THE DANGERS OF SIMPLE USAGE OF MICROWAVE SOFTWARE

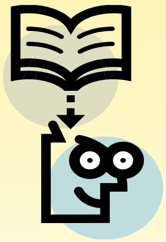
Ulrich L Rohde *, Hans L. Hartnagel **

* Synergy Microwave Corp.

** Technische Universitäet Darmstadt,

Introduction:

- There are two main sources of inaccuracy, measurement and simulation. In the case of an oscillator the important parameters are output power, harmonic content and, most important, phase noise.
- CAD introduces two weaknesses. The device used for the application needs to be characterized, many times by curve fitting, and needs to match a model of the simulator which itself is mostly an analytical model rather than physics based.
- We will use a simple but in the end highly non-linear circuit, where we will demonstrate the accuracy of our approach using simulations, sets of analytical time domain equations and of course accurate measurements using test equipment from two established manufacturers, Agilent and R&S. Each step of this design provides much better insight in the functionality than the standard teaching approach of this topic resorting to too much CAD. In the following we will show three cases, which will highlight the problems.

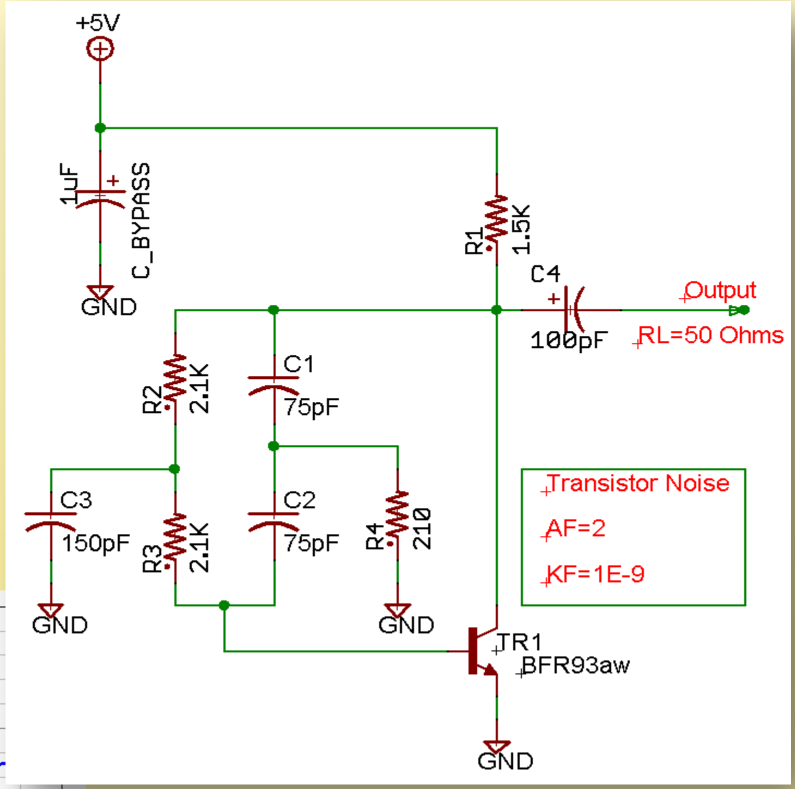


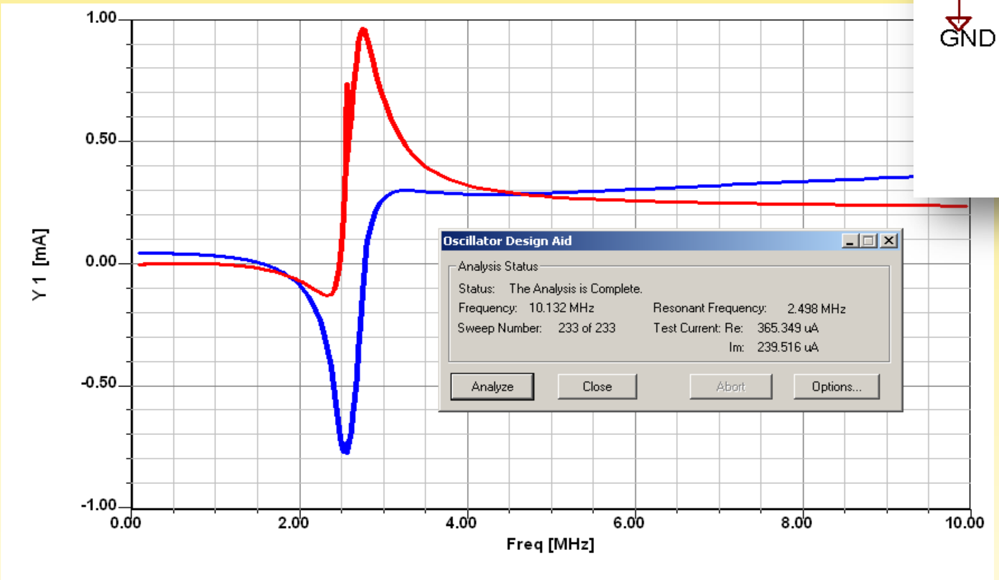
Case1- Linear simulation result different from non Linear

- Linear analysis indicates: F_{res}=2.498MHz
- Bias condition

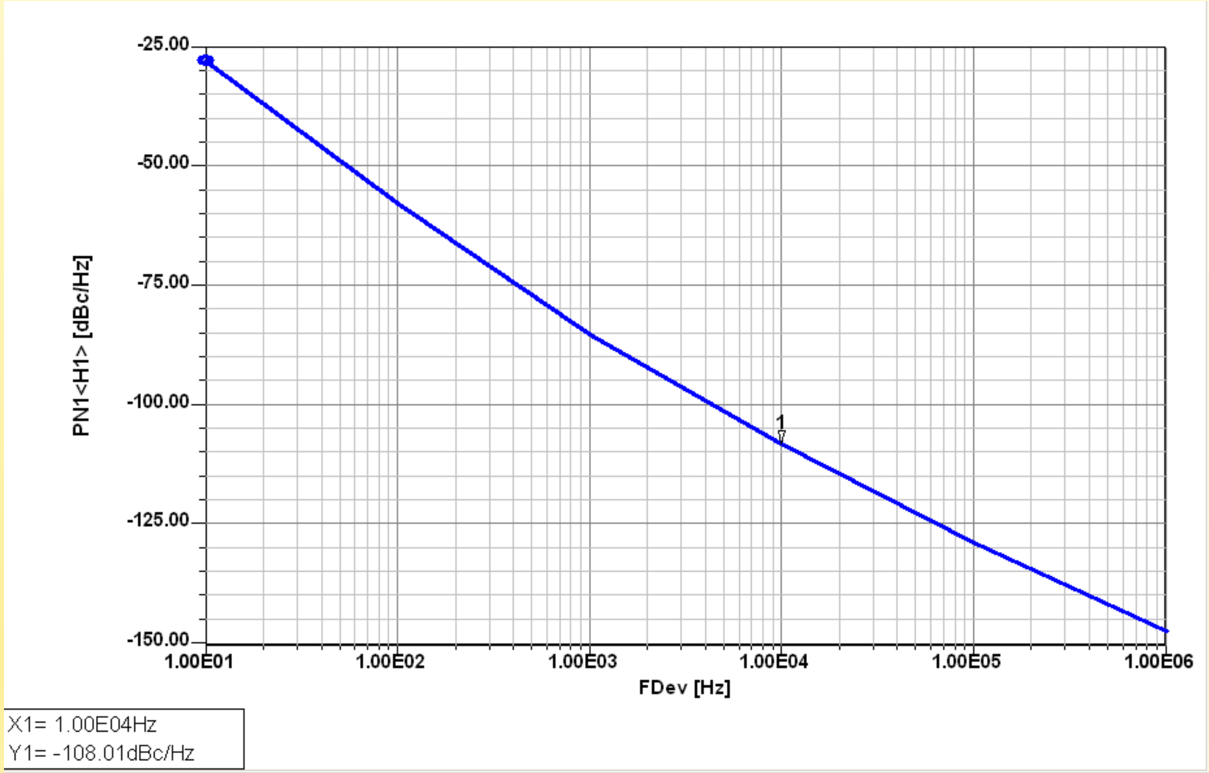
  V_{ce} = 0.86V

  I_c = 2.7mA





CASE1- NON LINEAR SIMULATION PHASE NOISE PLOT



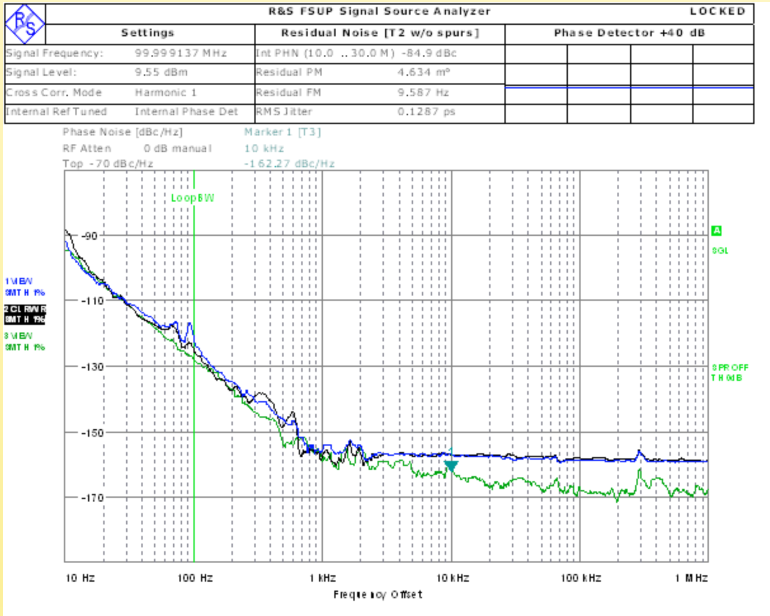
- Note: Non-Linear analysis indicates F_{res} = 1.6MHz v/s Linear ~2.5MHz
- Harmonic suppression: 14dB
- The loaded output terminated into 50 ohms is –19dBm
- With CMOS gates as load to the oscillator a practical load of 9 KΩ then the voltage swing at the output is 1.8 Vp-p at the end to drive the gate.

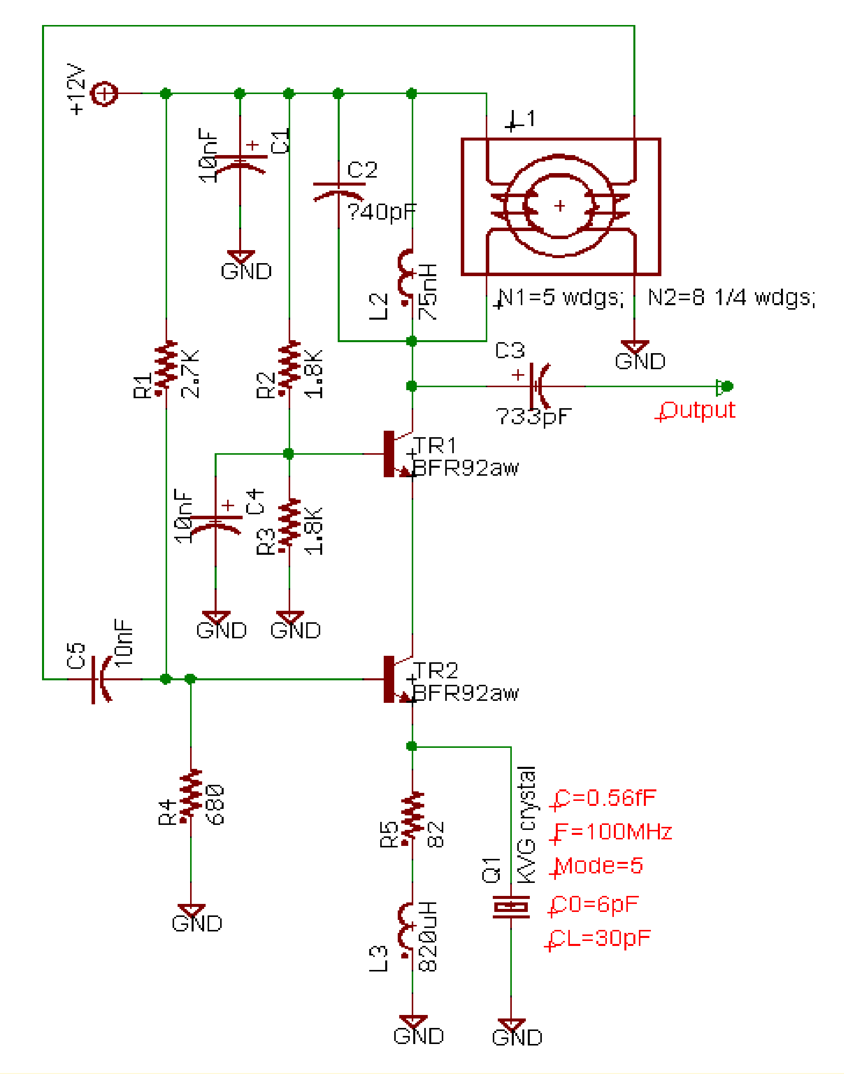
CASE1- WHY IS THIS BARELY FOUND IN LITERATURE?

- Most of the CAD tools cannot analyze this accurately. An important test is to validate the existence of the flicker corner frequency. In our case it is at 1 kHz. This is typical for a microwave transistor at this DC current, an audio type transistor or a FET to show much smaller number.

- Majority of phase noise setups does not operate below 10MHz; Measurements of 5MHz are typically done using a diode multiplier at higher frequency.

Case2- Driscoll 100MHz crystal oscillator and measured result

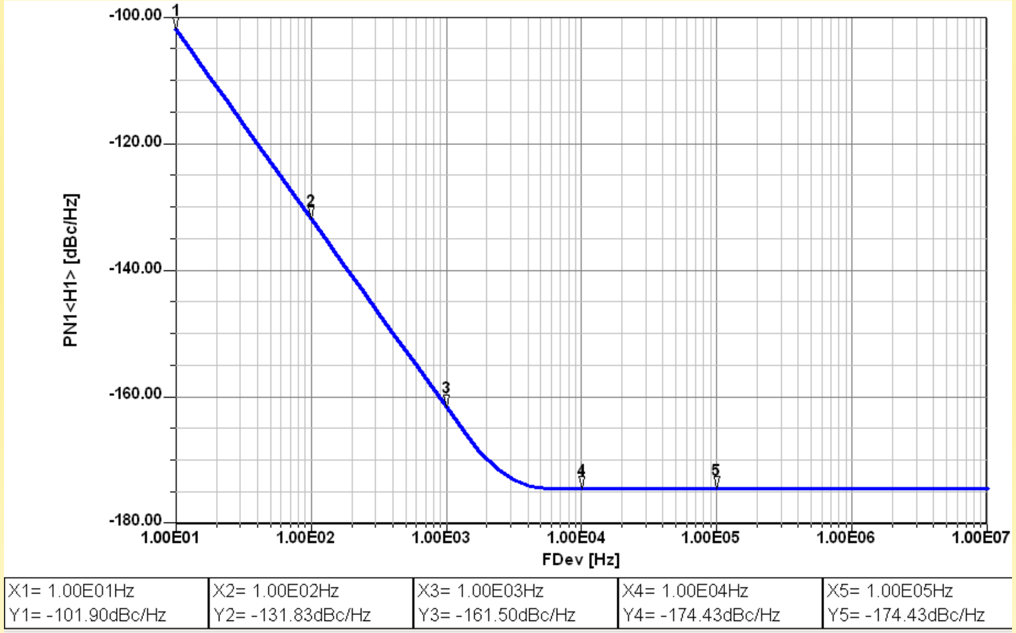




- Measurement taken without the buffer (green)
- Measurement with the buffer amplifier, BGA614, dual Darlington amplifiers (blue curve).

CASE2- DRISCOLL 100MHZ CRYSTAL OSCILLATOR NON-LINEAR SIMULATION

Frequency offset	10Hz	100Hz	1KHz	10KHz	100Khz
Simulation result	-102dBc	-132dBc	-161.5dBc	-174dBc	-174dBc
Measurement result	-90dBc	-125dBc	-155dBc	-162dBc	-170dBc



- F_{res} = 99.998MHz.
- Crystal is a high Q device (Q ≈ 1e6) that maintains its high Q, so we can expect the circuit simulator to give a similar answer in the nonlinear mode.
- Output power-9.58dBm
- Predicted harmonic suppression - 22 dB.

Case2- what happened?

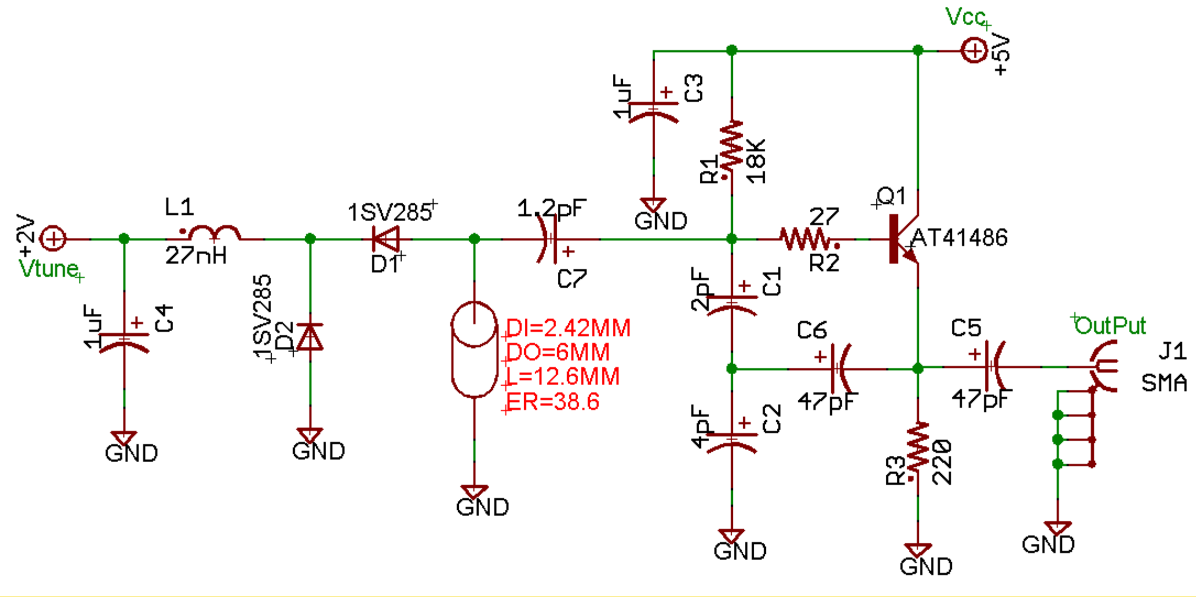
- Having spent $50,000 for the simulator and $80,000 for the test equipment the simulator is 10dB optimistic.

- The reason for this lays in the uncertainty of the flicker frequency which none of the manufacturers are willing to give guarantee for, and a type of flicker noise that the crystal has itself. The standard crystal models are not sufficiently accurate for the good modeling.

CASE3 – COLPITTS OSCILLATOR FOR 800-900MHZ

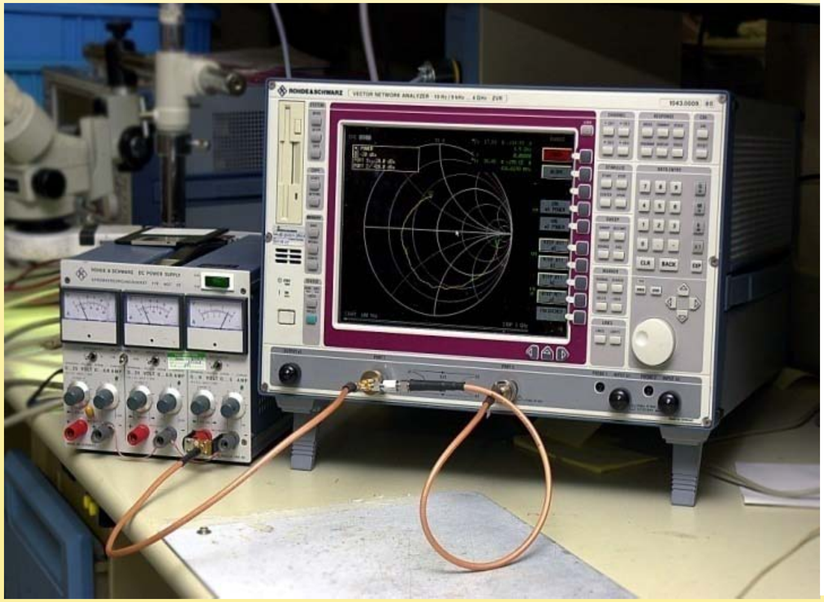
- The simulated results in the book strongly disagree with the simulation [1, page 315 figure 7.19]

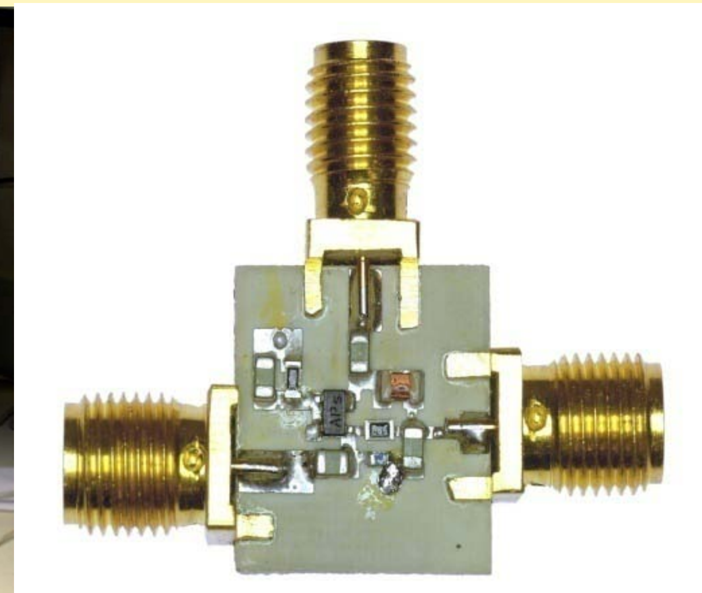
- A non-linear approach is used. It fits both the analytical solution and the CAD tools.



Frequency offset	100Hz	1KHz	10KHz	100Khz	1Mhz
Simulation result with diode	-22dBc	-52dBc	-82dBc	-111dBc	-136dBc
Simulation result without diode	-51dBc	-81dBc	-110dBc	-137dBc	-158dBc

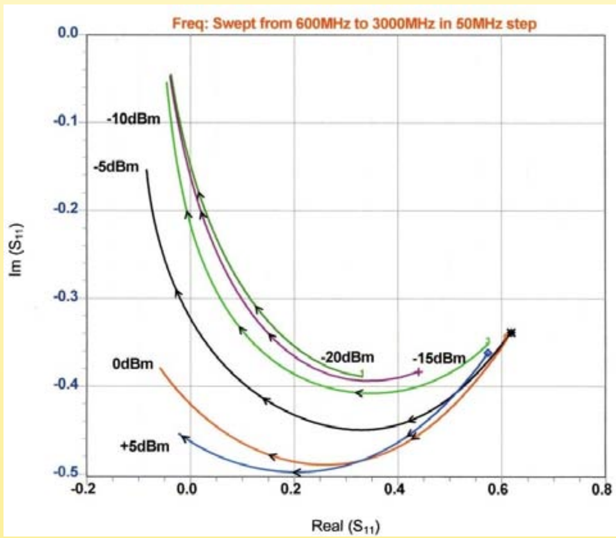
CASE3 – MEASUREMENT OF NON-LINEAR PARAMETERS ON BFP520 TRANSISTOR

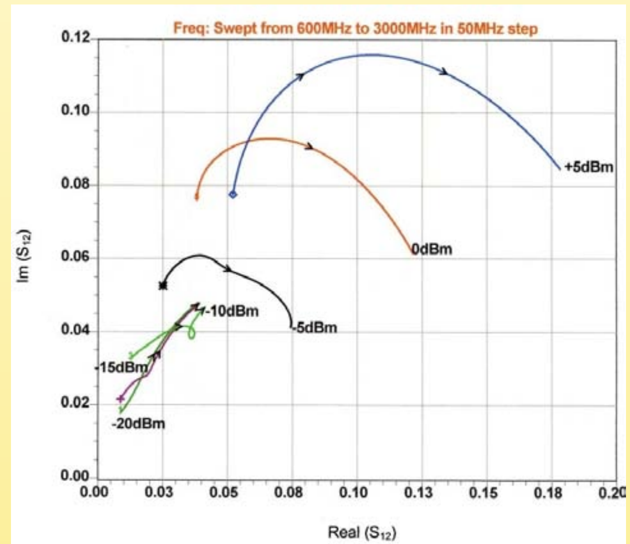


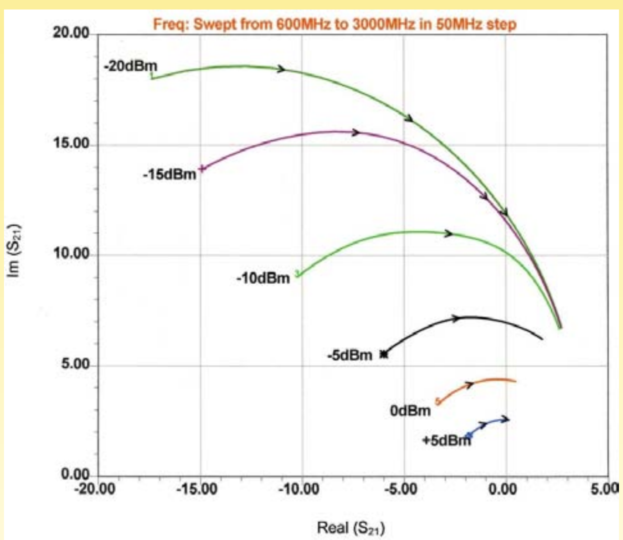


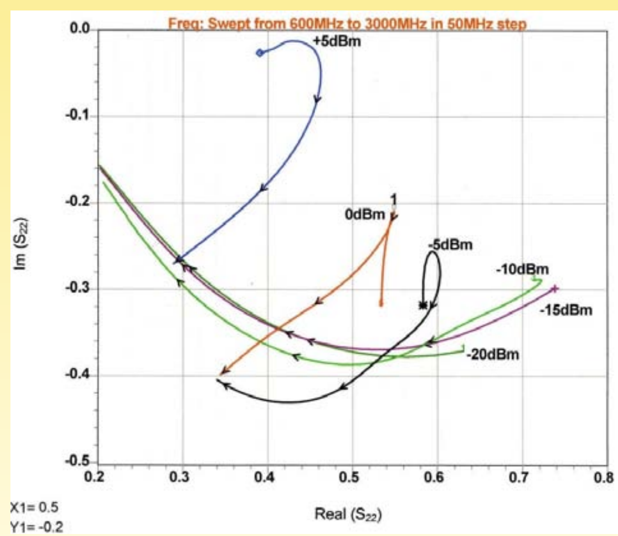
- They show the dramatic change of S_{12} and S_{22} as a function of frequency and bias level. For the Colpitts oscillator, where the collector is separated S22 is less relevant and since the feedback is external, S12 also less important, depending on the frequency. If calculating the negative resistance to compensate the losses, we must insert the large signal frequency depending value for Y_{21}.

CASE3 – MEASURED NON-LINEAR PARAMETERS ON BFP520 TRANSISTOR









Case3 – Linear Phase Noise Equation

$$L^*(f_m) = 10\log\left\{\left[1+\frac{f_0^{\,2}}{(2f_mQ_L)^2}\right]\left(1+\frac{f_c}{f_m}\right)\frac{FkT}{2P_{sav}} + \frac{2kTRK_0^{\,2}}{f_m^{\,2}}\right\}$$

- * noise equation made more complete by Rohde [5]
- Where,
- $L\ (f_m)$ = ratio of sideband power in a 1 Hz bandwidth at f_m to total power in dB
- f_m = frequency offset, f_0 = center frequency
- f_c = flicker frequency, F = noise factor
- Q_L = loaded Q of the tuned circuit
- $kT = 4.1 \times 10^{-21}$ at 300 K_0 (room temperature)
- P_{sav} = average power at oscillator output
- R = equivalent noise resistance of tuning diode (typically 50 Ω - 10 kΩ), and
- K_o = oscillator voltage gain

CASE3 – NON-LINEAR PHASE NOISE EQUATION

- To start the nonlinear noise calculation, we look at the noise sources. The resonator noise is [2, Ch-8, pp. 159-232]. $\left|\overline{e_R^2(f)}\right|_{\omega=\omega_0} = 4kTBR_S$
- The oscillators negative resistance equation is

$$L\frac{di(t)}{dt} + (R_L - R_N(t))i(t) + \frac{1}{C'}\int i(t)dt = e_N(t)$$

- Where $\overline{R_N(t)}$ is the average negative resistance under large signal condition and contrary to common publications, this is a time variant resistance; ideally it does not degrade the Q outside the on condition. This resistance however is "noisy".
- Since the negative resistance is related to the large signal transconductance and the feedback capacitors of the Colpitts oscillator, the phase noise under large signal conditions becomes:

$$\boxed{L(\omega) = 10 \times \log\left[\left[k_0 + \left(\frac{k^3 k_1 \left[\frac{Y_{21}^+}{Y_{11}^+}\right]^4 [y]^{4p}}{\left[Y_{21}^+\right]^6 [y]^{6q}}\right)\left(\frac{1}{(y^2+k)}\right)\right]\left[\frac{[1+y]^2}{y^2}\right]\frac{Q_{max}^2}{Q_0^2}\right]}$$

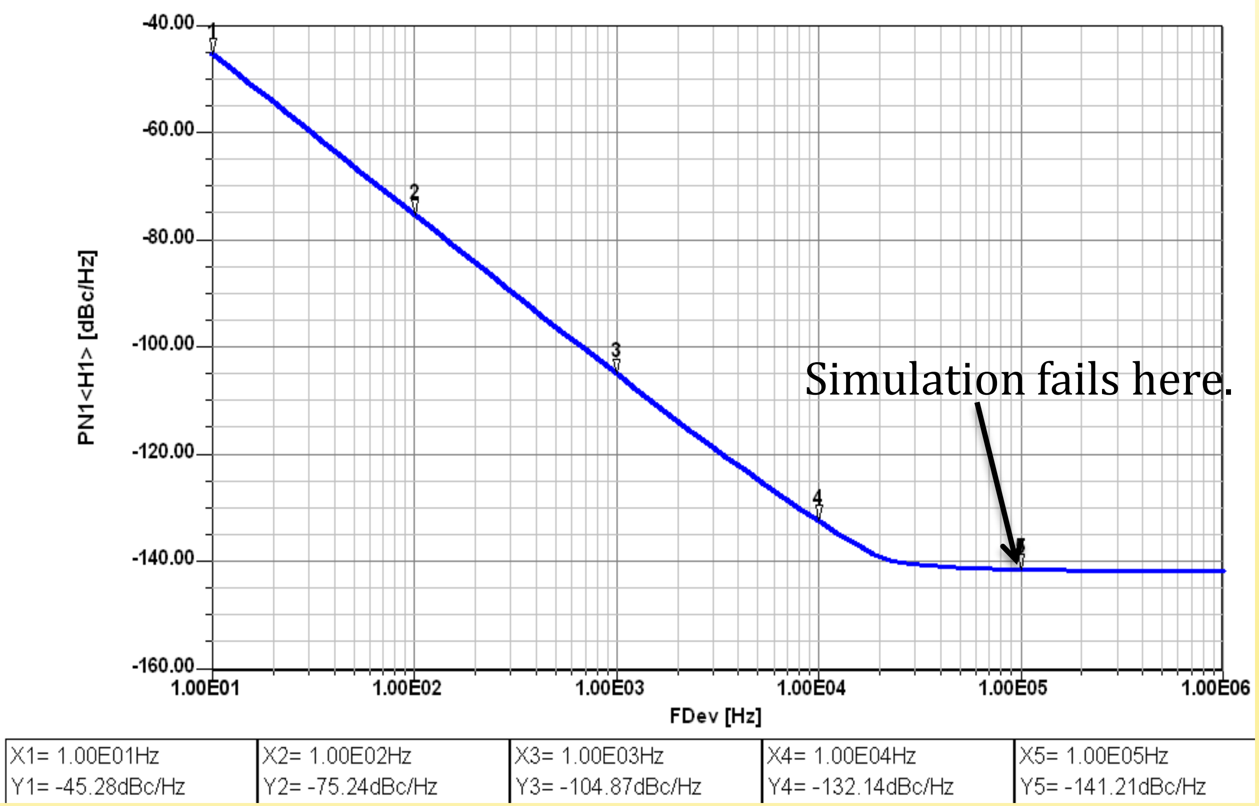
$$where\ y = \frac{C_1}{C_2},$$

$$k_0 = \frac{kTR}{\omega^2\,\omega_0^2 L^{*2} V_{cc}^2 C_2^2},$$

$$k_1 = \frac{qI_c g_m^2 + \frac{K_f I_b^{AF}}{\omega} g_m^2}{\omega^2\,\omega_0^4 L^{*2} V_{cc}^2},$$

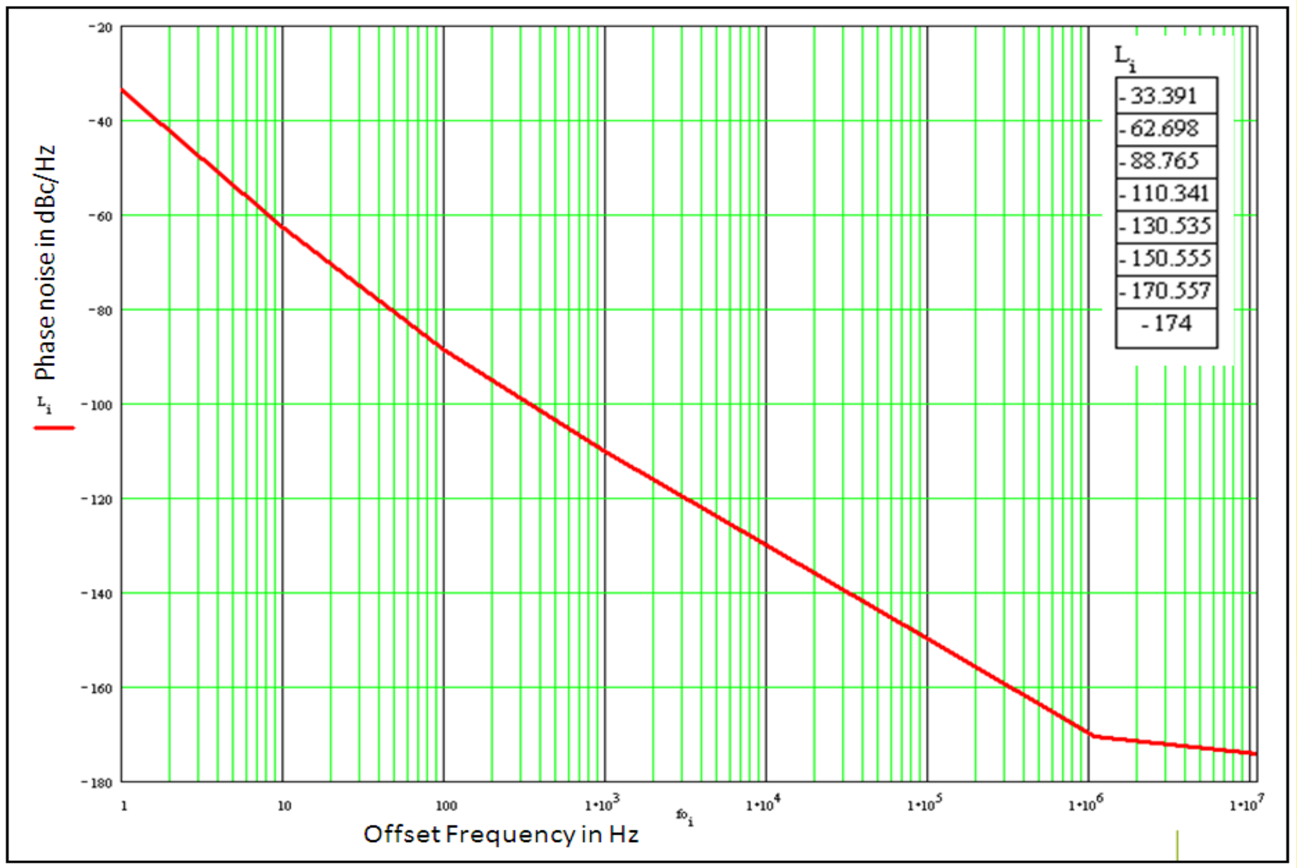
$$k_2 = \omega_0^4(\beta^+)^2, \quad k_3 = \omega_0^2(gm)^3, \quad L^* = j\frac{Z}{\omega}\tan\left(\frac{\omega}{v_P}l\right) and\ k = \frac{k_3}{k_2 C_2^2}$$

CASE3 – PREDICTED PHASE NOISE



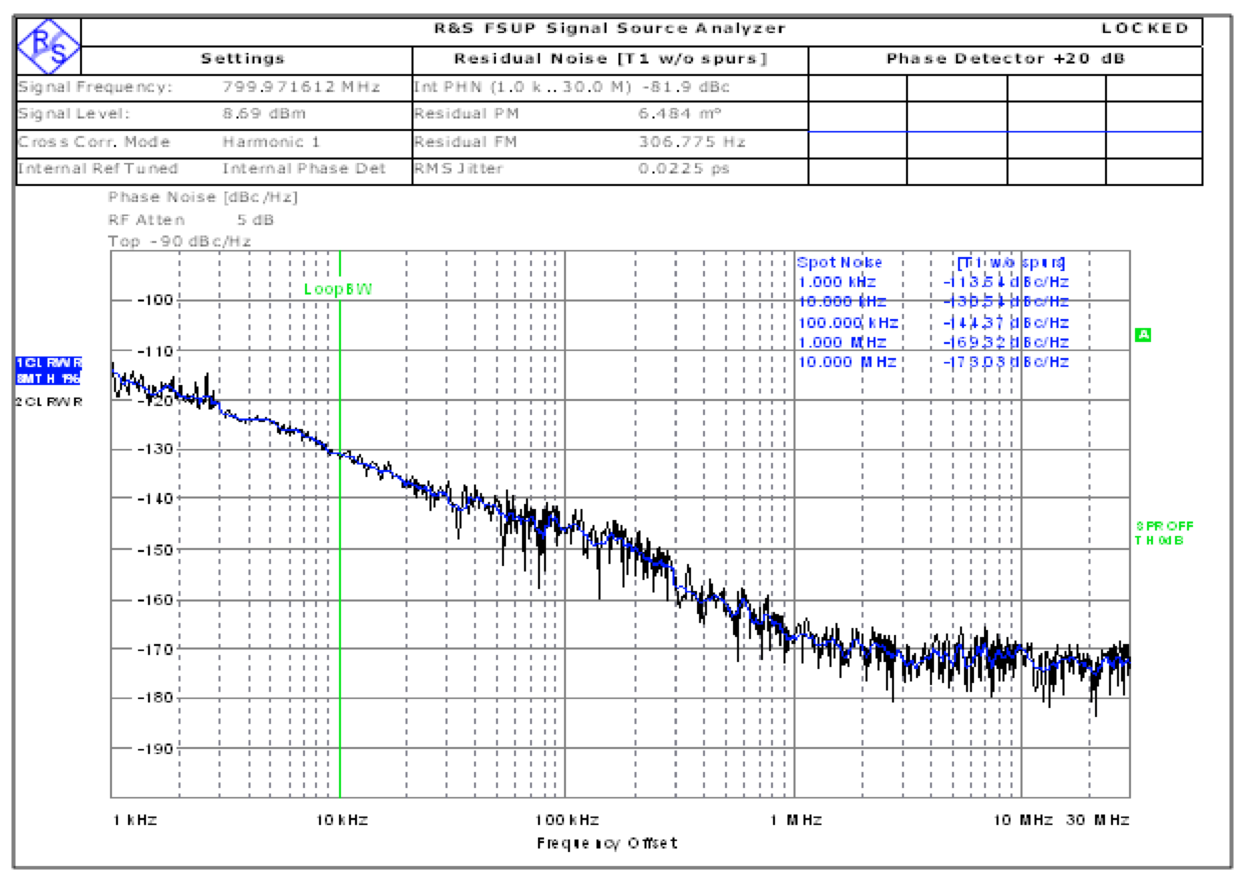
- An existing VCO from Synergy microwave designed for 800 MHz is evaluated for the Non-linear phase noise calculations.
- The flicker corner frequency is at about 1kHz; it is not visible distinctly due to the high Q resonator, and the phase noise at 10KHz is -132.14Bc/Hz.

CASE3 – COMPUTED PHASE NOISE FROM MATHCAD



- The flicker corner frequency is at about 1kHz and the phase noise at 10 KHz is -130.5dBc/Hz

CASE3 – MEASURED PHASE NOISE



- The flicker corner frequency is at about 1kHz and the phase noise at 10 KHz is -130.15dBc/Hz. Same result verified with Agilent analyzer E5052A.

Acknowledgements

- Thank You:
  - Rucha Lakhe

Any Queries?

Reference

1. Randall W. Rhea, *Discrete Oscillator Design,* Artech House, Boston, 2009.
2. U. L. Rohde, A. K. Poddar, and G. Boeck, *The Design of Modern Microwave Oscillators for Wireless Applications: Theory and Optimization*, Wiley, New York, 2005.
3. U. L. Rohde, *Transistoren bei höchsten Frequenzen,* Verlag Für Radio-Foto-Kinotechnik, Germany 1965, page 92.
4. H. Zinke and Brunswig, Volume 1 *Lehrbuch der Hochfrequenz-technik,* New York 1986 page 77.
5. G. Vendelin, A. Pavio and U. L. Rohde, *Microwave circuit design using Linear and nonlinear techniques,* Wiley, New York, 2005 page 577.
6. Michael M.Driscoll, Two-Stage Self-Limiting Series Mode Type Quartz Crystal Oscillator Exhibiting Improved Short-Term Frequency Stability, IEEE Transactions on Instrumentation and Measurement June 1973, pp130 – 138, modified by Chris Bartram, *Notes on the Driscoll VHF Overtone Crystal Oscillator and a New Low-Noise VHF Crystal Oscillator Topology* 2008