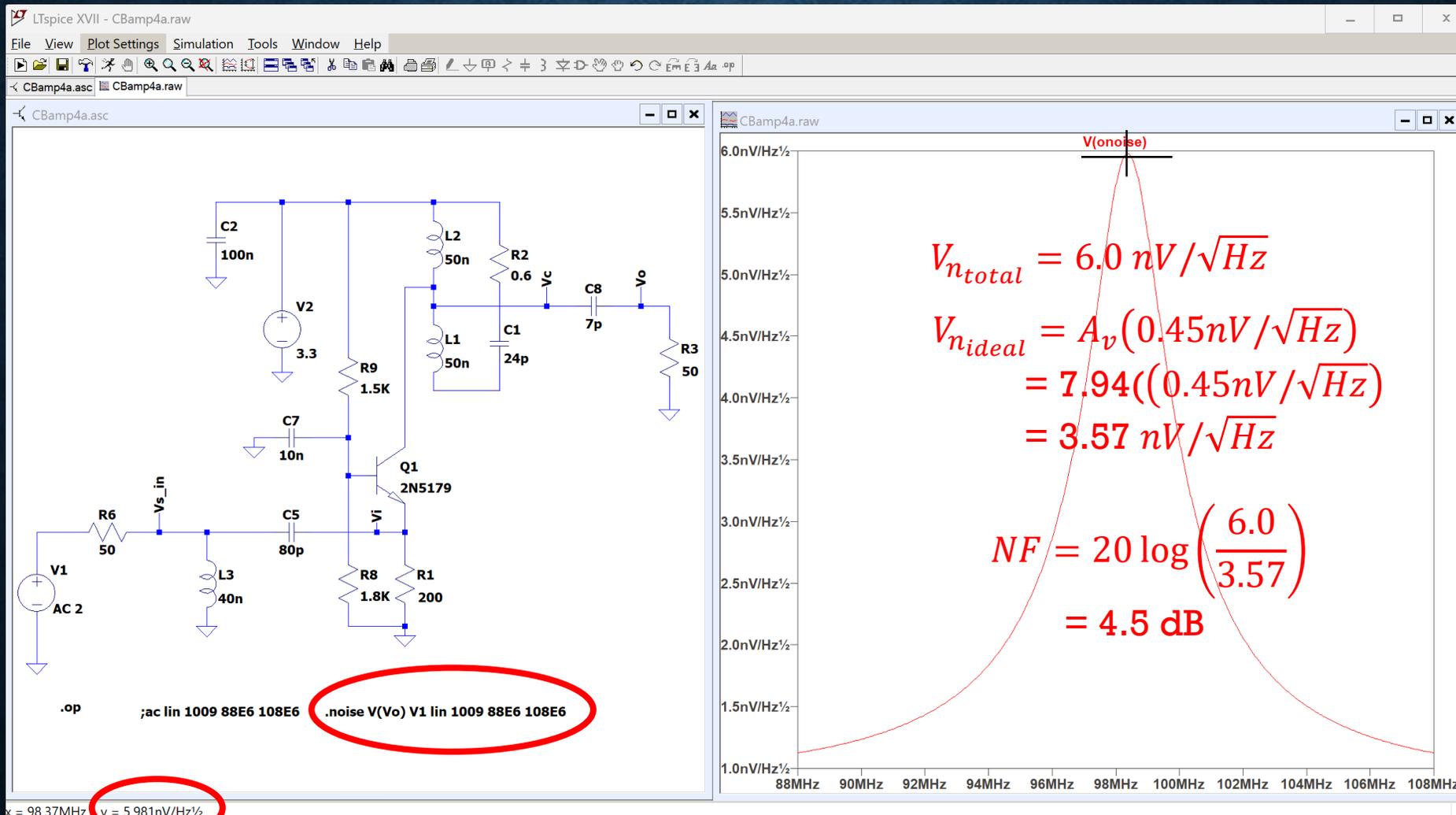
(except maybe step 5)

1. Solve DC and AC circuits to get g_m , and A_v at f_o
2. Use A_v to find expected V_{nideal} at output from R_s alone (ignore V_s)
3. Solve for gains from each component's noise source to output and individual V_n at output from each
4. Add all V_n on an RMS basis
5. Find NF as $20 \log(V_{ntotal}/V_{nideal})$

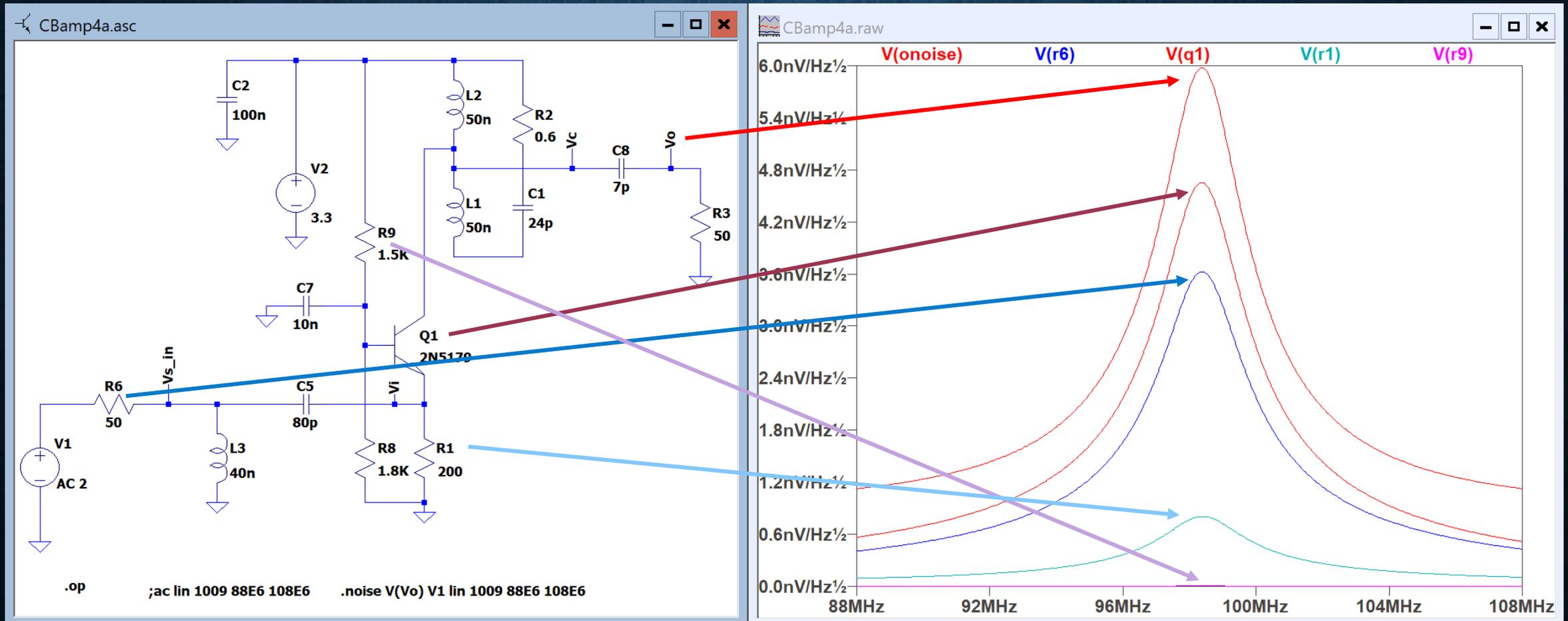
LT-Spice: AC sim to get Gain



LT-Spice Noise Analysis



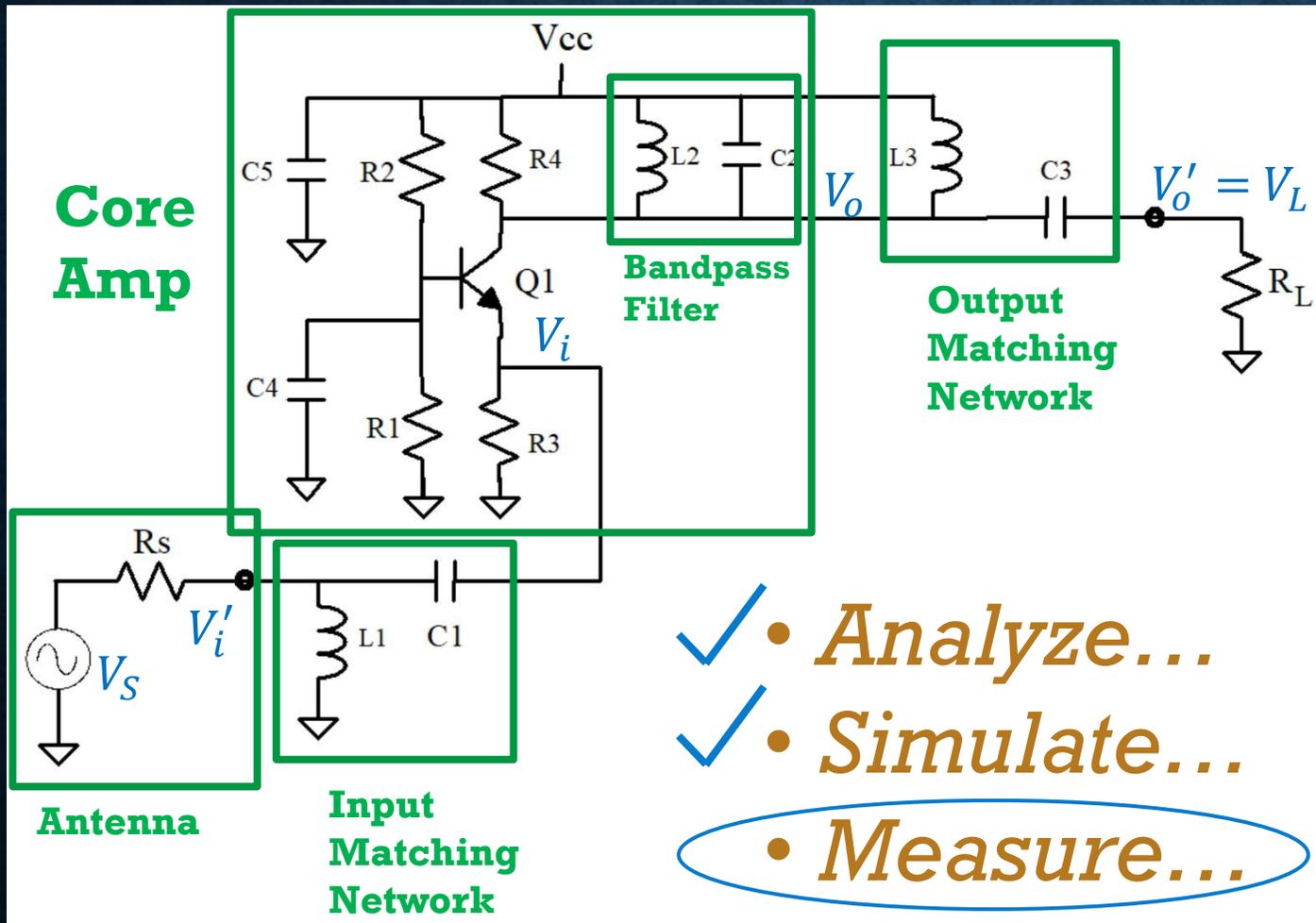
Evaluating Individual Contributions



Presentation Outline

- Noise Figure Definition and Basics
- Circuit-level noise models
- Circuit noise analysis
- Simulation – with examples
-  NF measurement

How Do We Find the NF of This LNA ?



Common-base LNA
from Radio Design 101 series

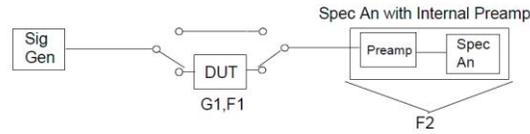
- ✓ • Analyze...
- ✓ • Simulate...
- Measure...

NF Measurement Class Handouts

Noise Figure Measurements

(See also: HP Application Note 57-1)

Signal Generator Method



Procedure

- 1) Setup the signal generator and spectrum analyzer to measure at the appropriate frequency.
- 1) Measure gain G_1 of DUT, accounting for cable losses as appropriate. You should use the "insertion-gain method" where you measure power with device in-circuit and then bypassed (using a barrel connector), and take the ratio of powers (difference of dBm). Be sure to use a low power when measuring gains (e.g. -50 dBm from generator) to prevent amplifier compression.
- 2) Turn on the spectrum analyzer's internal preamp, set the reference level to -40 dBm, and set the input attenuator to lowest non-zero value (e.g. 5 dB). Then measure the 'output' noise power N_{o2} from stage 2 (the LNA/SpecAn only) with its input terminated in 50 Ohms (Attach a 50 Ohm load to its input).
- 3) Next, with the internal preamp on and the attenuator set to 5dB, measure the output noise power N_{o12} with the DUT included (with its input terminated).
- 4) Compute the noise figures F_2 and F_{12} using the definition of noise figure:

$$F_2 = \frac{N_{o2}}{kT_oB}$$

$$F_{12} = \frac{N_{o12}}{kT_oBG_1}$$

- 5) Solve for F_1 using cascade formula

$$F_{12} = F_1 + \frac{F_2 - 1}{G_1}$$

NOTES:

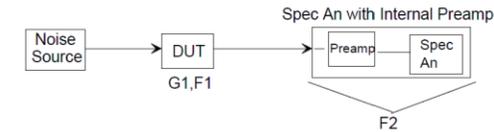
- For improved accuracy in noise measurements, use the spectrum analyzer's noise measurement mode which reports noise power levels in a 1 Hz bandwidth (and accurately accounts for the resolution bandwidth filter's "noise bandwidth").
- Be sure to convert dB and dBm to ratios and powers before crunching formulas!
- The noise figure measurement accuracy is dependent on the spectrum analyzer's ability to accurately measure absolute power levels, and on the gain measurement of G_1 , G_2 . The analyzer may be accurate to about a half a dB, but this can lead to cumulative errors of more than 1 dB (not a good thing if you're trying to measure NF of 1 to 2 dB!).
- Cable losses should be carefully considered. E.g. if you used cables between the amp and spectrum analyzer in the gain measurement, use the same cables for the noise measurement.
- The DUT gain G_1 should be much greater than F_2 to avoid significant errors in the computation of F_1 .

10/29/12 WBK

Noise Figure Measurements

(See also: HP Application Note 57-1)

Hot/Cold Source ("Y-Factor") Method



- 1) Measure DUT gain and Spectrum analyzer noise factor F_2 as in Signal Generator Method.
- 2) Measure output noise with noise source power supply on (hot), and then off (cold). We will call these N_h and N_c .
- 3) Compute the Y-factor ratio $Y = N_h / N_c$, and then the noise figure F_{12} from:

$$F_{12} = \frac{ENR - 1}{Y - 1}$$

(see HP AN 57-1 with $T_c = T_o$)

- 4) Solve for F_1 using cascade formula

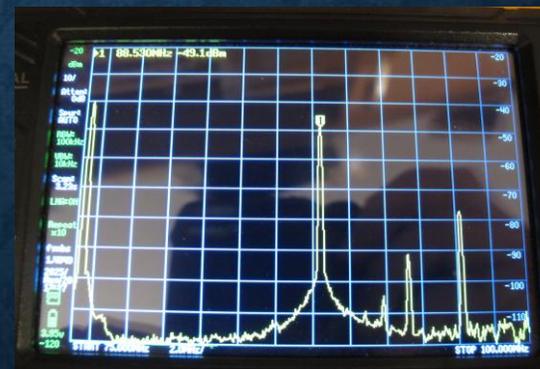
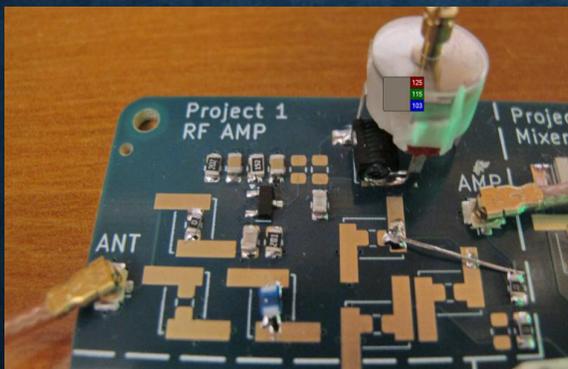
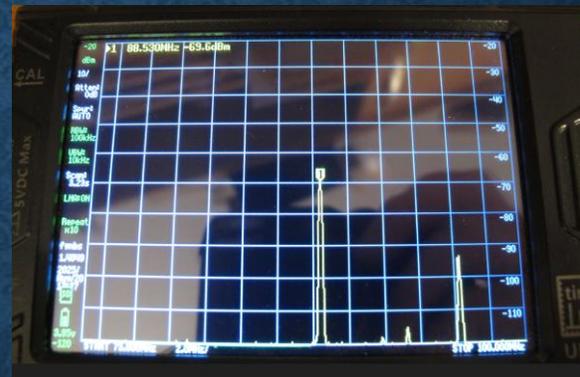
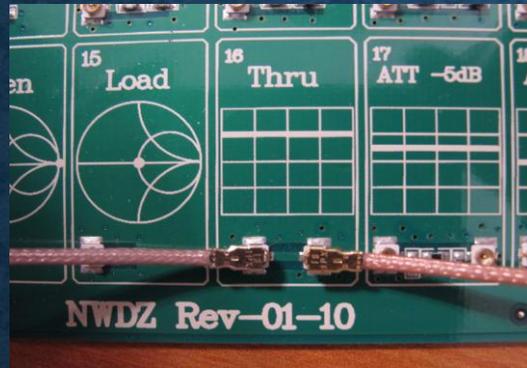
$$F_{12} = F_1 + \frac{F_2 - 1}{G_1}$$

NOTES:

- This method is more accurate than the signal generator method, since it does not rely on absolute power measurement accuracy.
- ENR is the excess noise ratio, marked on the noise source. Be sure to convert from dB to ratio form.
- For method to work well, however, the noise source have $ENR > F_1$.
- For even better accuracy, you may want to use the Y-factor approach to refine your measurement of F_2 above, although if G_1 is $\gg F_2$, this is not critical.
- Note that if $ENR \gg 1$ and $Y \gg 1$, then $NF_{12} \approx ENR_{dB} - Y_{dB}$. Further, if $G_1 \gg F_2$, then $NF_1 \approx NF_{12}$.

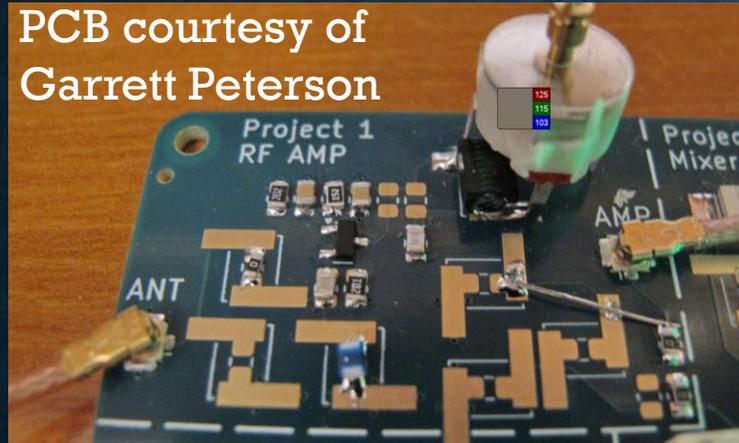
10/29/12 WBK

Insertion Gain Measurement Using 2 TinySAs



} Insertion Gain
= (-49.1 dBm) - (-69.6 dBm)
= 20.5 dB

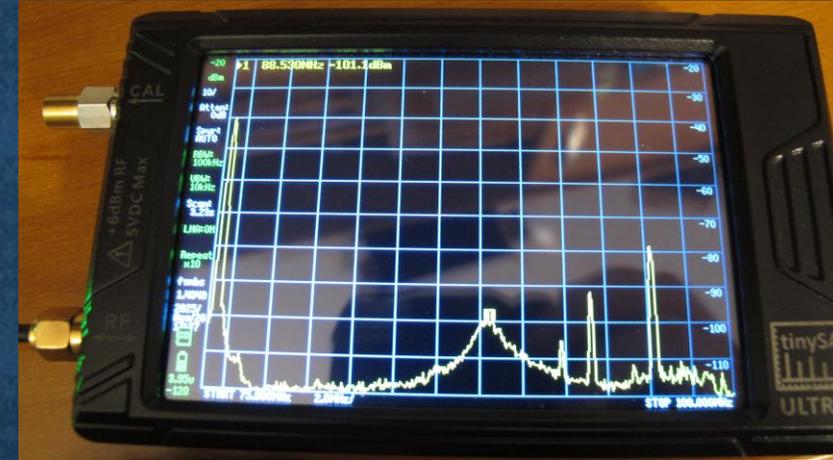
Noise Figure Measurement



PCB courtesy of
Garrett Peterson

To
50 Ohm
Load

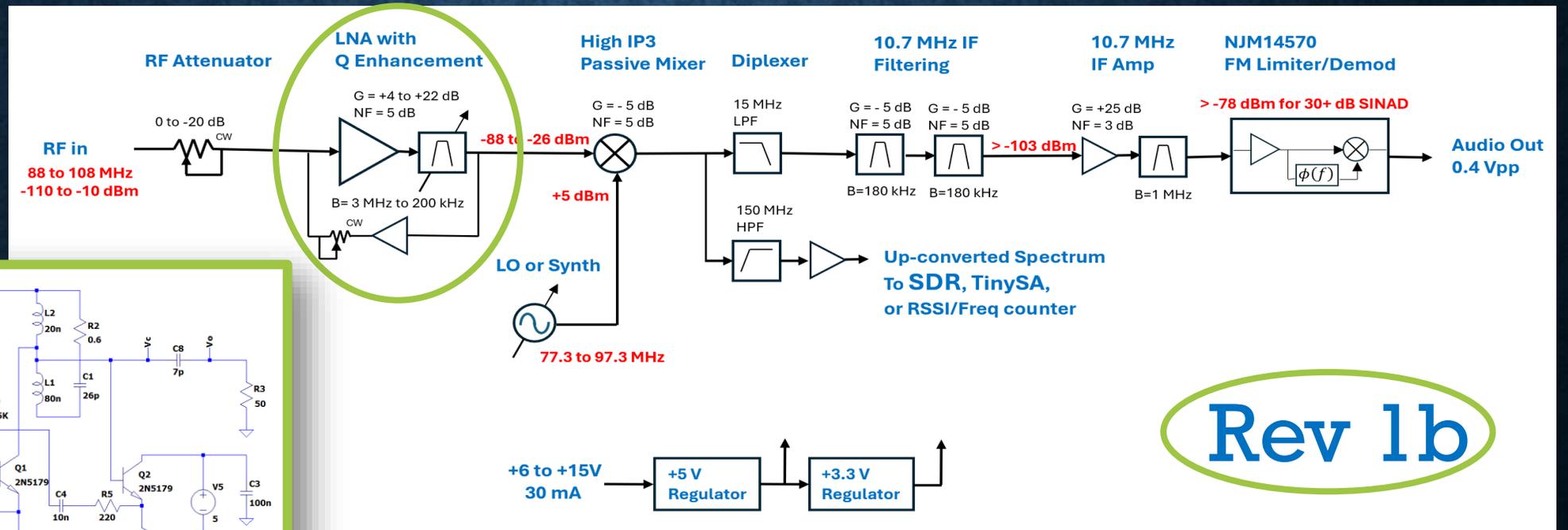
To
TinySA
Ultra



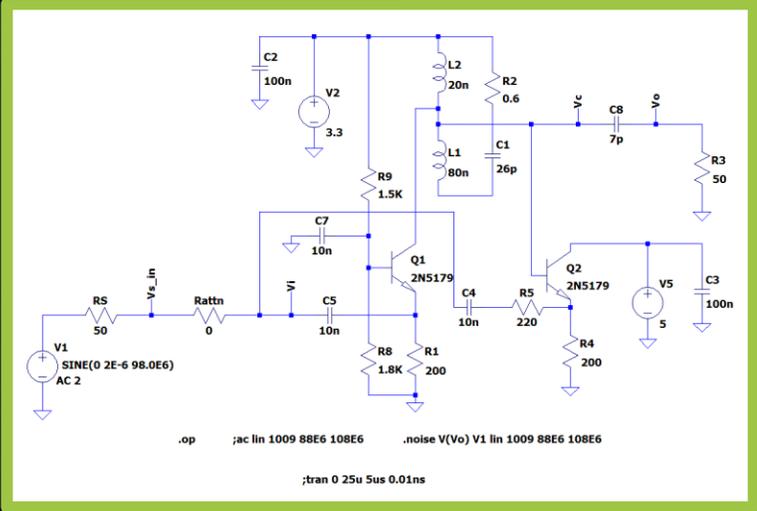
- **TinySA reports -101.1 dBm Noise in 100 kHz RBW**
- **Ideal noise from 50 Ohm term:** $-174 \text{ dBm} + 10 \log(100 \text{ kHz}) + 20.5 \text{ dB} = -103.5 \text{ dBm}$
- **Difference of 2.4 dB is the measured NF** (accuracy depends on spectrum analyzer power and noise-bandwidth accuracy)
- **Use hot/cold method for more precision (if needed)**

Upcoming Videos

Our Goal: More Front-End Selectivity (and Good IIP3) to receive more stations 😊

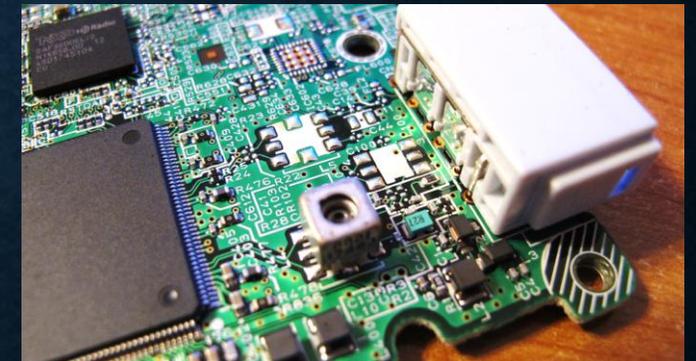
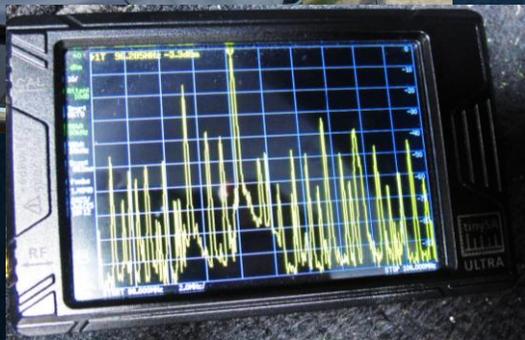


Rev 1b



Benchmarking / Scoring

Including a Honda FM Radio Teardown ☺



*Thanks For
Watching !*

Background: RD-401 Episodes 1 - 5

1



Low Power Receivers in Crowded Spectrum...

MegawattKS • 1.6K views • 6 months ago

2



Episode 1 Part 2 in Radio Design 401

MegawattKS • 1.1K views • 5 months ago

3



Episode 1, Part 3 (of 3) in Radio Design 401

MegawattKS • 1.1K views • 5 months ago



SNR, Noise Figure, and Receiver Sensitivity - Radio Desi...

This is Episode 2 of our advanced series: Radio Design 401. In this episode we discuss signal-to-noise ratios, componen...



RFI Noise in Buildings -- Radio Design 401, Episode 3

This episode examines radio frequency interference in commercial and residential buildings. We concentrate on R...



Intermodulation in Real-World Receivers - Radio Design ...

This episode covers essential aspects of Intermodulation distortion in radio receivers but goes beyond the traditional...



High Performance Receiver Design - Radio Design 401, ...

In this episode, we launch our "semester project" by reviewing key points from the Radio Design 101 and 401...