Tutorial on Modern Ultra Low Noise Microwave Transistor Oscillator Design

Columbia University
September 11, 2009

Ulrich L. Rohde, Ph.D.*
Chairman Synergy Microwave Corp.
*Prof. of RF Circuit and Microwave Circuit Design
Brandenburg University of Technology
Cottbus, Germany

SYNERGY®
MICROWAVE CORPORATION

Faculty 3
Mechanical Engineering,
Electronic Engineering
and Industrial Engineering

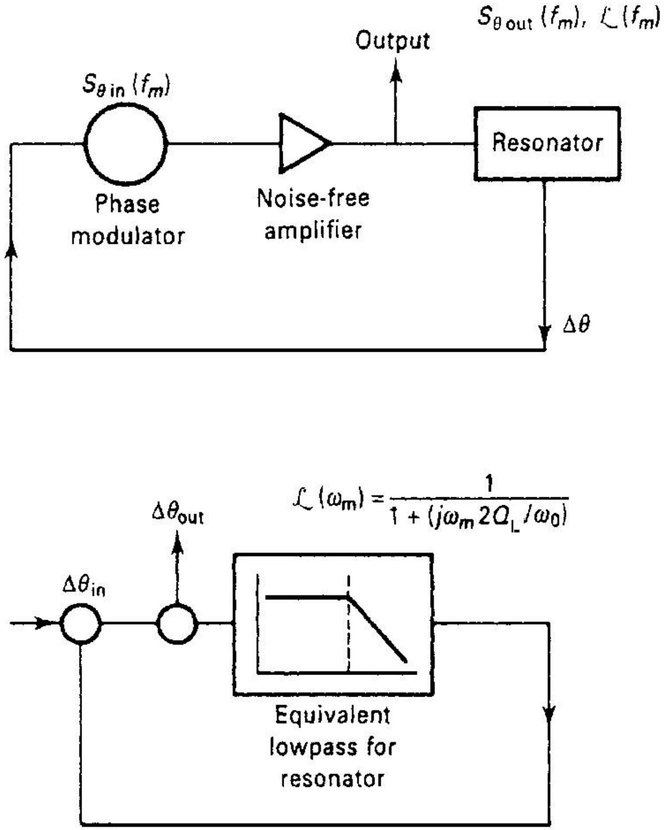
BTU

Brandenburg University of Technology Cottbus

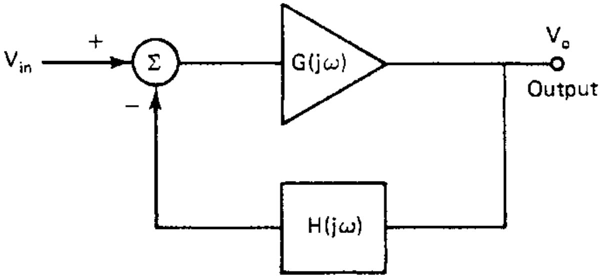
Ulrich L. Rohde, Prof. Dr.-Ing. Dr. h. c. mult.
RF and Microwave Circuit Design Techniques

P.O. Box 10 13 44
03013 Cottbus
Konrad-Wachsmann-Allee 1
03046 Cottbus, Germany

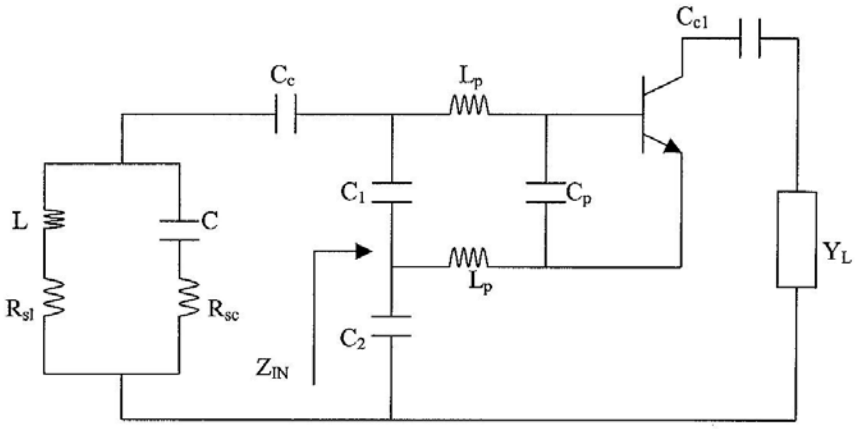
phone: +49 355 69-5062
fax: +49 355 69-2150
e-mail: rohdeu@tu-cottbus.de
www.kt.tu-cottbus.de



A typical linear oscillator phase noise model (block diagram)
Leeson Model



A typical block diagram of feedback oscillator circuit

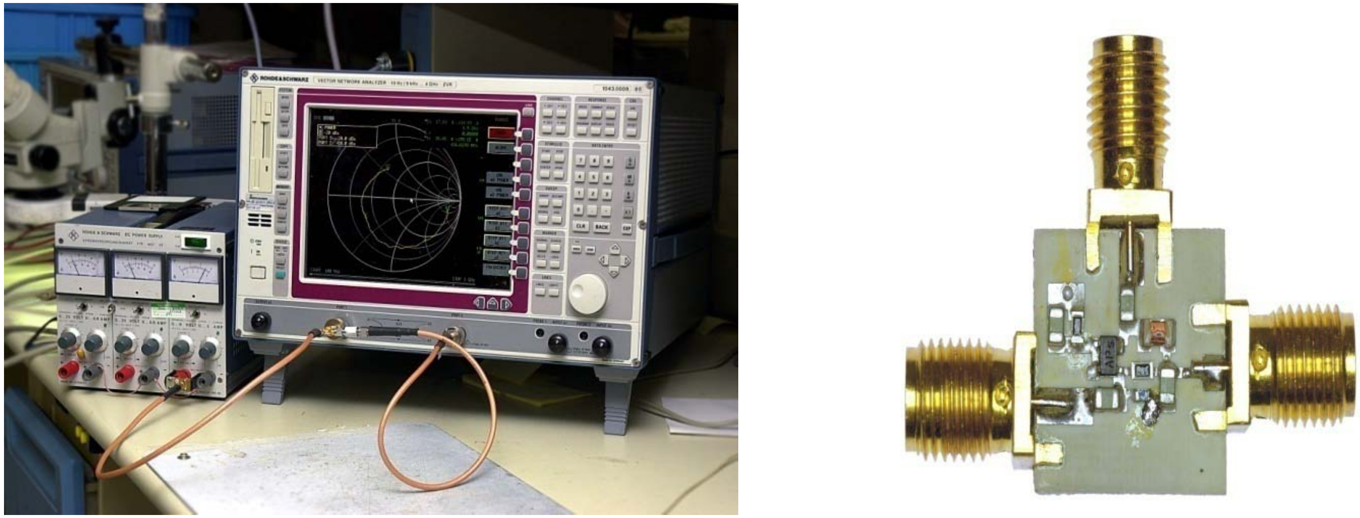


Colpitts oscillator with base-lead inductances and package capacitance. C_C is neglected.

The expression of input impedance is given as

$$Z_{IN}\Big|_{pacakage} = -\left[\frac{Y_{21}}{\omega^2 (C_1 + C_p)C_2}\frac{1}{(1+\omega^2 Y_{21}^2 L_p^2)}\right] - j\left[\frac{(C_1 + C_P + C_2)}{\omega(C_1 + C_P)C_2} - \frac{\omega Y_{21} L_P}{(1+\omega^2 Y_{21}^2 L_p^2)}\frac{Y_{21}}{\omega(C_1 + C_P)C_2}\right]$$

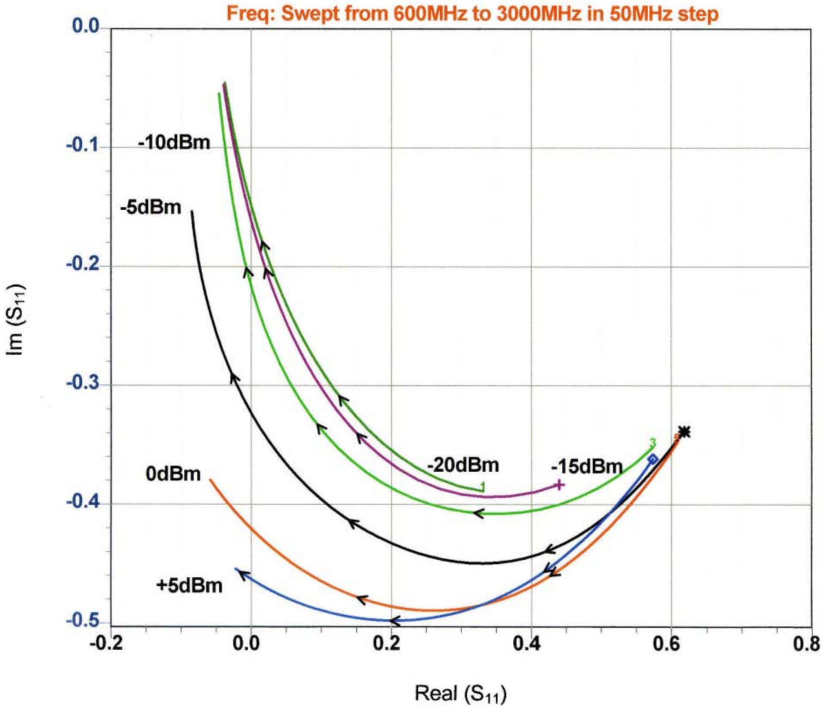
This Figure shows the R&S vector analyzer and the test fixture



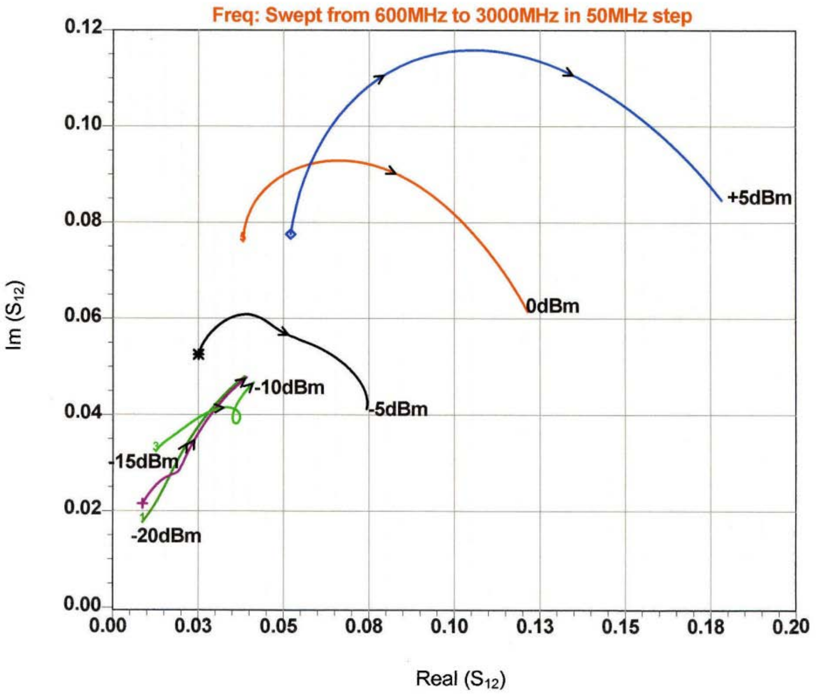
Typical measurement setup for evaluation of large signal parameters (R&S vector analyzer and the test fixture for the transistor of choice)

Agilent now calls this X Parameters

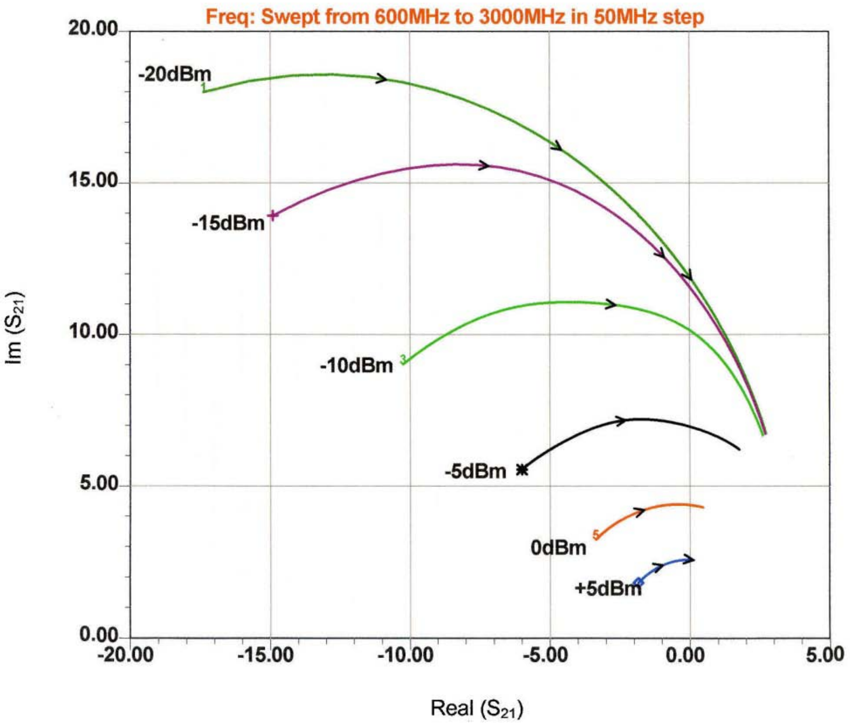
The bias, drive level, and frequency dependent S parameters are then obtained for practical use.



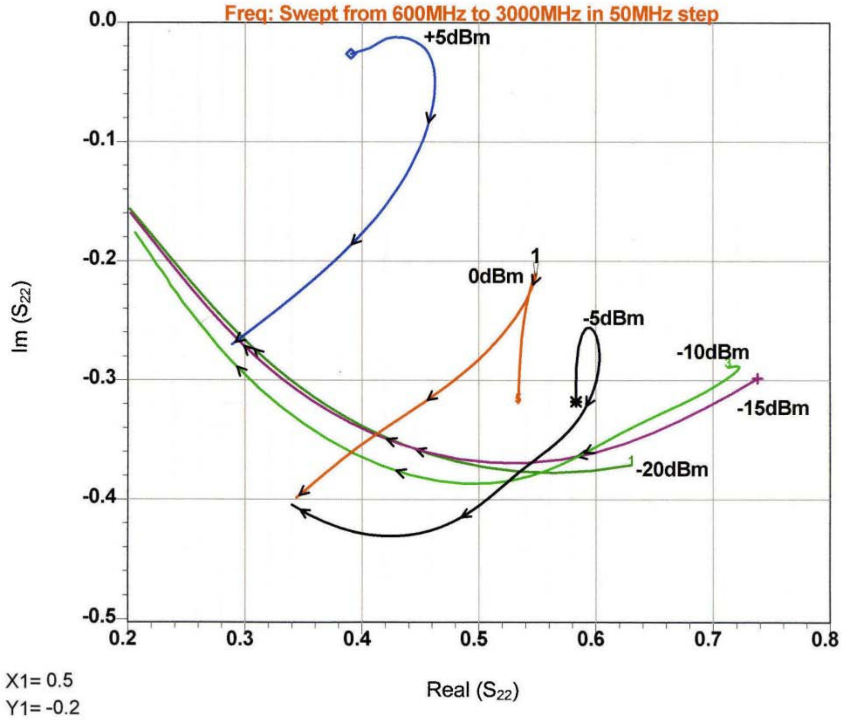
Measured large-signal S_{11} of the BFP520



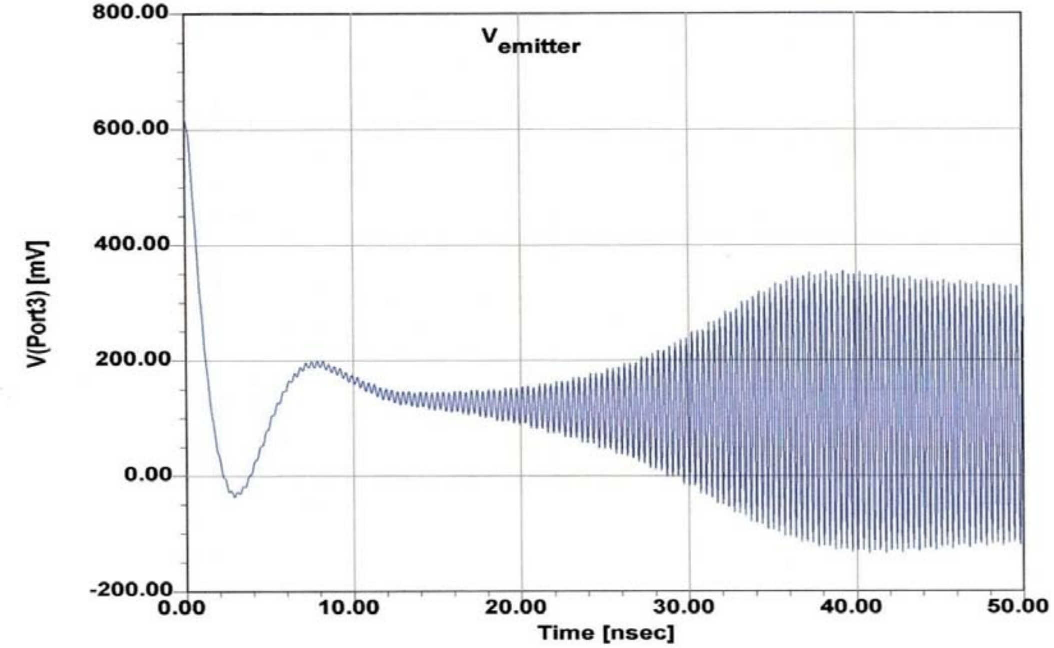
Measured large-signal S_{12} of the BFP520



Measured large-signal S_{21} of the BFP520

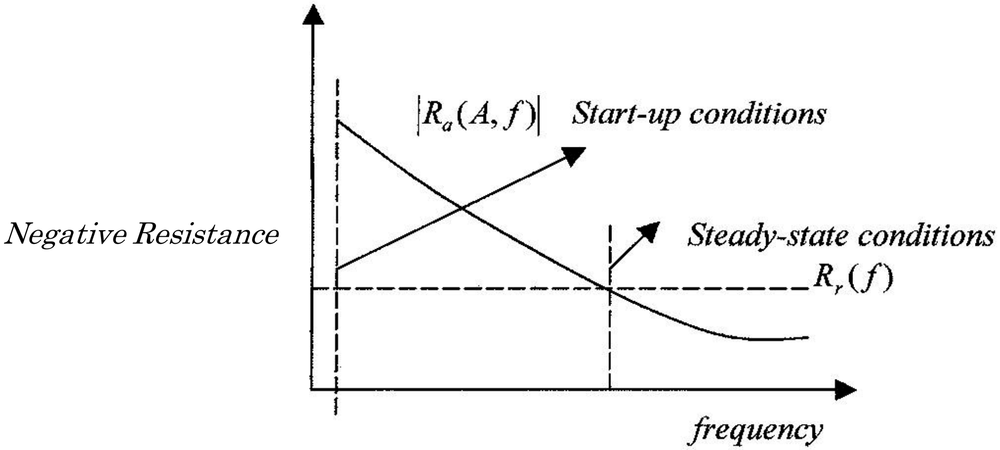


Measured large-signal S_{22} of the BFP520



Typical transient simulation of a ceramic resonator-based high-Q oscillator (node of the voltage for display is taken from the emitter)

This Figure illustrates the start and steady-state oscillation conditions.



A typical start and steady-state oscillation conditions.

$R_a(A, f)$ is the starting negative Resistance, which gets lower as the amplitude increases.
Therefore, feedback must be sufficient to maintain enough negative resistance to sustain oscillating.

Y_{21} Large Signal Calculation

$$Y_{21} = \left.\frac{I_{1peak}}{V_{1peak}}\right|_{fundamental-frequency}$$

$$I_1\Big|_{n=1} = I_{dc}\left[1+2\sum_{1}^{\infty}\frac{I_1(x)}{I_0(x)}\cos(wt)\right] \Rightarrow I_{1peak} = 2I_{dc}\frac{I_1(x)}{I_0(x)}$$

x = normalized drive level

$$V_1\Big|_{peak} = \frac{kT}{q}x$$

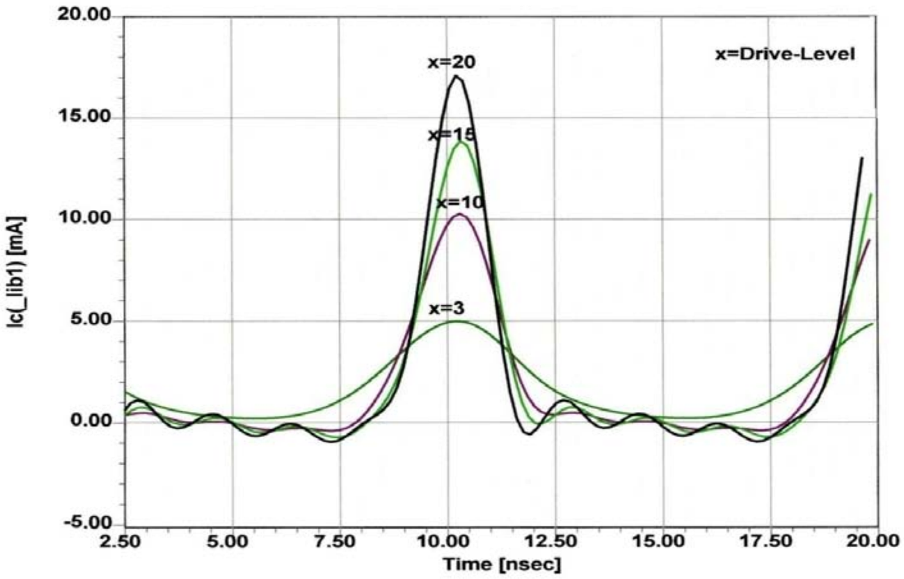
$$Y_{21}\Big|_{l\arg e-signal} = G_m(x)$$

$$Y_{21}\Big|_{small-signal} = \left.\frac{I_{dc}}{kT/q}\right| = g_m$$

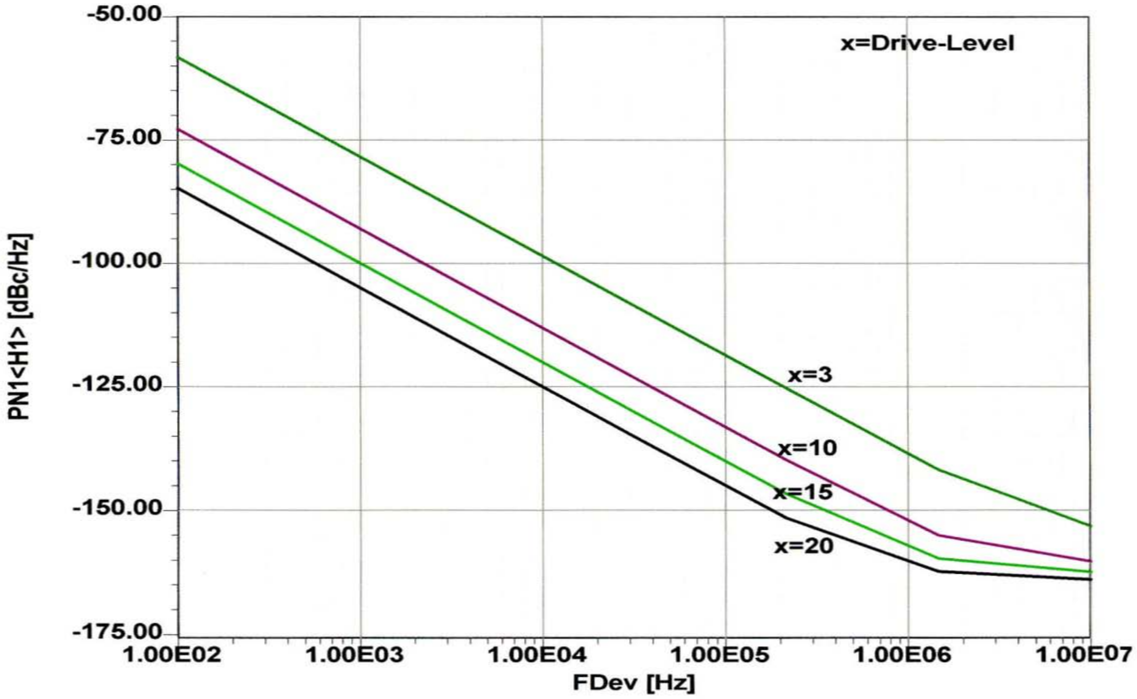
$$Y_{21}\Big|_{l\arg e-signal} = G_m(x) = \frac{qI_{dc}}{kTx}\left[\frac{2I_1(x)}{I_0(x)}\right]_{n=1} = \frac{g_m}{x}\left[\frac{2I_1(x)}{I_0(x)}\right]_{n=1}$$

$$\frac{[Y_{21}|_{l\arg e-signal}]_{n=1}}{[Y_{21}|_{small-signal}]_{n=1}} = \frac{G_m(x)}{g_m} \Rightarrow \frac{2I_1(x)}{xI_0(x)}$$

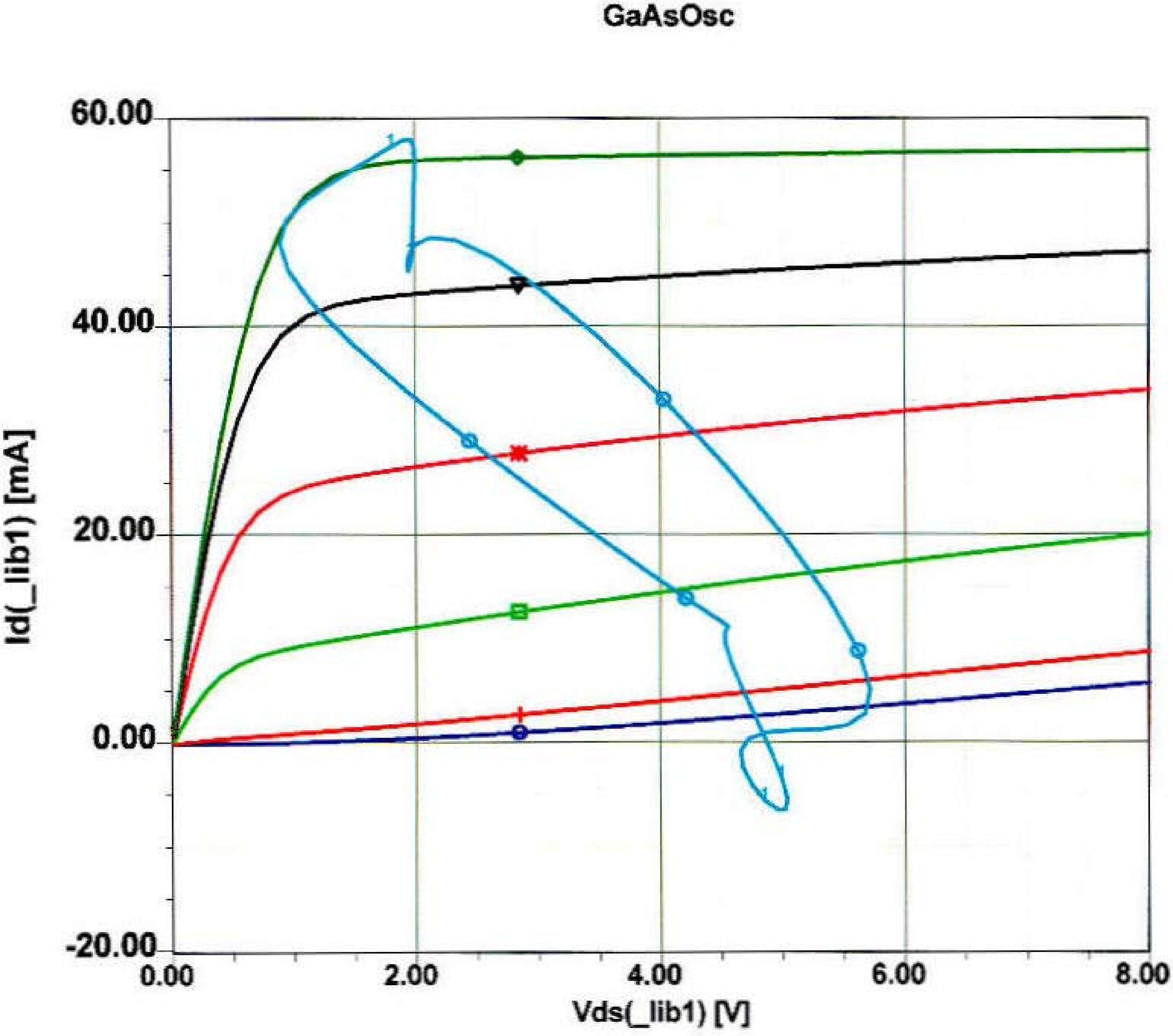
$$|Y_{21}|_{small-signal} > |Y_{21}|_{l\arg e-signal} \Rightarrow g_m > G_m(x)$$



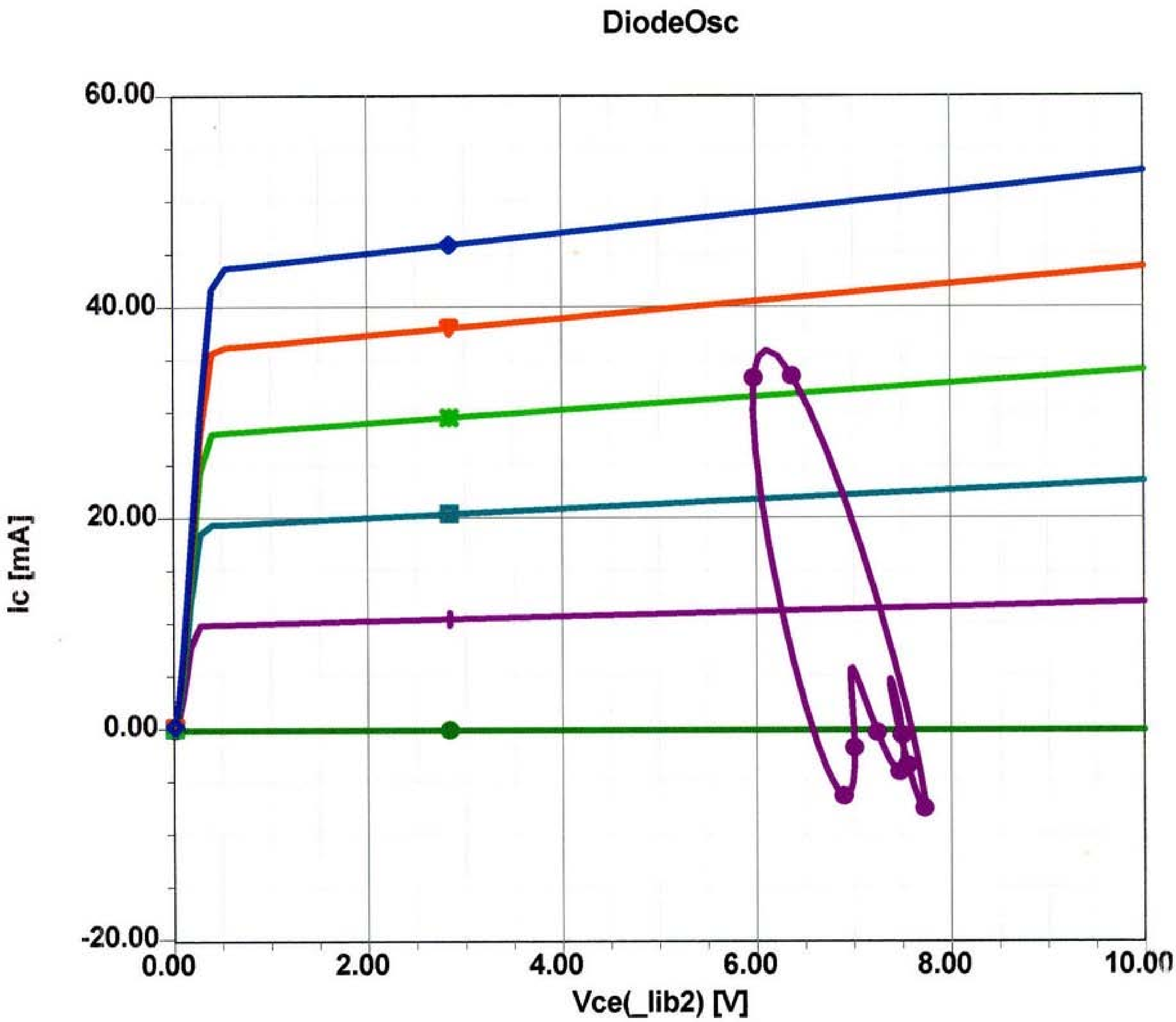
Plot shows the collector current as a function of time with respect to normalized base drive Voltage *x*.

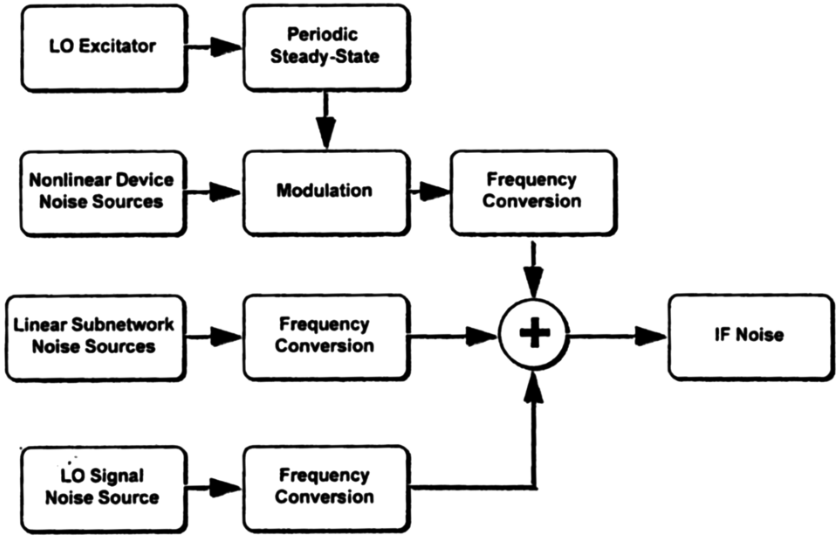


A typical phase noise plot of LC-based 1GHz oscillator as a function of x



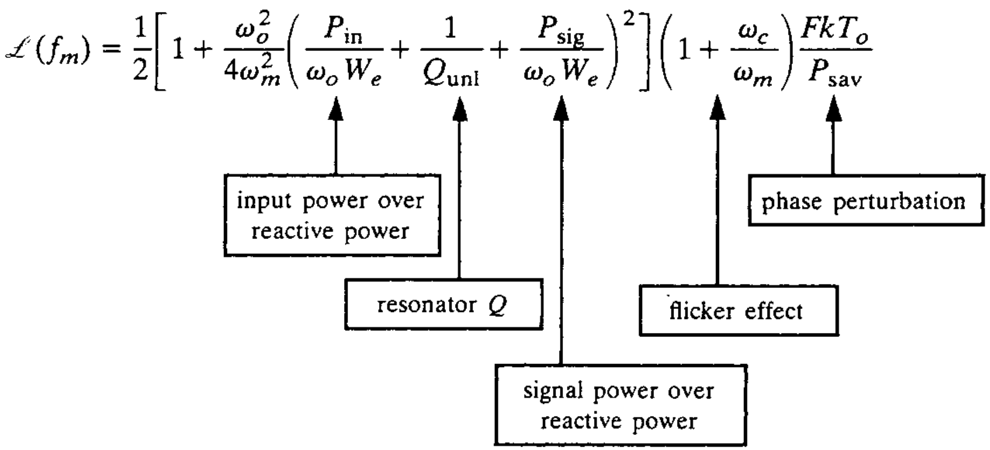
GaAsOsc
60.00
40.00
20.00
0.00
-20.00
Id(_lib1) [mA]
0.00
2.00
4.00
6.00
8.00
Vds(_lib1) [V]


DiodeOsc
60.00
40.00
20.00
0.00
-20.00
Ic [mA]
0.00
2.00
4.00
6.00
8.00
10.00
Vce(_lib2) [V]



A typical block diagram where oscillator acts like a mixer.

The resulting phase noise in linear terms can be calculated as



$$\mathcal{L}(f_m) = \frac{1}{2}\left[1 + \frac{\omega_o^2}{4\omega_m^2}\left(\frac{P_{\text{in}}}{\omega_o W_e} + \frac{1}{Q_{\text{unl}}} + \frac{P_{\text{sig}}}{\omega_o W_e}\right)^2\right]\left(1 + \frac{\omega_c}{\omega_m}\right)\frac{FkT_o}{P_{\text{sav}}}$$

input power over reactive power

resonator Q

signal power over reactive power

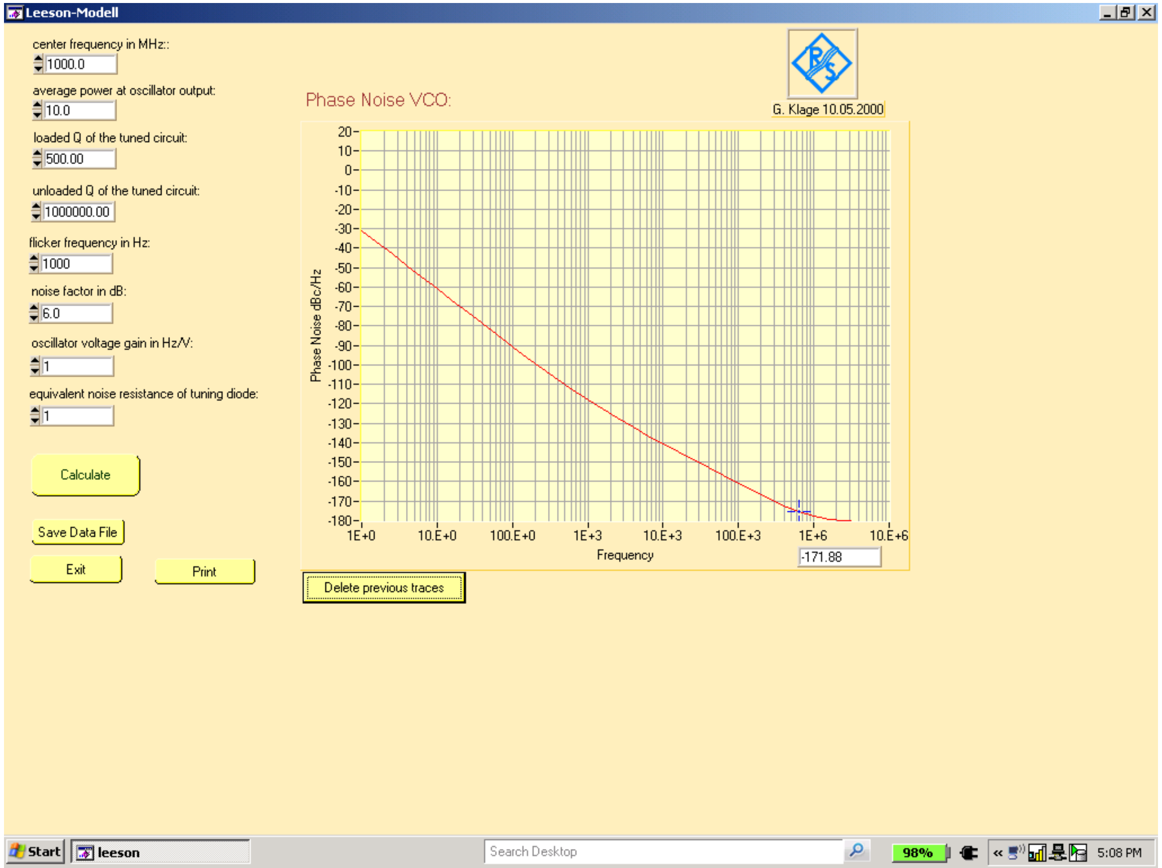
flicker effect

phase perturbation

This equation is the linear Leeson equation, with the pushing effect omitted and the flicker term added by Dieter Scherer (Hewlett Packard, about 1975); the final version with the pushing (supply voltage dependency VCO effect added by Rohde 2004), is

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

This pushing also applies to the VCO case.



Leeson-Modell

center frequency in MHz:: 1000.0

average power at oscillator output: 10.0

loaded Q of the tuned circuit: 500.00

unloaded Q of the tuned circuit: 1000000.00

flicker frequency in Hz: 1000

noise factor in dB: 6.0

oscillator voltage gain in Hz/V: 1

equivalent noise resistance of tuning diode: 1

Phase Noise VCO:

G. Klage 10.05.2000

A typical phase noise plot for an ideal 1 GHz oscillator phase noise of about – 140 dBc/Hz at offset of 10 kHz offset, assuming unloaded Q of 1 million loaded Q of 500, noise factor 6 dB, flicker frequency 1kHz, oscillator voltage gain 1Hz/V, equivalent noise resistance of tuning diode 1Ohm and average power at oscillator output 10 dBm. No diode contribution

Non-Linear Oscillator Equation

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

This is a nonhomogeneous differential equation, which can be simplified to [1, Ch-8, pp. 159-232]

$$L\left[-I_1(t)(\omega+\frac{d\varphi_1(t)}{dt})\sin[\omega t+\varphi_1(t)]+\frac{dI_1(t)}{dt}\cos[\omega t+\varphi_1(t)]\right]+\left[(R_L-R_N(t))I(t)\right]+$$

$$\frac{1}{C}\left\{\left[\frac{I_1(t)}{\omega}-\frac{I_1(t)}{\omega^2}\left(\frac{d\varphi_1(t)}{dt}\right)\right]\sin[\omega t+\varphi_1(t)]+\frac{1}{\omega^2}\left(\frac{dI_1(t)}{dt}\right)\cos[\omega t+\varphi_1(t)]\right\}=e_N(t)$$

Further

where $\overline{R_N(t)}$ is the average negative resistance under large signal condition.

$$\overline{R_N(t)}=\left[\frac{2}{T_0 I}\right]\int_{t-T_0}^{t}R_N(t)I(t)\cos^2[\omega t+\varphi)]dt$$

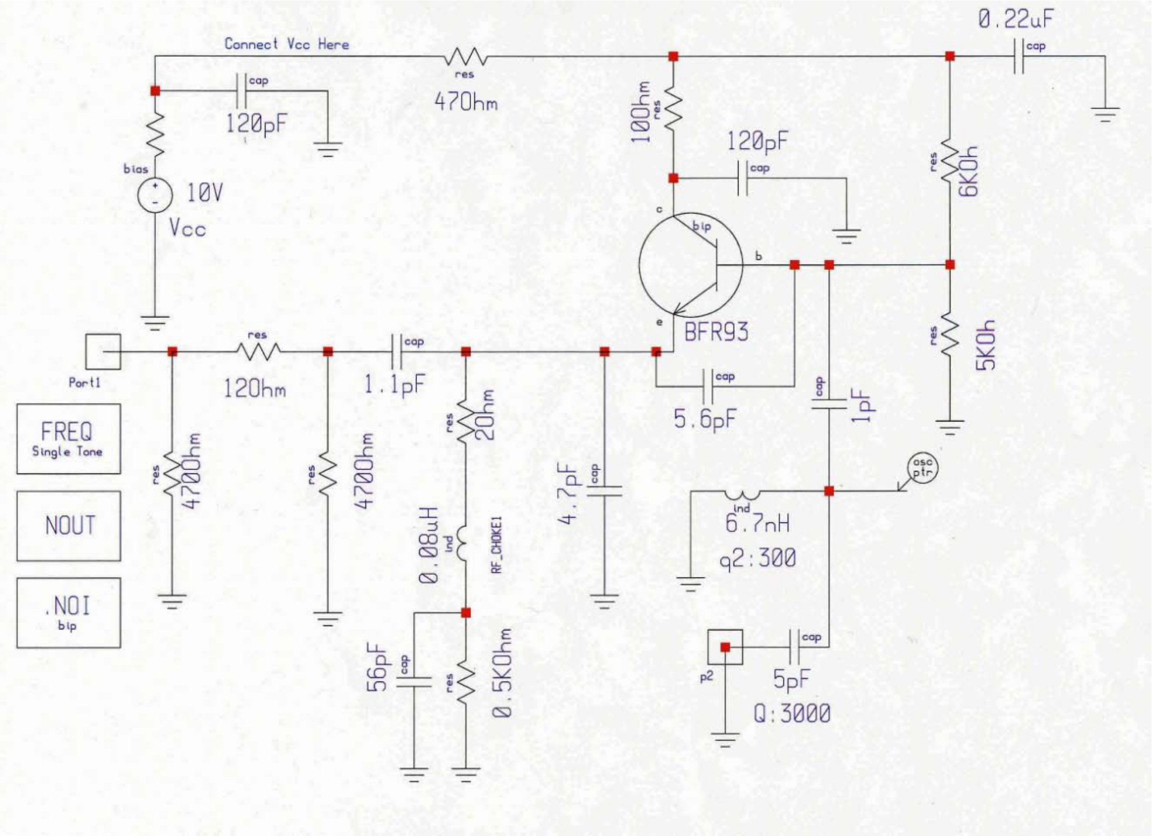
And The SSB Phase Noise Is:

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

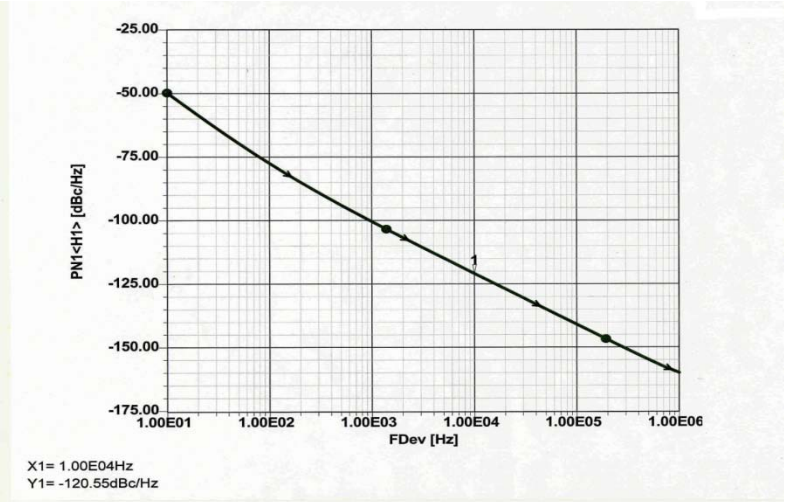
Where

$$y=\frac{C_1}{C_2}\qquad k_0=\frac{kTR}{\omega^2\,\omega_0^2L^2V_{cc}^2C_2^2}\qquad k_1=\frac{qI_cg_m^2+\frac{K_fI_b^{AF}}{\omega}g_m^2}{\omega^2\,\omega_0^4L^2V_{cc}^2}\qquad k_2=\omega_0^4(\beta^{+})^2\qquad k=\frac{k_3}{k_2C_2^2}$$

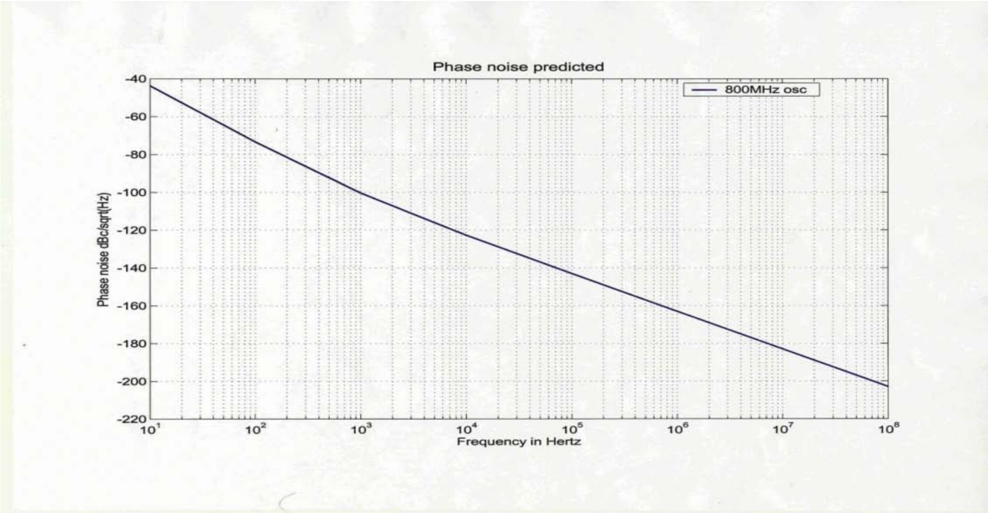
First ever complete and correct large signal phase noise calculation (Rohde 2004)



A typical 1 GHz oscillator circuit



A CAD Simulated (Ansoft Designer) phase noise plot for 1 GHz oscillator circuit

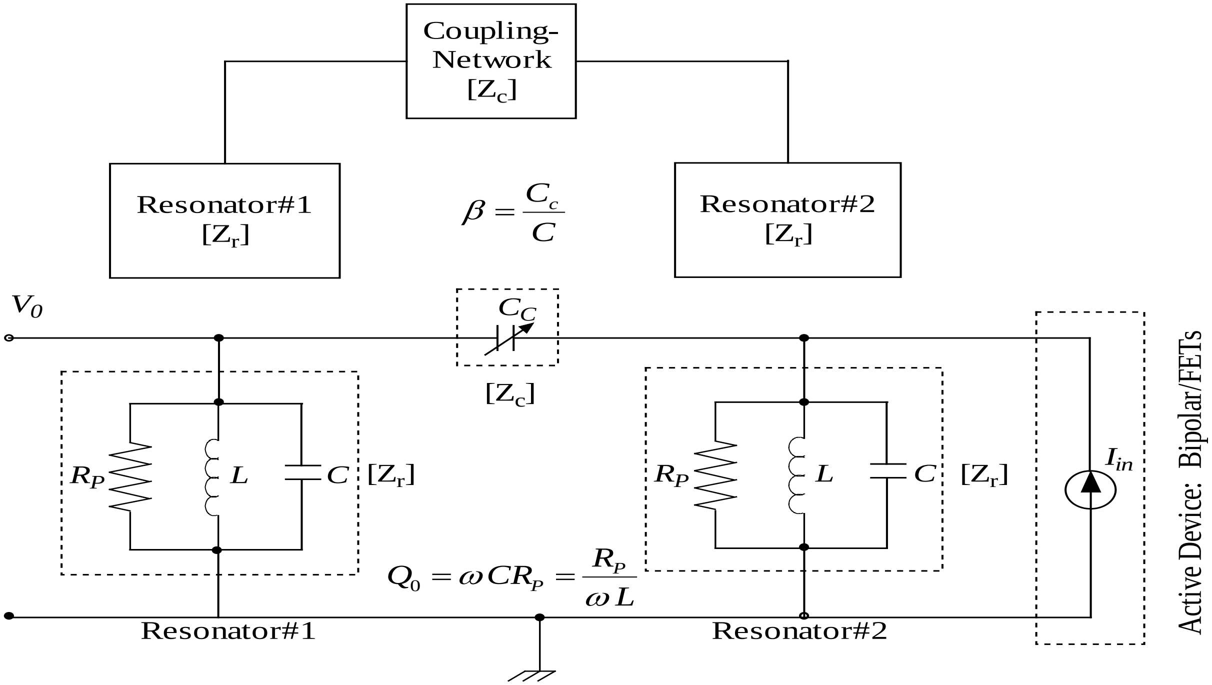


A CAD Simulated (MATLAB) phase noise plot for 1 GHz oscillator circuit

Multiple Magnetically Coupled Resonators

The quality factor of the coupled resonator network previously shown is given by

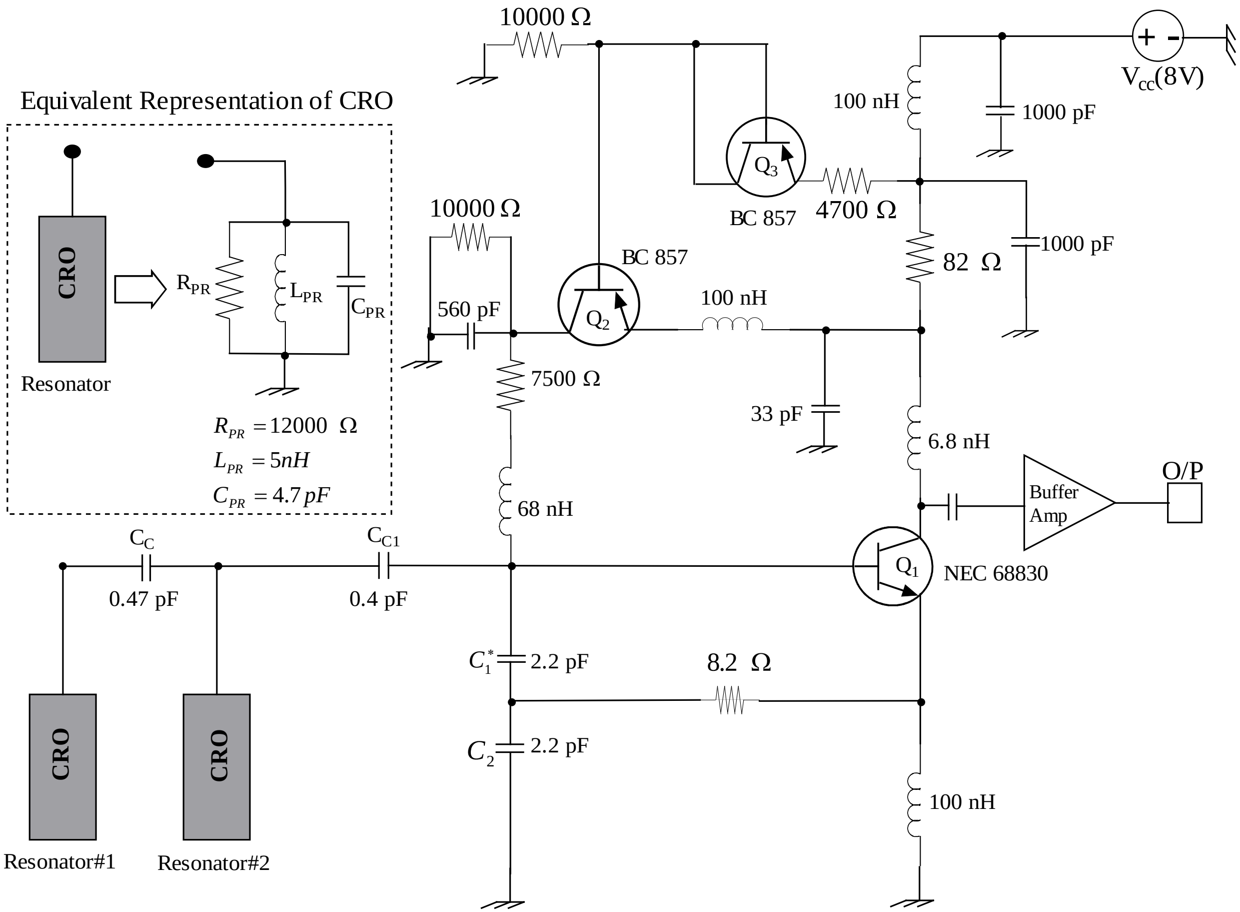
$$[Q_{coupled}(\omega)]_{\omega=\omega_0} = \frac{\omega_0}{2}\left[\frac{\partial\phi}{\partial\omega}\right] \Rightarrow \frac{2Q_0(1+\beta)}{(1+Q_0^2\beta^2)} \rightarrow \left[\frac{2Q_0(1+\beta)}{(1+Q_0^2\beta^2)}\right]_{\beta<<1} \approx 2Q_0$$



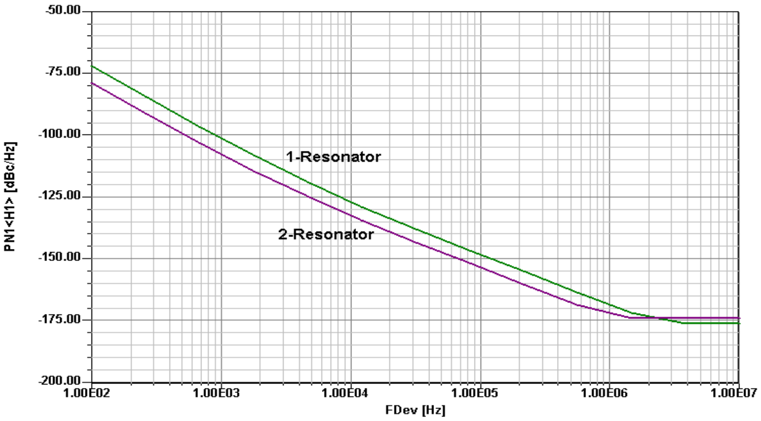
$$\beta = \frac{C_c}{C}$$

$$Q_0 = \omega C R_P = \frac{R_P}{\omega L}$$

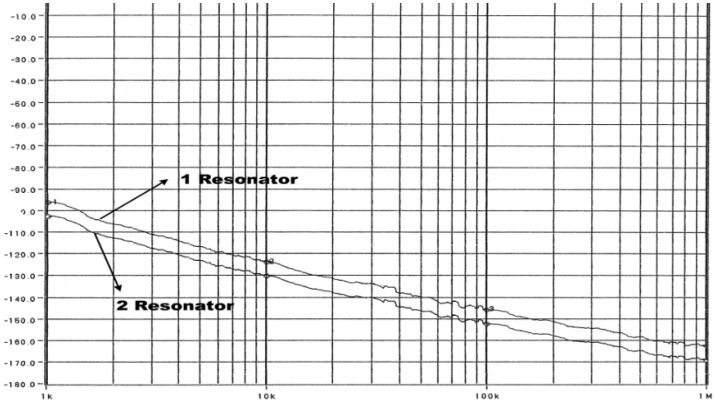
Capacitive coupled 2 resonators



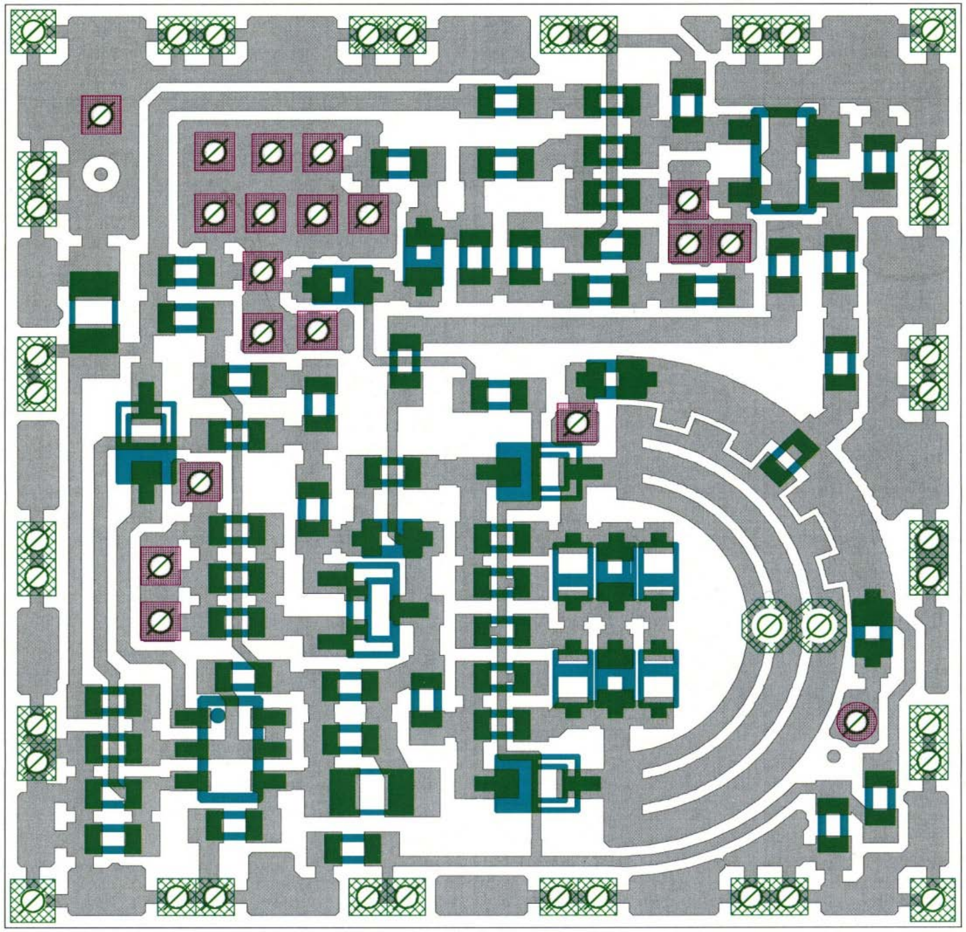
Circuit with Resonators



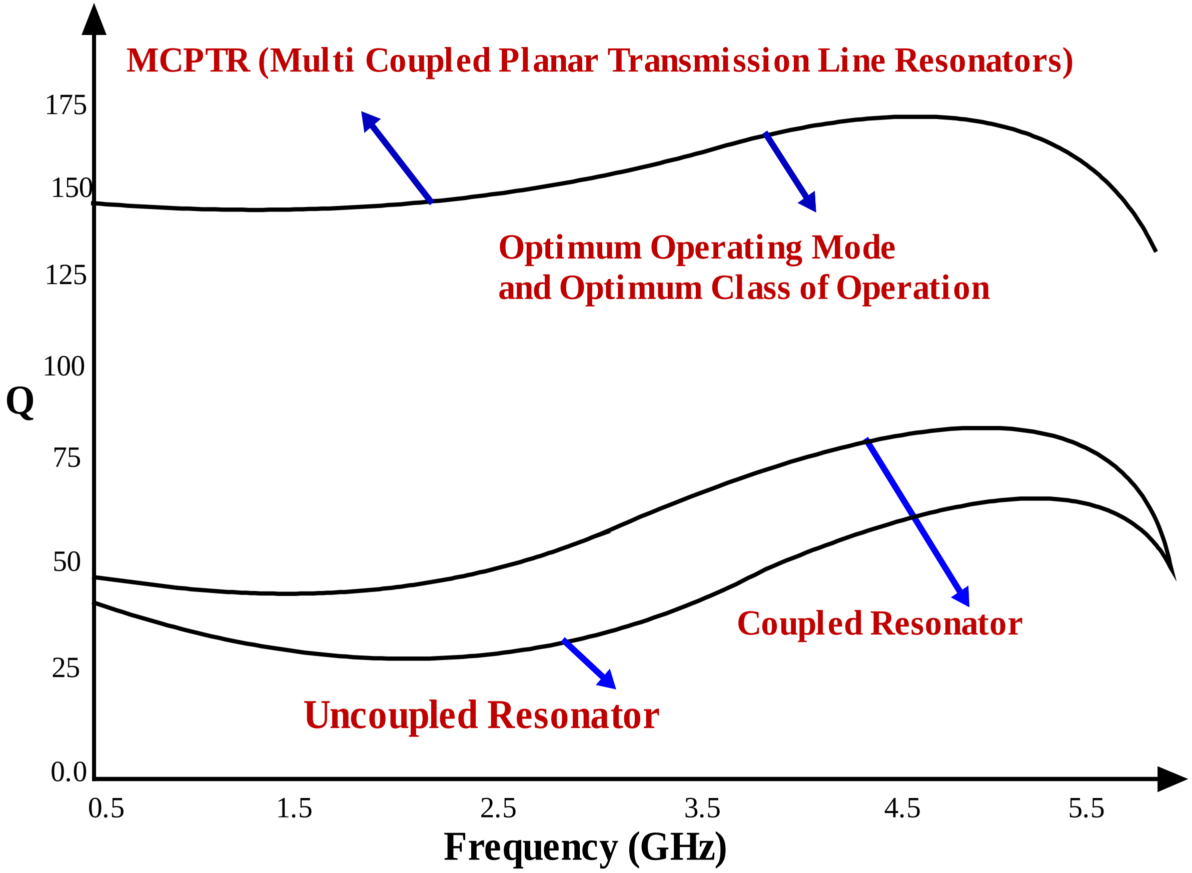
CAD simulated phase noise plot for the single resonator (1-resonator) and the identical coupled resonator (2-resonators)



Measured phase noise plots for the single resonator (1-resonator) and the identical coupled resonator (2-resonator



Layout of the MCLR VCO (500MHz-2500MHz) (Patented)



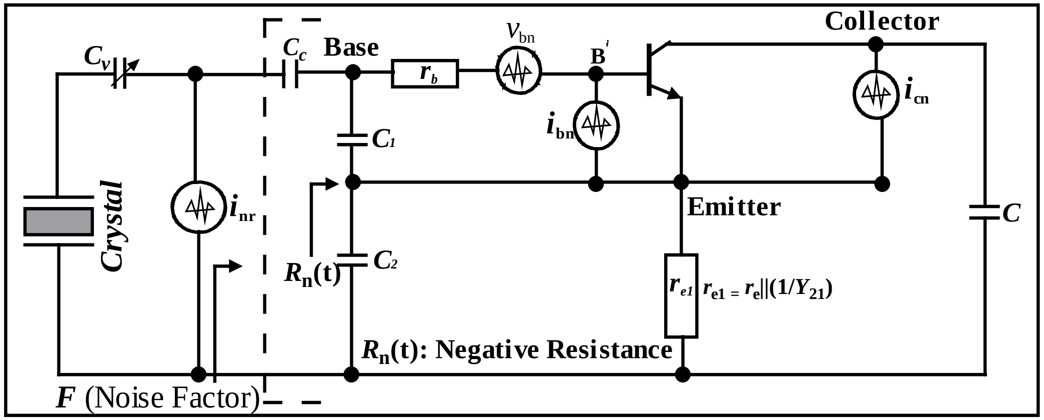
Measured Q of resonators (uncoupled, coupled and MCLR)

Noise Optimization

$$\frac{d}{dm}\left[10\log\left\{\left[1+\frac{f_0^{\,2}}{[2f_mQ_0m(1-m)]^2}\right]\left(1+\frac{f_c}{f_m}\right)\frac{FkT}{2P_0}+\frac{2kTRK_0^2}{f_m^{\,2}}\right\}\right]_{m_{opt}}$$

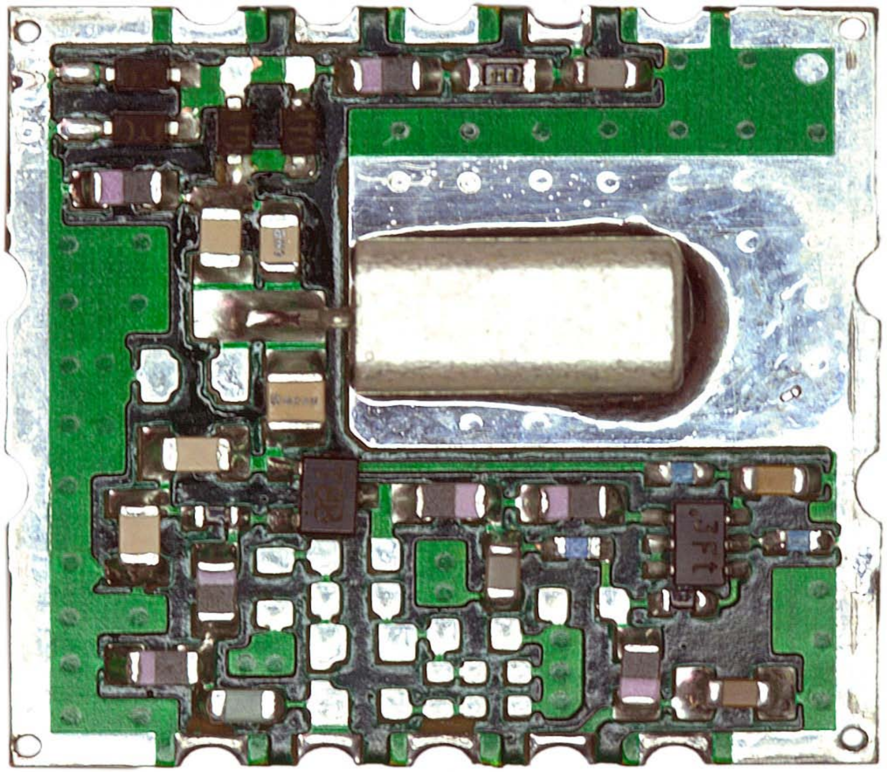
$$m_{opt}\rightarrow 0.5\Rightarrow\left[\frac{d\phi}{d\omega}\right]_{,\phi=\phi_{opt}}=\frac{Q_{unloaded}}{\omega_0}$$

Coupling Factor = 0.5

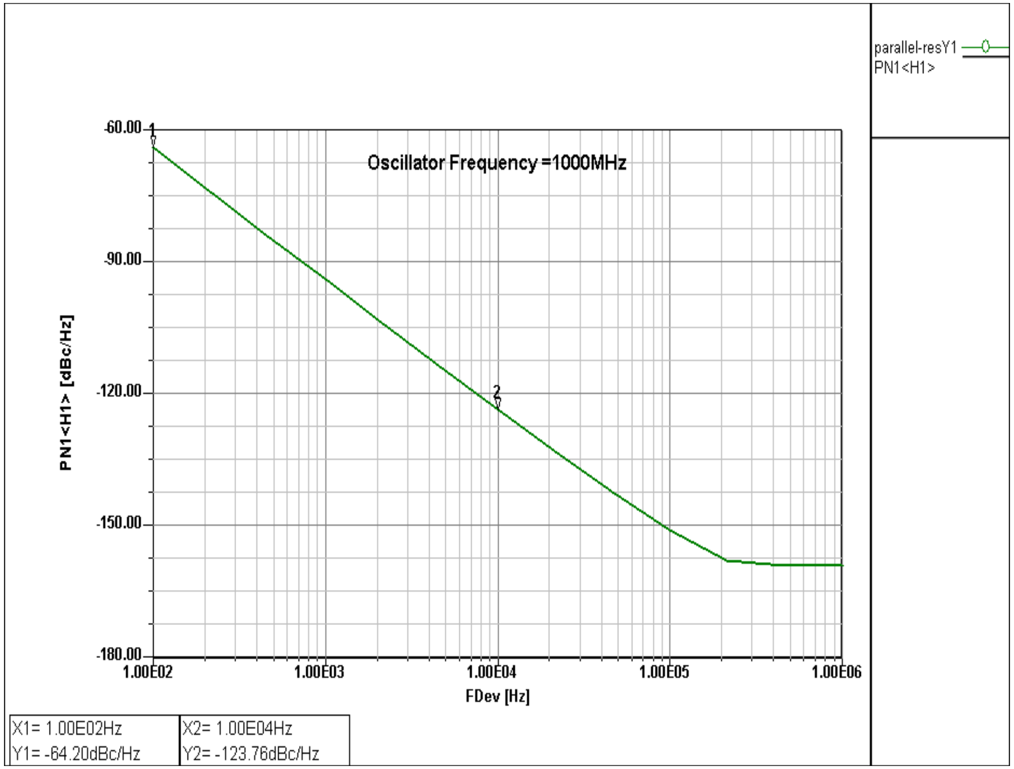


$$F=1+\frac{Y_{21}^{+}C_2C_c}{(C_1+C_2)C_1}\left[r_b+\frac{1}{2r_e}\left(r_b+\frac{(C_1+C_2)C_1}{Y_{21}^{+}C_2C_c}\right)^2\left(\frac{1}{\beta^{+}}+\frac{f^{\,2}}{f_T^{\,2}}\right)+\frac{r_e}{2}\right]$$

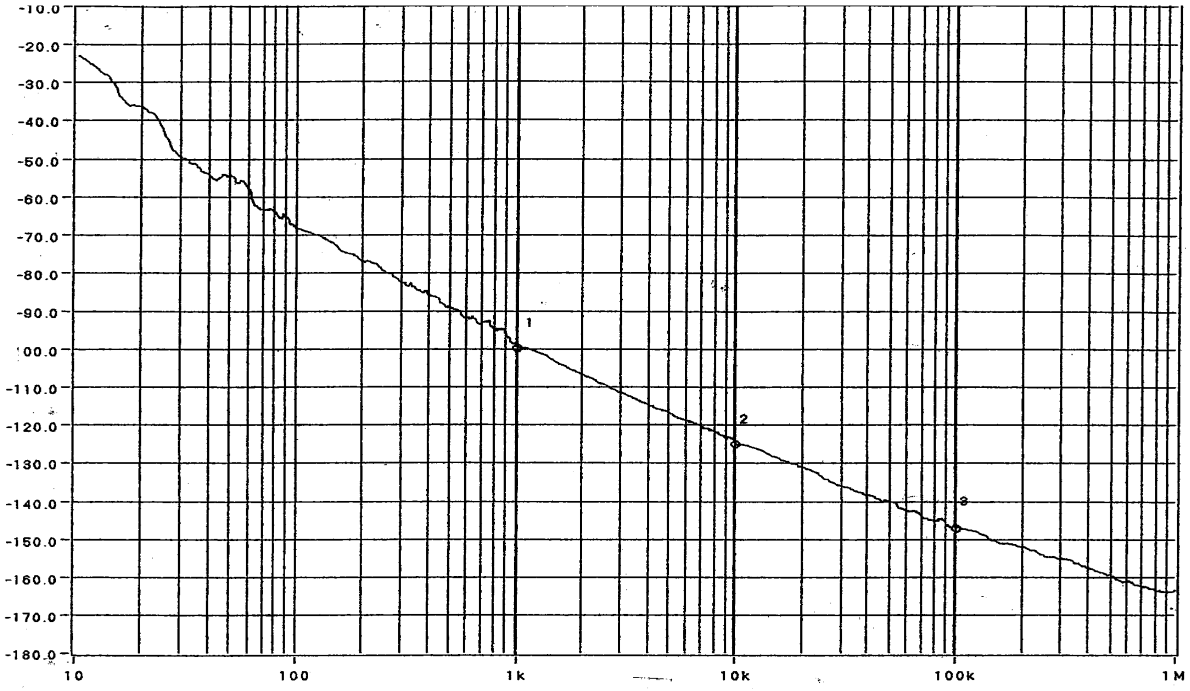
Noise Factor of Oscillator



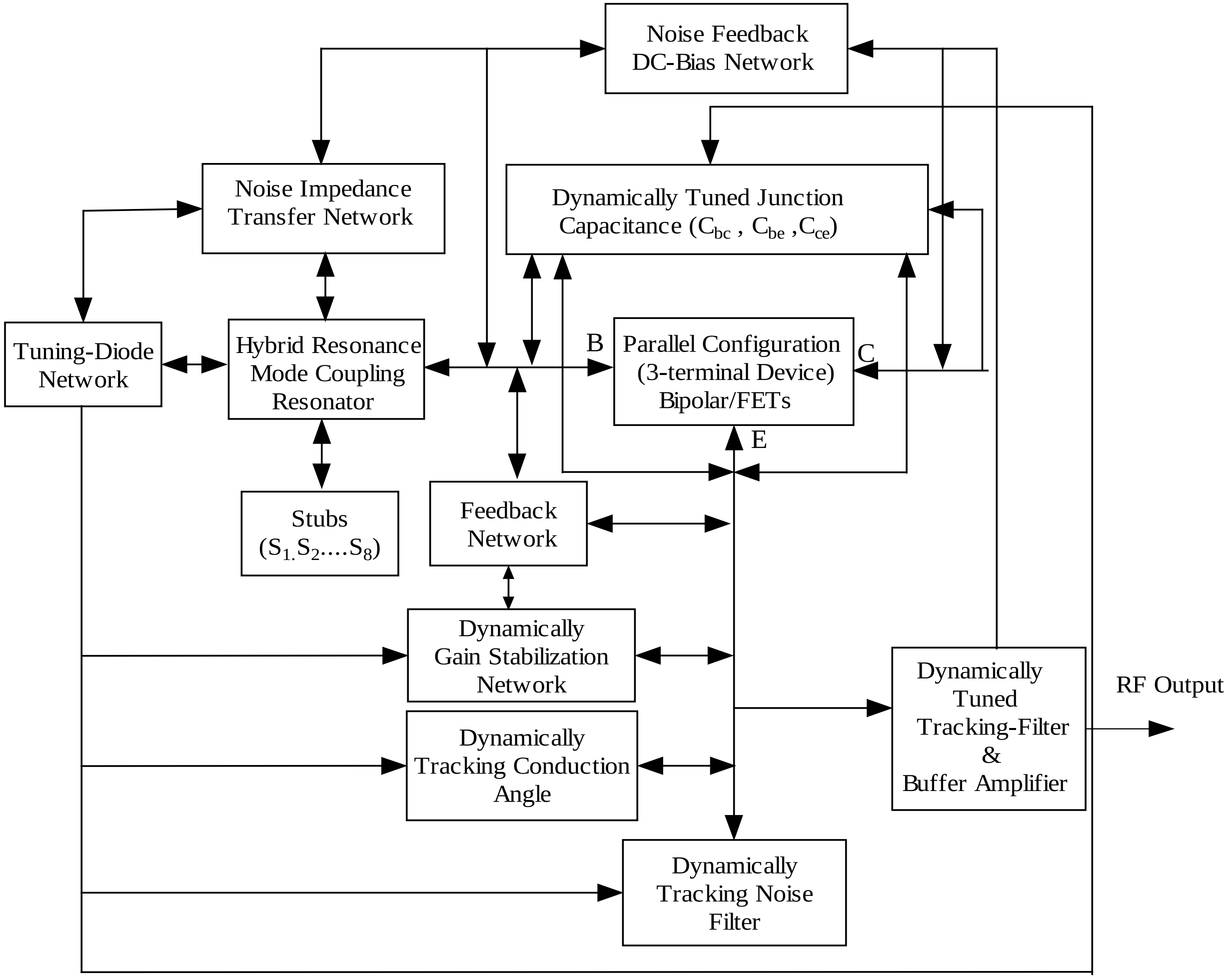
Layout of 1GHz Colpitts oscillator (Ceramic resonator oscillator)



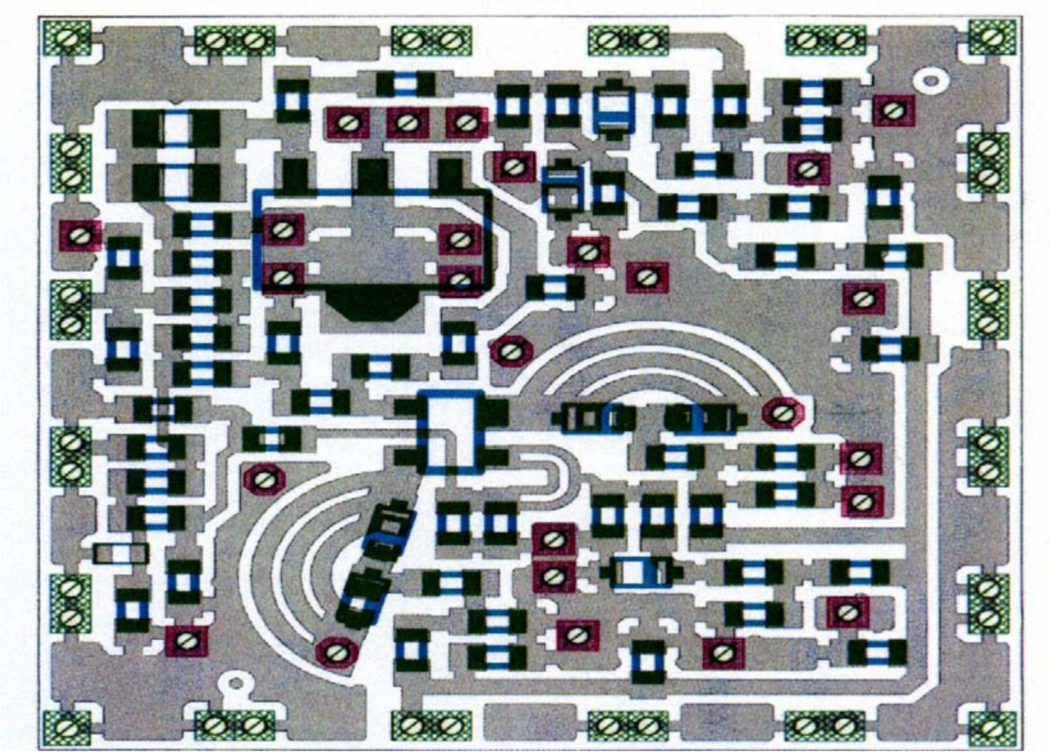
Simulated phase noise plot of for CRO



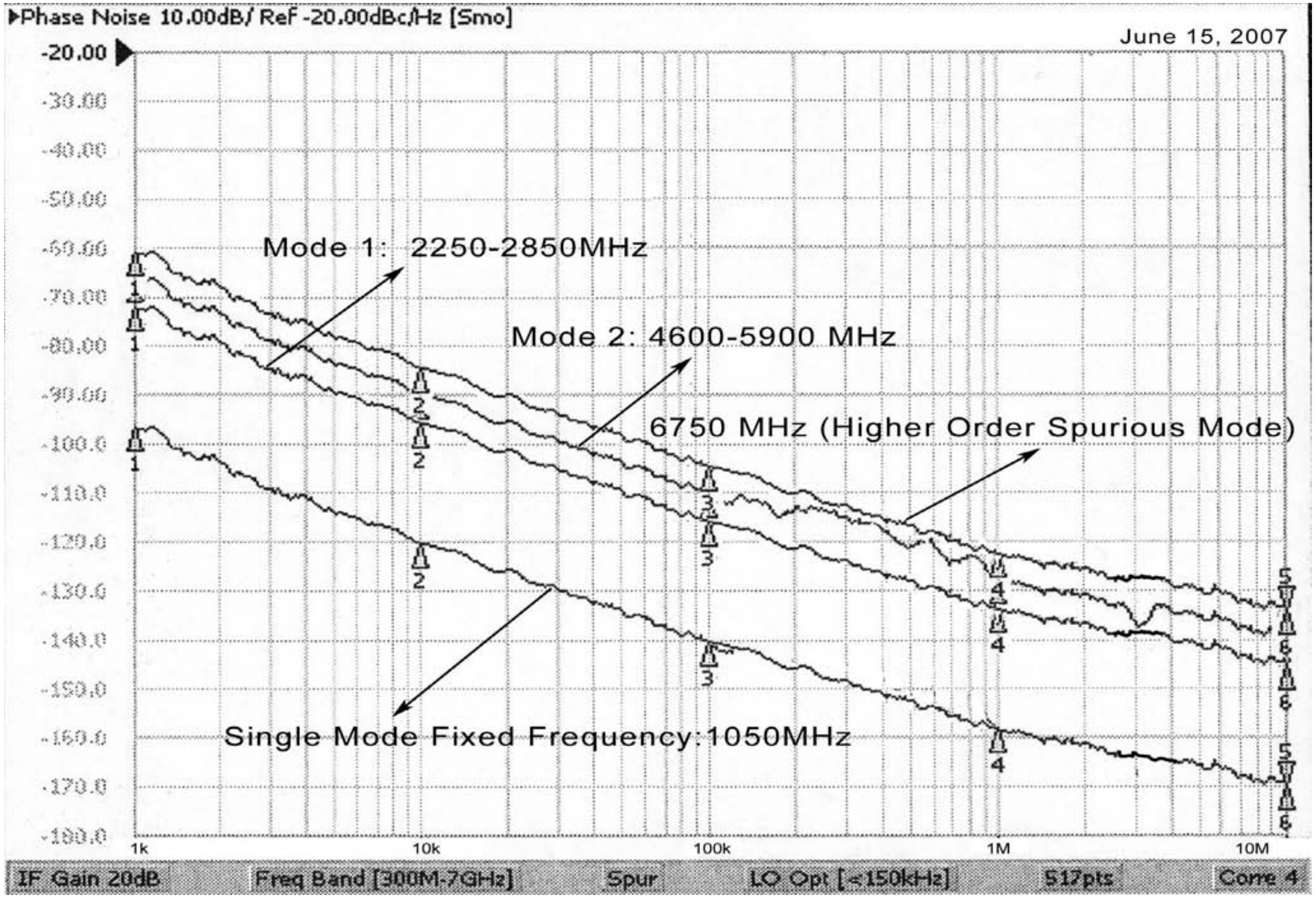
Measured phase noise plot of the CRO



Block diagram of a user-defined MCLR VCO



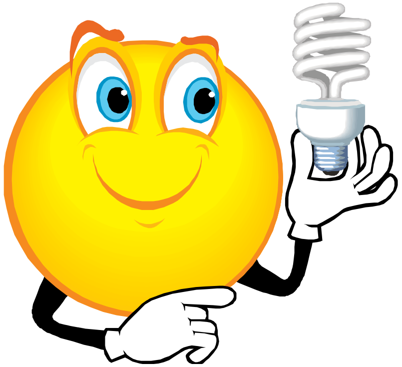
Layout of dual-band RCO (Patent pending)



Phase noise plot of the dual-band VCO

Thank You

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK



Are there any questions?