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Noise in Oscillators with Active Inductors

Presented to the Faculty 3 : Mechanical engineering, Electrical engineering and industrial engineering, Brandenburg University of Technology Cottbus, and accepted with a Dissertation to obtain the Habilitation Status of

“Dr.-Ing. habil.”

October 20, 2011

OUTLINE

- What is an Oscillator
- Oscillator Basics
- Typical Microwave Oscillator (Colpitts Oscillator)
- Oscillator Transistors Large Signal Operations
- Frequency Variation of the Oscillator
- Introduction of the Spiral Inductor
- Introducing the Gyrator
- Surface area of the Passive Inductor
- Noise sources in the Oscillator
- Active Inductor Based Oscillator
- Active Inductor Oscillator Phase Noise
- Calculation of the Active Inductor Noise
- Validation Circuits
- Summary

DEFINITION OF AN OSCILLATOR

- An Oscillator is an Electronic Circuit that converts DC power to RF power, this can range from a few Hz to Tera Hz and higher
- An oscillator consists of an active device acting as an amplifier, a resonator, and a feedback circuit
- A small amount of energy feedback is needed to sustained oscillation and the majority of available energy appears at the output terminals
- Resonators can be LC based circuits, transmission line based, crystal, ceramic, dielectric resonator ,YIG (Yttrium Garnet) based, and others

For RF application, the most relevant features besides size are:

- Output power
- Harmonic content
- Phase Noise
- Power consumptions, to name a few

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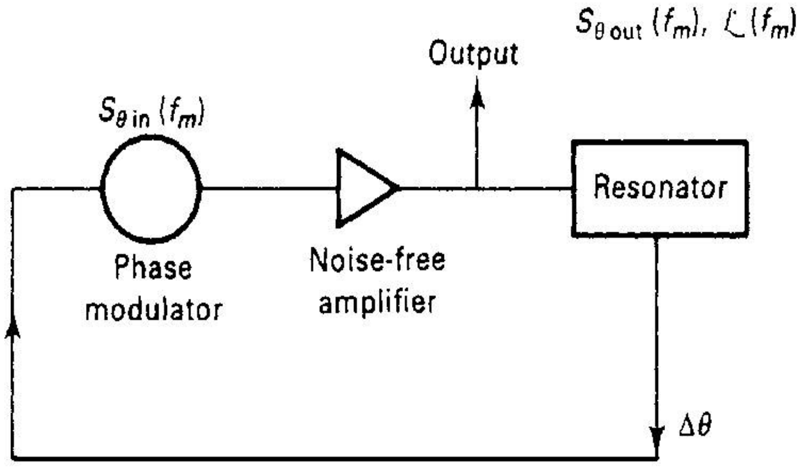
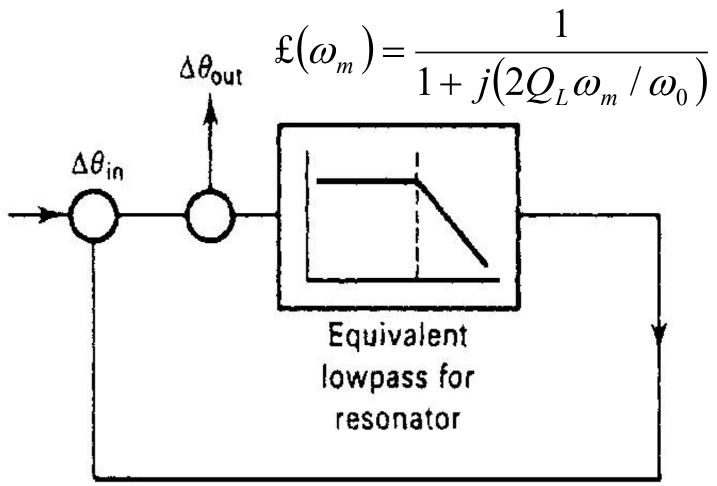
OSCILLATOR BASICS

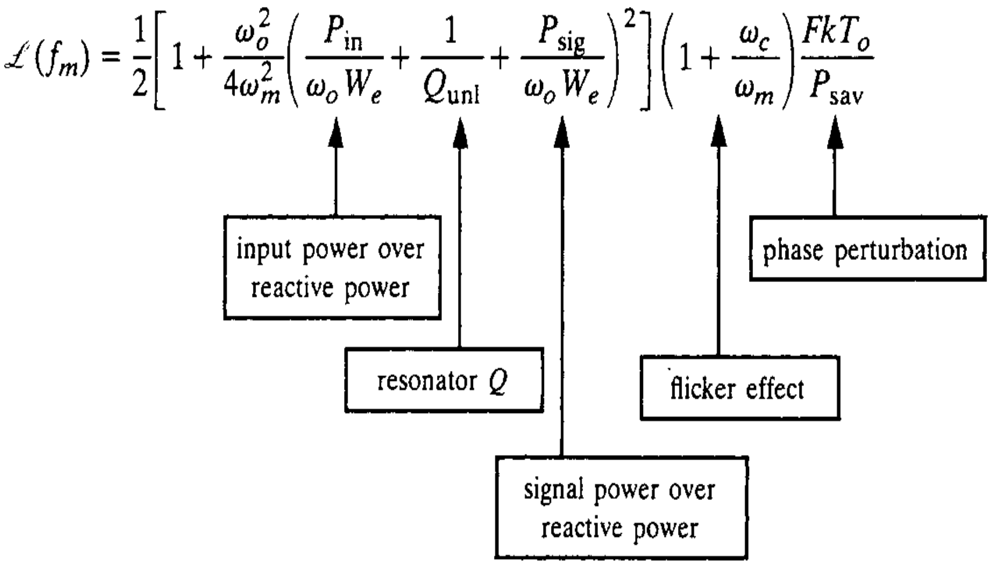
A typical linear oscillator phase noise model (block diagram) Leeson Model





$$£(\omega_m) = \frac{1}{1 + j(2Q_L\omega_m / \omega_0)}$$

The resulting phase noise in linear terms can be calculated as



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

This equation is the linear Leeson equation, with the pushing effect omitted and the flicker term added by Dieter Scherer (Hewlett Packard, about 1975).

Phase noise is a dimensionless number, and expressed in dBc/Hz, measured at an offset of Δf (f_m) from the carrier relative to the RF output power. At 0 dBm output, the ideal phase noise level far off the carrier is -174dB (T_0= 300 Kelvin)

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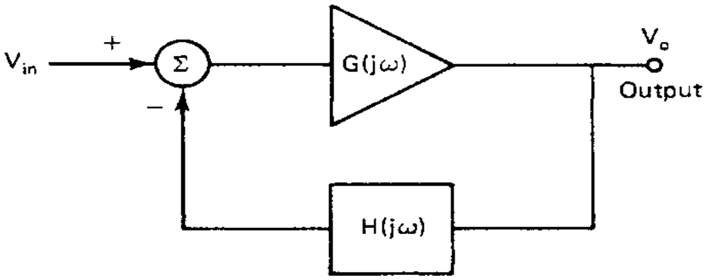
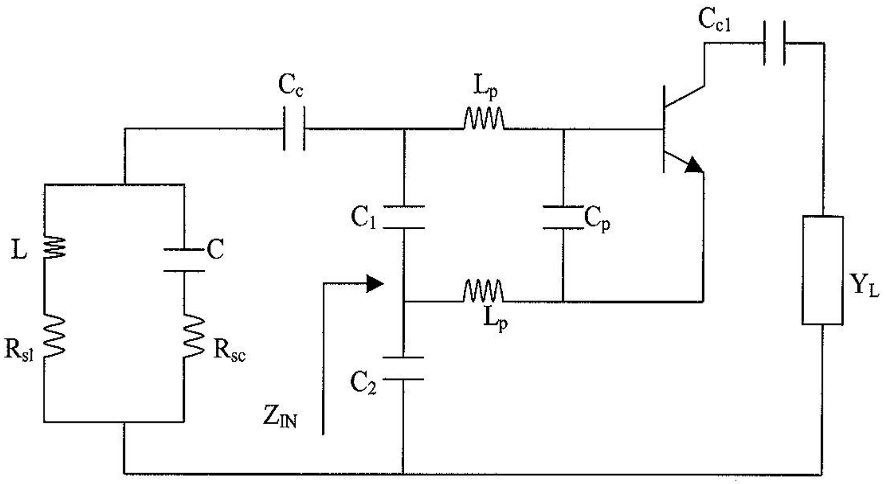
TYPICAL MICROWAVE OSCILLATOR

- Microwave oscillators are based on the negative resistance principle to compensate for the loses.
- Maximum frequency of oscillation can be determined from linear analysis for start-up conditions, but not necessarily for sustaining oscillation (large signal condition will reduce the gain and shift the frequency).
- Linear analysis is unreliable to determine resonance frequency and other dynamic parameters, beware of parasitics.

A typical block diagram of feedback oscillator circuit



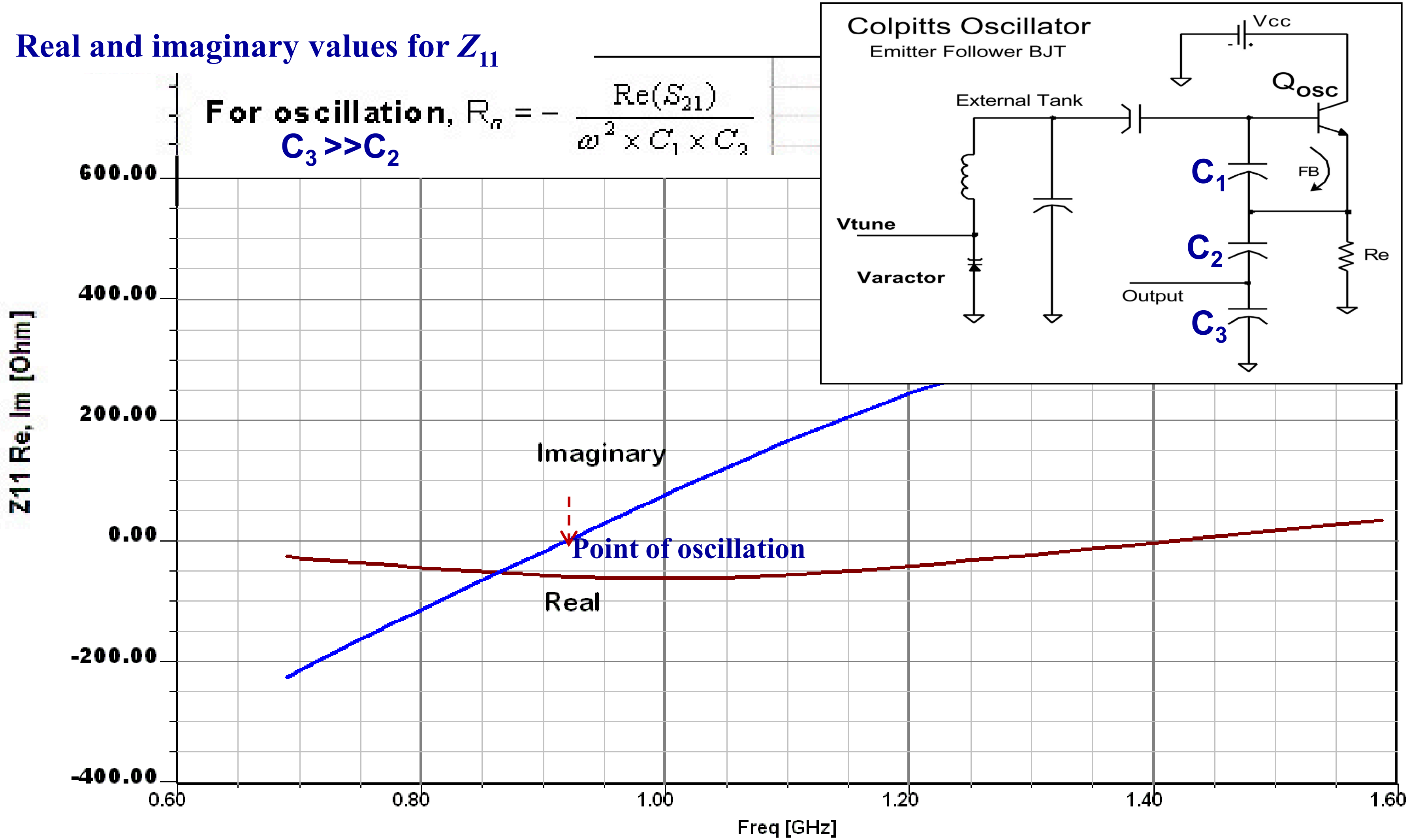


$$Z_{IN}\Big|_{pacakage} = -\left[\frac{Y_{21}^{*}}{\omega^{2}(C_1+C_p)C_2}\,\frac{1}{(1+\omega^{2}Y_{21}^{*2}L_p^{2})}\right] - j\left[\frac{(C_1+C_P+C_2)}{\omega(C_1+C_P)C_2} - \frac{\omega Y_{21}^{*}L_P}{(1+\omega^{2}Y_{21}^{*2}L_p^{2})}\,\frac{Y_{21}^{*}}{\omega(C_1+C_P)C_2}\right]$$

Y_{21}^{*} = **Large signal value of g_m=Y_{21DC}**

CONDITION FOR OSCILLATIONS

Real and imaginary values for Z_{11}



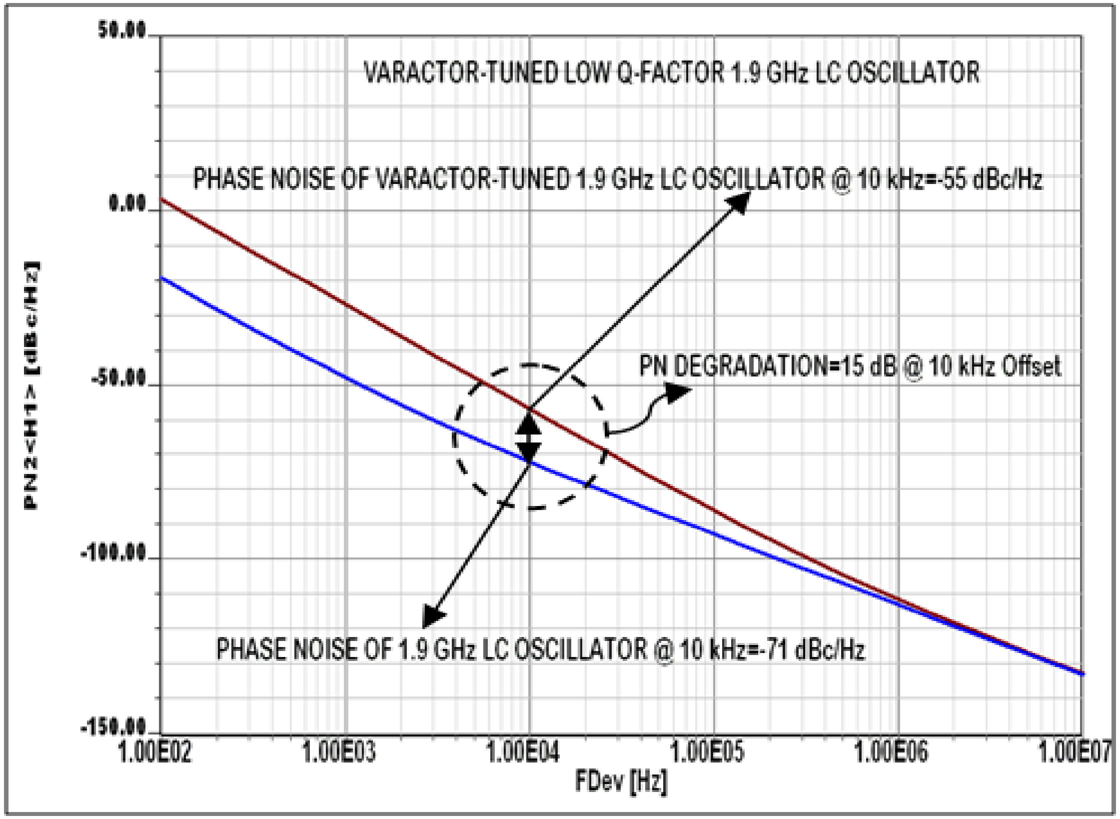
For oscillation, $R_n = -\frac{\mathrm{Re}(S_{21})}{\omega^2 \times C_1 \times C_2}$

$C_3 >> C_2$

Point of oscillation

Real (Z_{11}) must be slightly more negative than the loss resistance in the circuit for oscillation to start. The resulting dc shift in the transistor will then provide the amplitude stabilization as g_m will be reduced.

LC- COLPITTS OSCILLATOR PHASE NOISE



The Leeson phase noise equation is modified to accommodate the tuning diode noise contribution

$$£(f_m) = 10\log\left\{\left[1+\frac{{f_0}^2}{(2f_mQ_0)^2m^2(1-m)^2}\right]\left(1+\frac{f_c}{f_m}\right)\frac{FkT}{2P_0}+\frac{2kTRK_0^2}{f_m^2}\right\} \qquad m=\frac{Q_L}{Q_o}$$

The Equation above explain the phase noise degradation (as compared to the fixed frequency LC oscillator due to the oscillator voltage gain K_0 associated with the tuning diode network as described by Rohde). The reason for noise degradation is due to the increased tuning sensitivity of the varactor diode tuning network.

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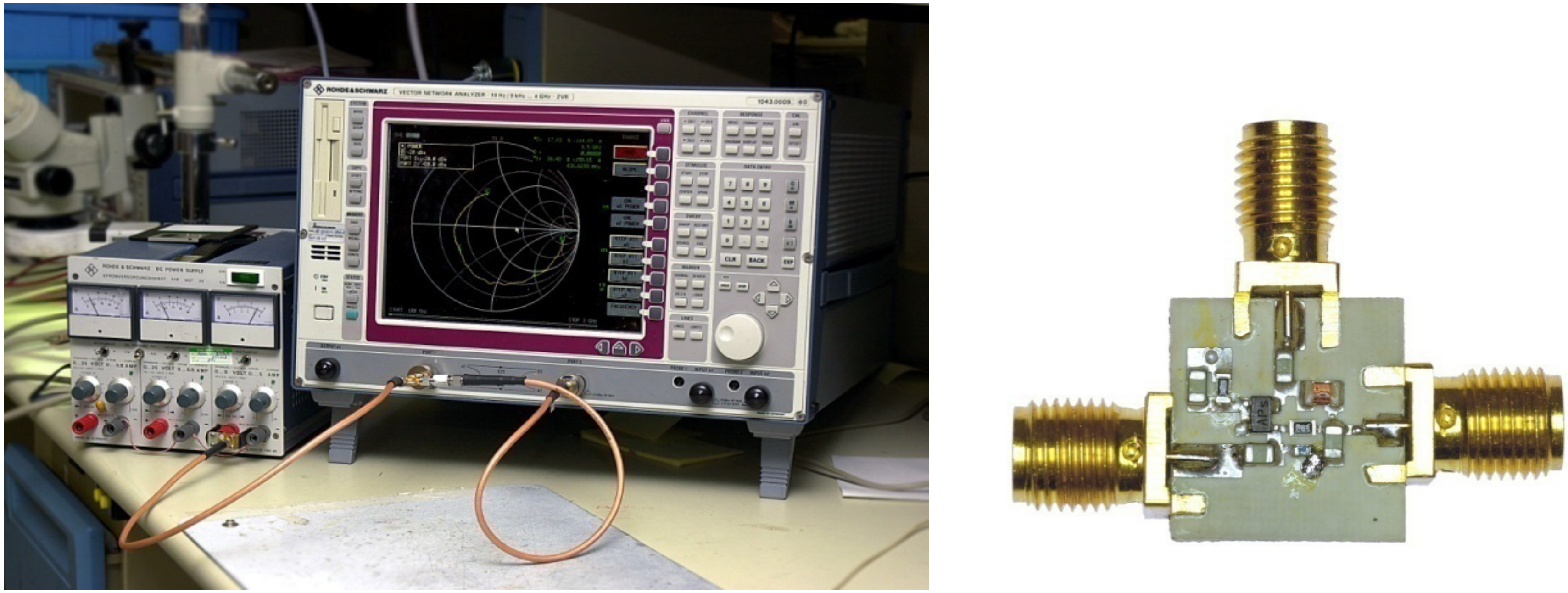
LARGE SIGNAL OPERATION

- **Definition: RF voltages/currents are of similar magnitude as the DC values. Test points were $V_c = 2\text{V}$, $I_c = 20\text{mA}$.**
- **The transistor behaves differently under large signal conditions.**
- **Large signal parameters can be obtained from simulation using SPICE parameters, calculating the Bessel functions of the currents of the intrinsic transistor and adding the parasitics and measurements.**

This Figure shows the R&S VNA and the test fixture for the transistor of choice

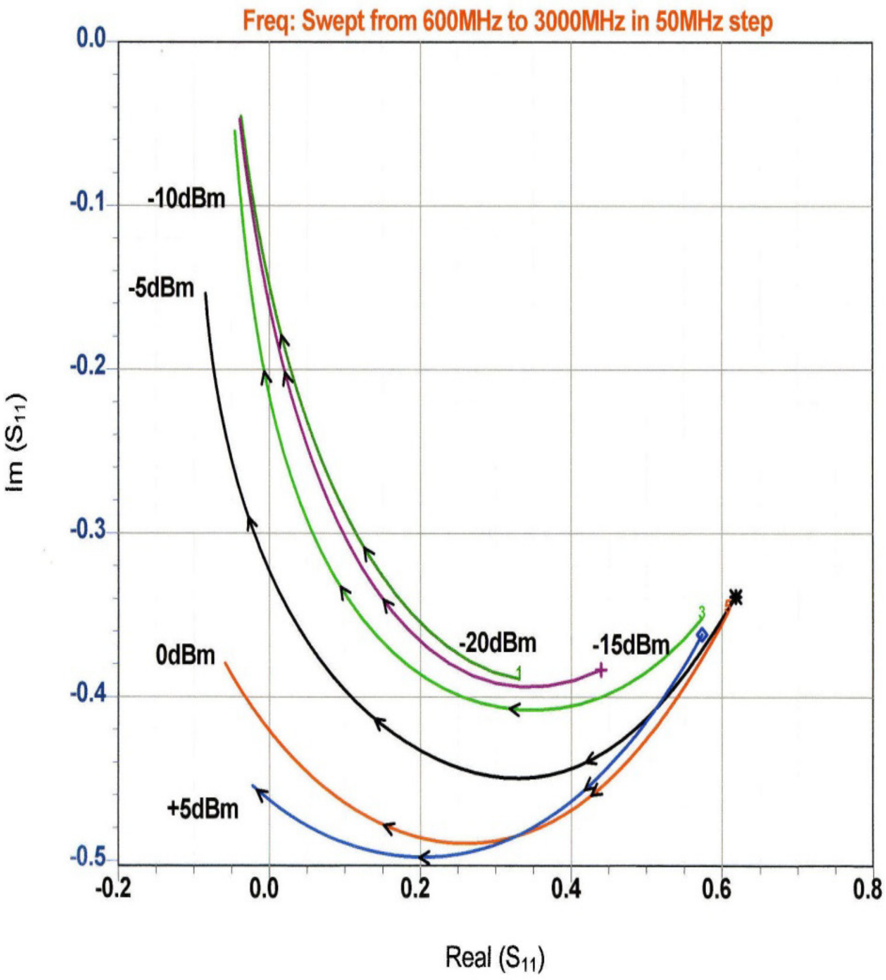


Typical measurement setup for evaluation of large signal parameters (R&S vector analyzer and the test fixture for the transistor of choice), Agilent now calls this X Parameters

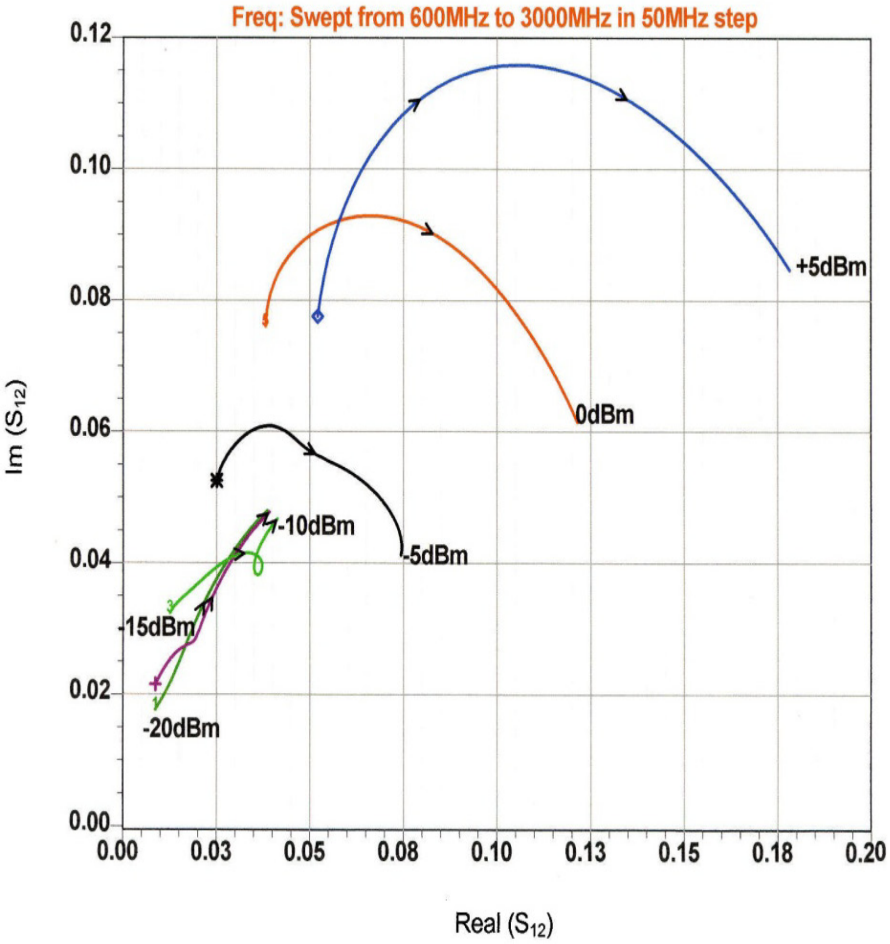
LARGE SIGNAL OPERATION , Cont'd.

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

Measured large-signal S_{11} of the BFP520



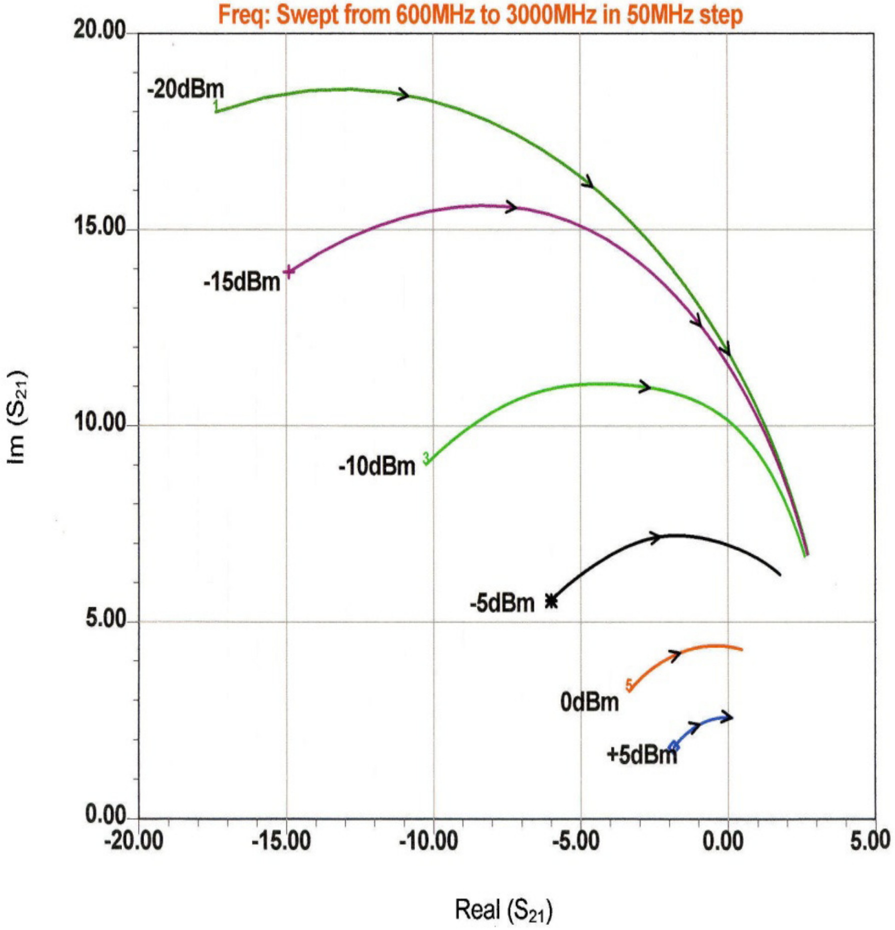
Measured large-signal S_{12} of the BFP520



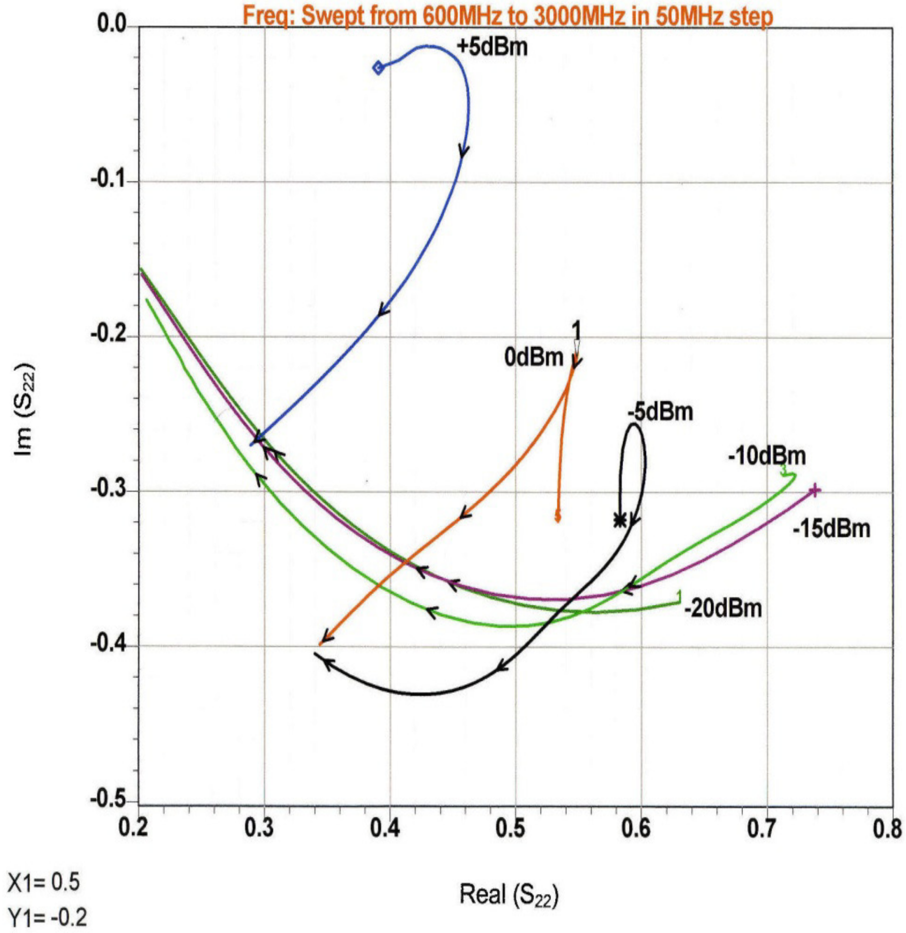
LARGE SIGNAL OPERATION , Cont’d.

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

Measured large-signal S_{21} of the BFP520

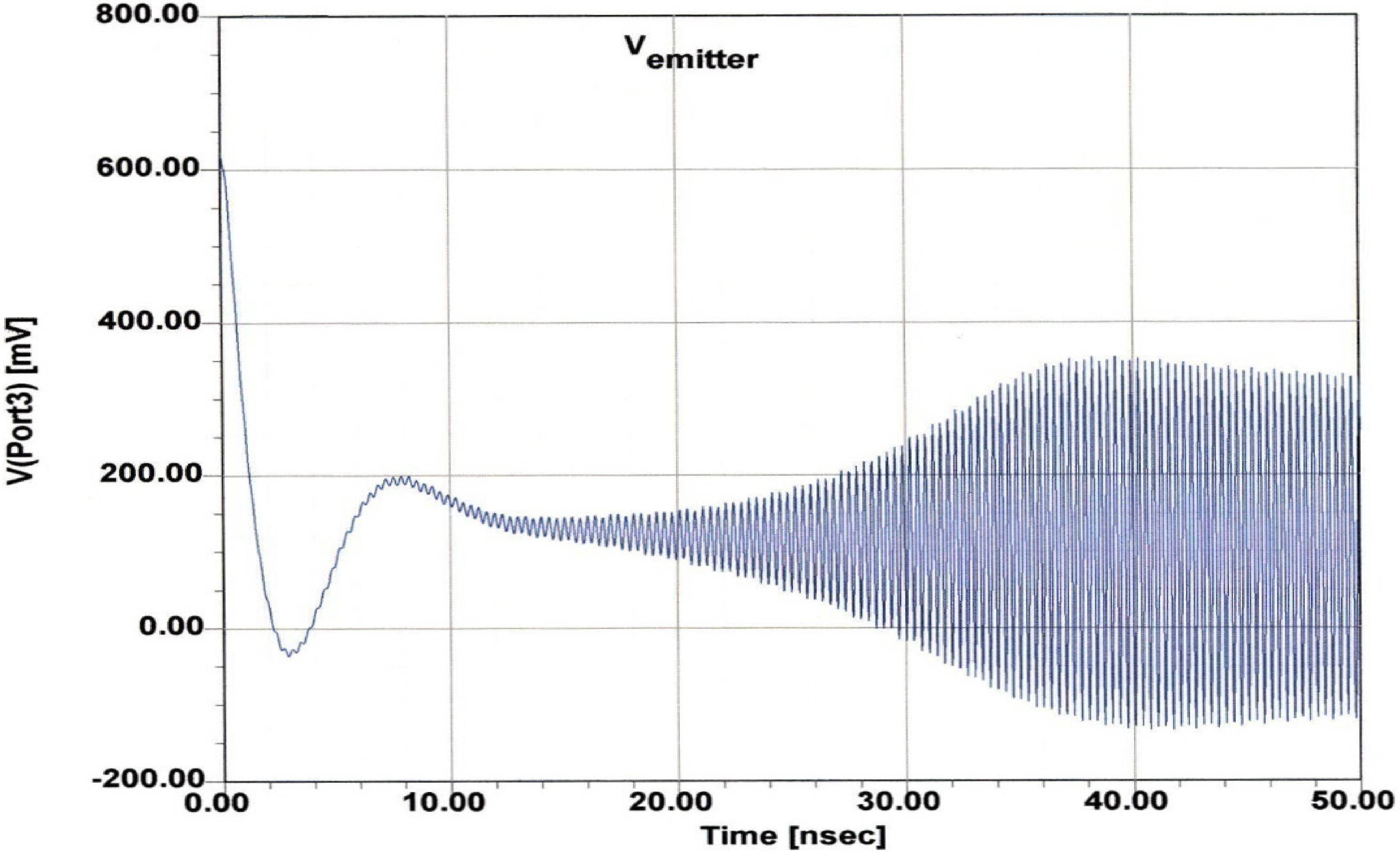


Measured large-signal S_{22} of the BFP520



LARGE SIGNAL OPERATION , Cont'd.

Typical transient simulation of a ceramic resonator-based high-Q, 1GHz oscillator (node of the voltage for display is taken from the emitter)



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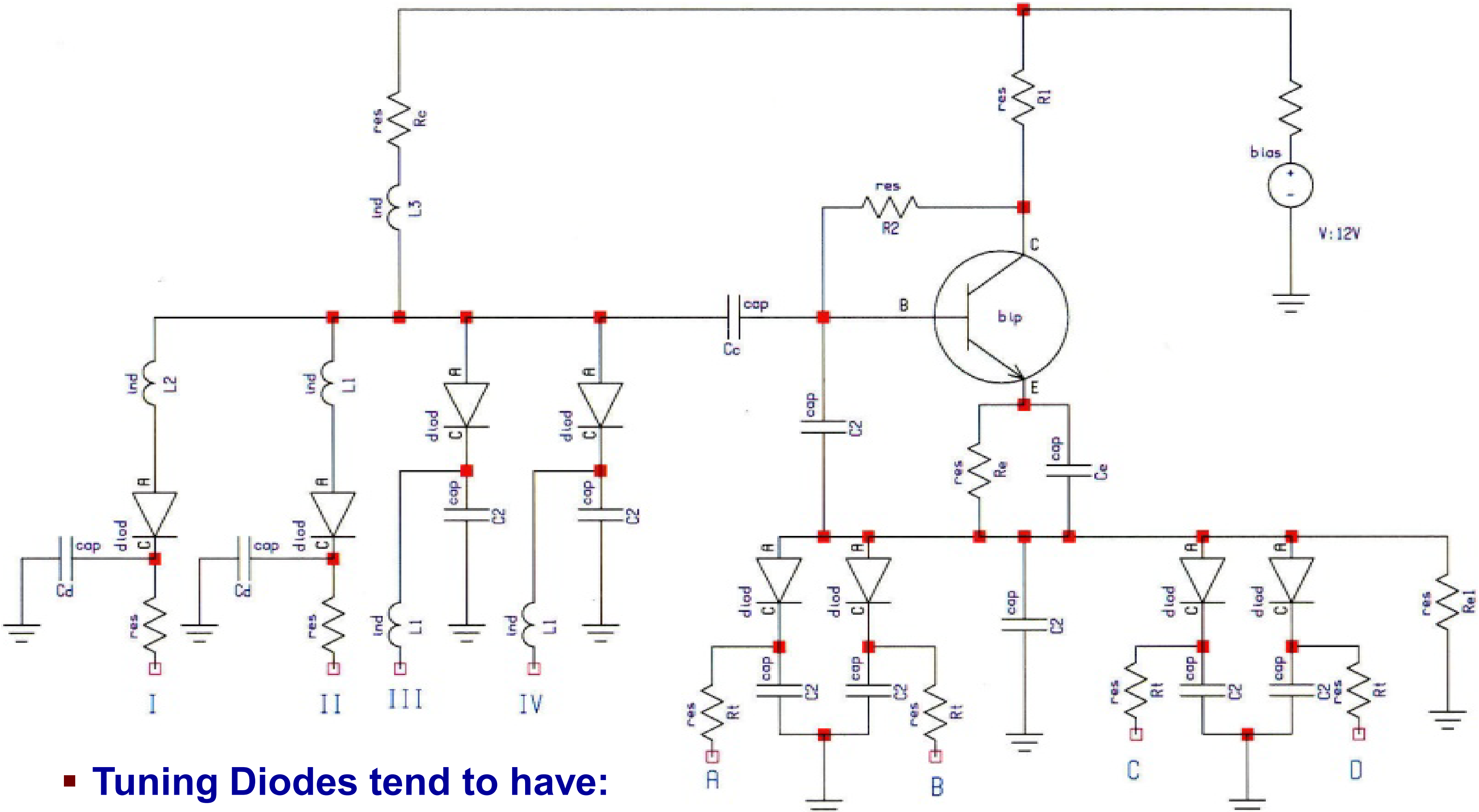
FREQUENCY VARIATION OF THE OSCILLATOR

Typical Schematic of Switched Mode and VCO Circuit

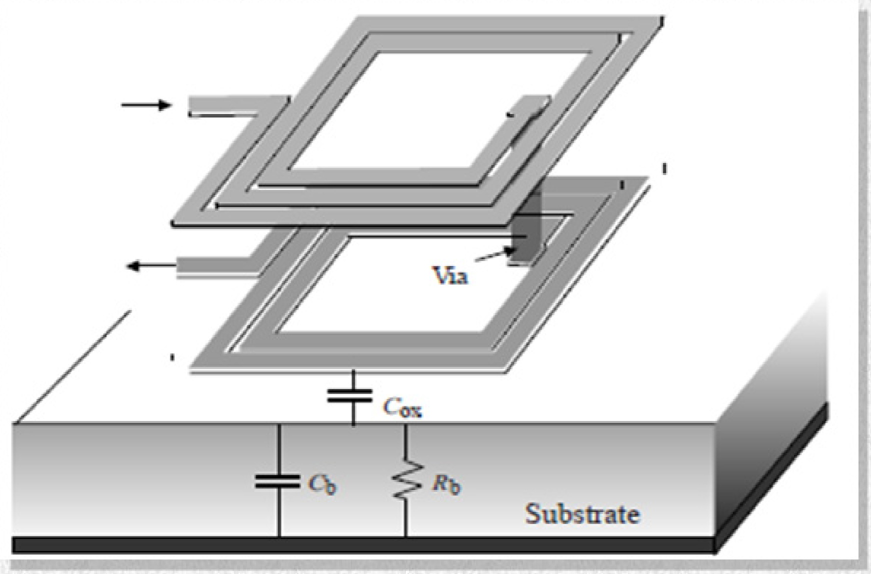


- **Tuning Diodes tend to have:**
  - ➢ **Low Q at RF & MW frequencies**
  - ➢ **Limits Tunability Due to Package Parasitic**
  - ➢ **Changes characteristics due to low SRF**
- **Active Tunable Inductor ATIs can over come the above difficulties**

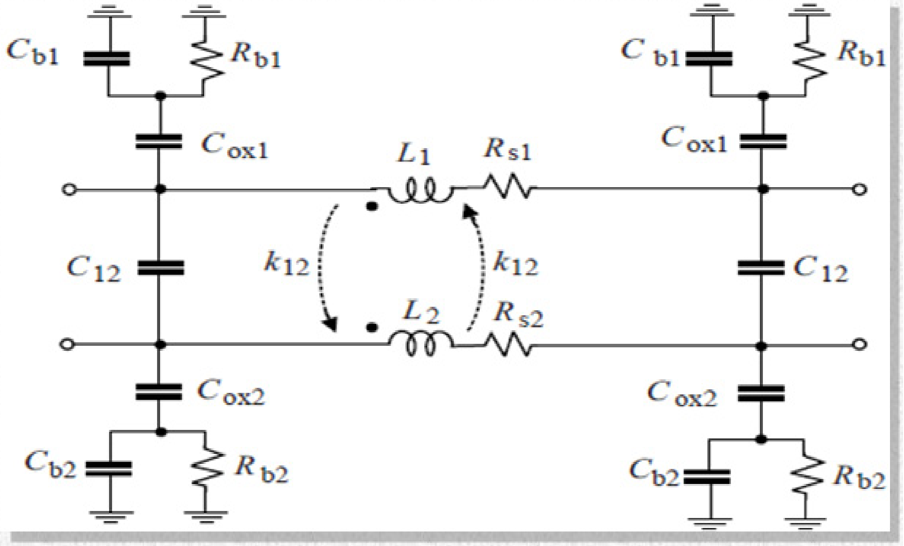
OUTLINE

INTRODUCTION OF THE SPIRAL INDUCTOR

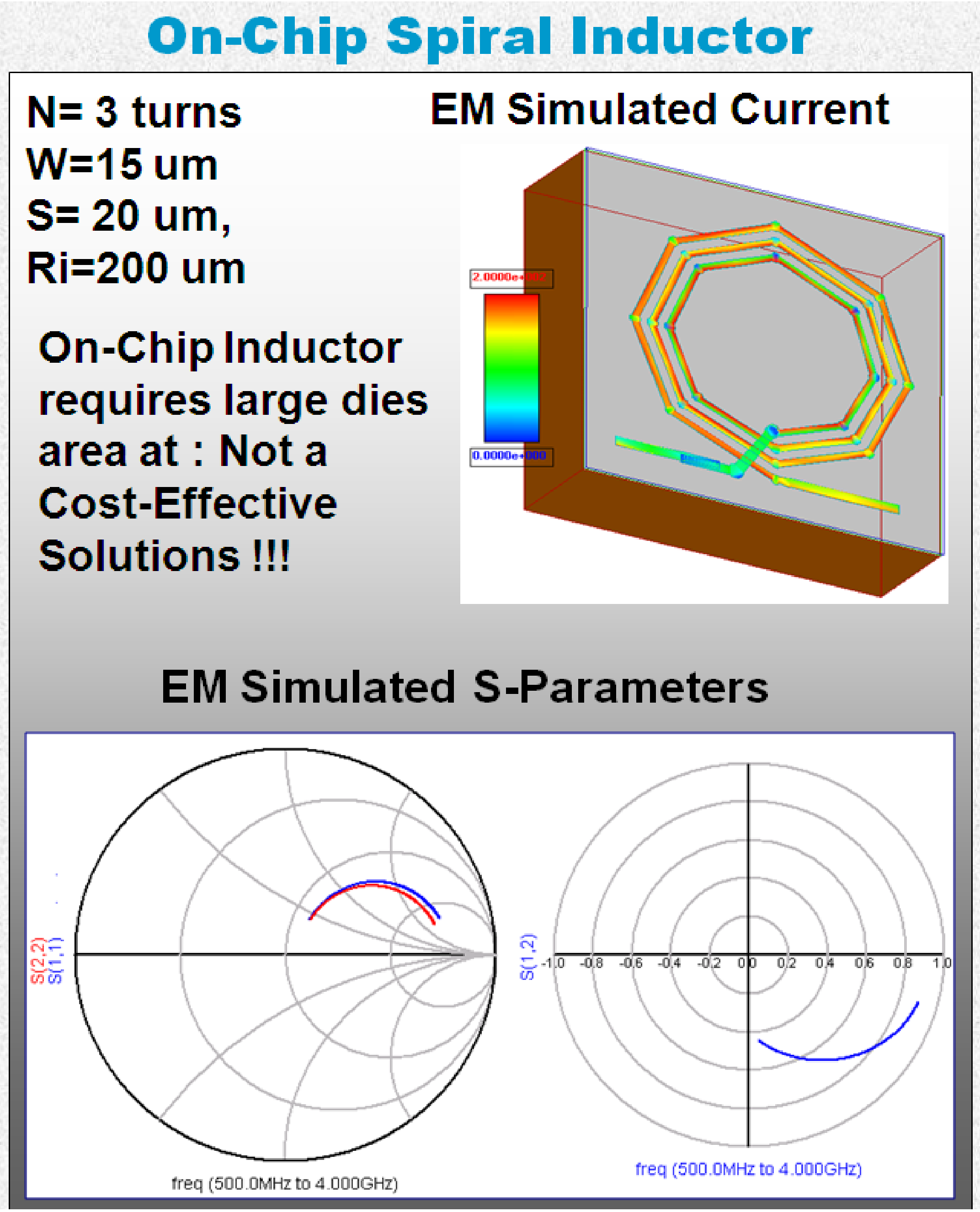
A typical sketch of spiral inductor



A lumped model of spiral inductor



PASSIVE SPIRAL INDUCTOR BEHAVIOUR



On-Chip Spiral Inductor

N= 3 turns
W=15 um
S= 20 um,
Ri=200 um

On-Chip Inductor requires large dies area at : Not a Cost-Effective Solutions !!!

EM Simulated Current

EM Simulated S-Parameters

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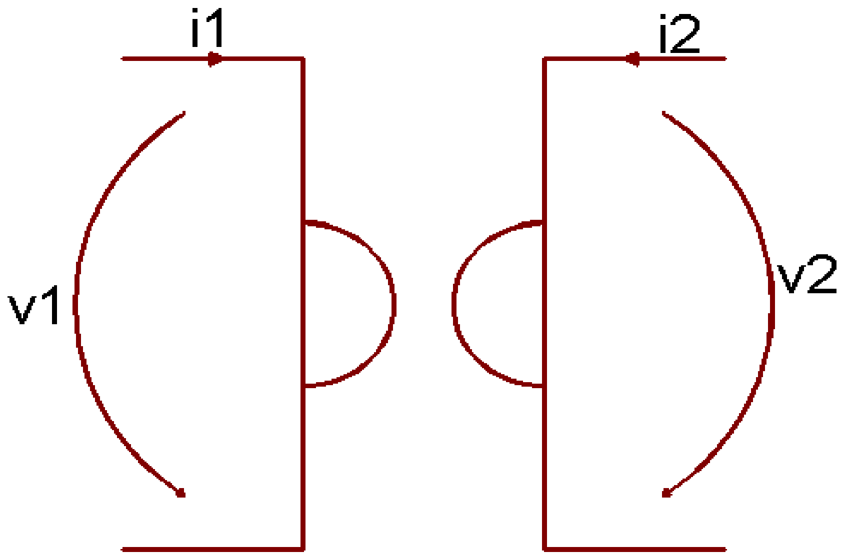
ACTIVE INDUCTOR USING GYRATOR

B. D. H. Tellegen of Philips Research Laboratory proposed a new 2-port network element, a Gyrator in 1948, which exhibits a immittance conversion property, needed to generate an synthesized active inductor.



$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} 0 & g \\ -g & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$$

Where 'g' is called gyration capacitance

An admittance Y connected to the secondary terminals is converted to its dual g^2/Y, this phenomena is called immittance conversion, C transforms into L, parallel tuned circuit into series tuned circuit

TUNABLE ACTIVE INDUCTOR BEHAVIOUR

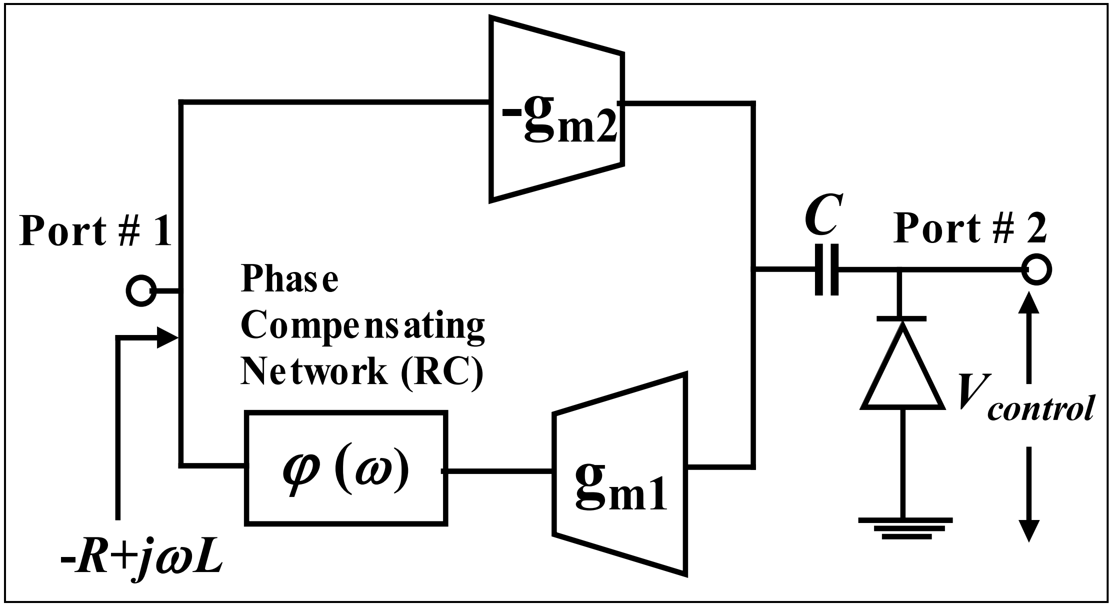
Tunable Active Inductor (TAI)

- ✓ **Integrable and Compact**
- ✓ **Cost-Effective**
- ✓ **Power-Efficient Solutions**

TAI: Design Challenges

- ✓ **High Power Consumption**
- ✓ **Noise Figure & Instability**
- ✓ **Low Dynamic Ranges**

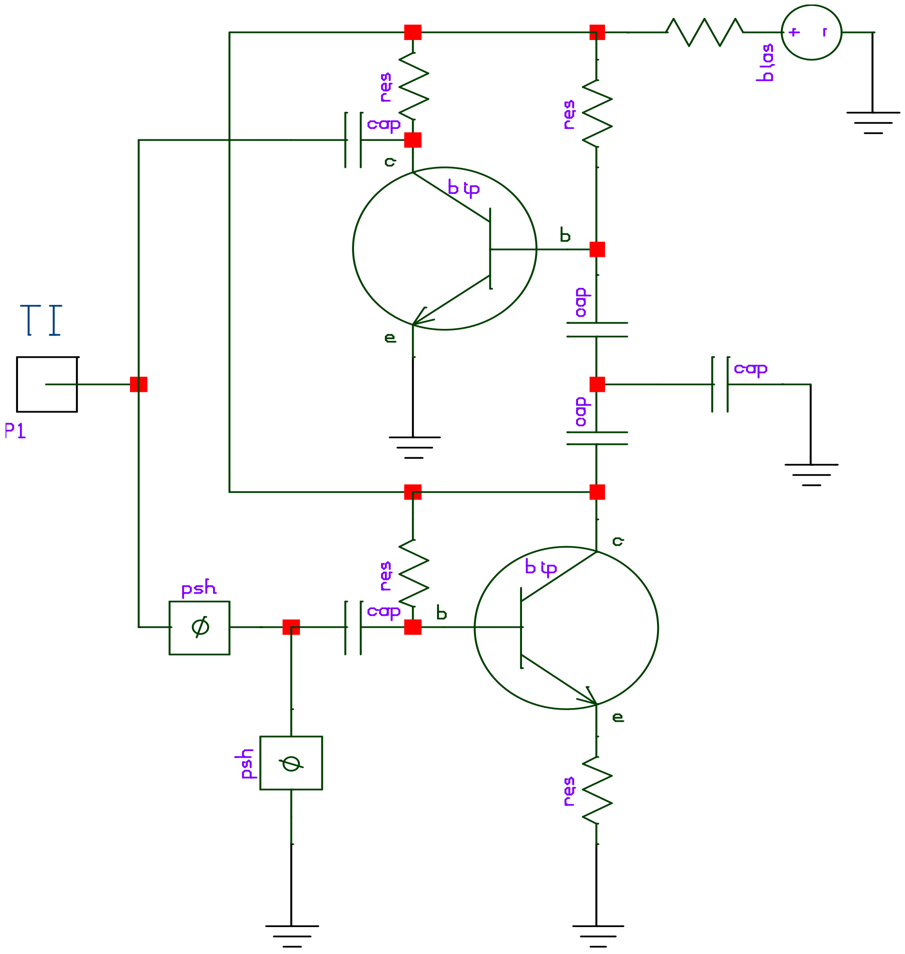
Tunable Active Inductor (TAI)



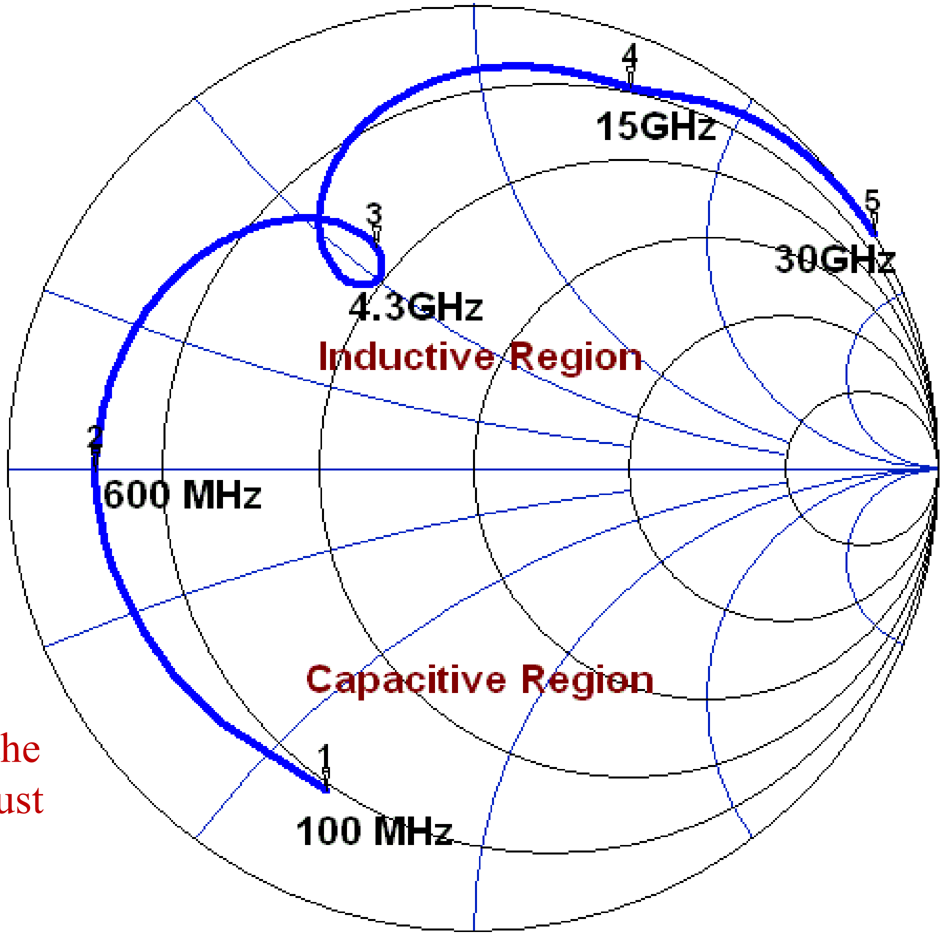
Phase shift network $\varphi(\omega)$ is required in TAI topology for suppressing the higher order modes and self oscillation

TUNABLE ACTIVE INDUCTOR BEHAVIOUR, cont’d.

Typical Schematic of Synthesized Inductor



Impedance Plot



Impedance plot reveals the inductive behavior of the circuit from 600MHz (#2) to 30GHz (#5). Care must be taken to avoid the encircling and crossing at 4.3GHz (#3), which limits the applications.

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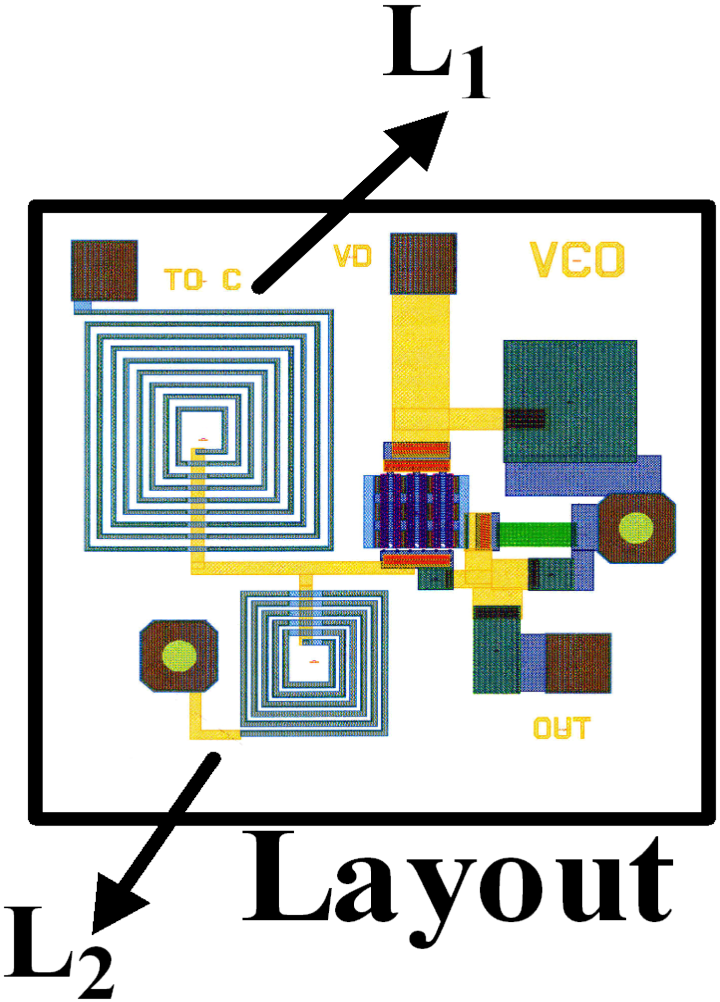
LAYOUT OF OSCILLATOR UISNG SPIRAL INDUCTOR

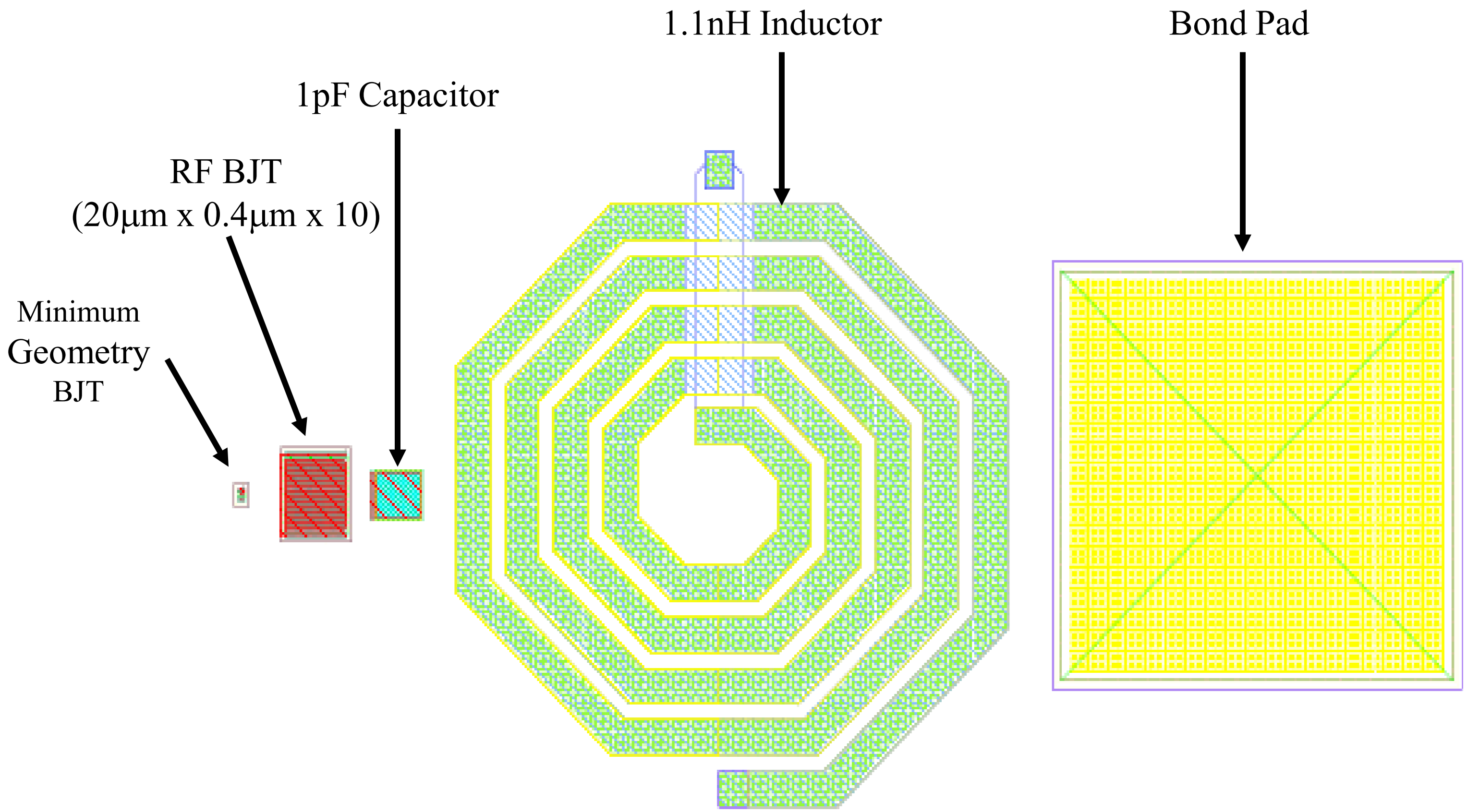
- **Why use an Active Inductor instead of an Spiral Inductor?**



Physical size of spiral inductor

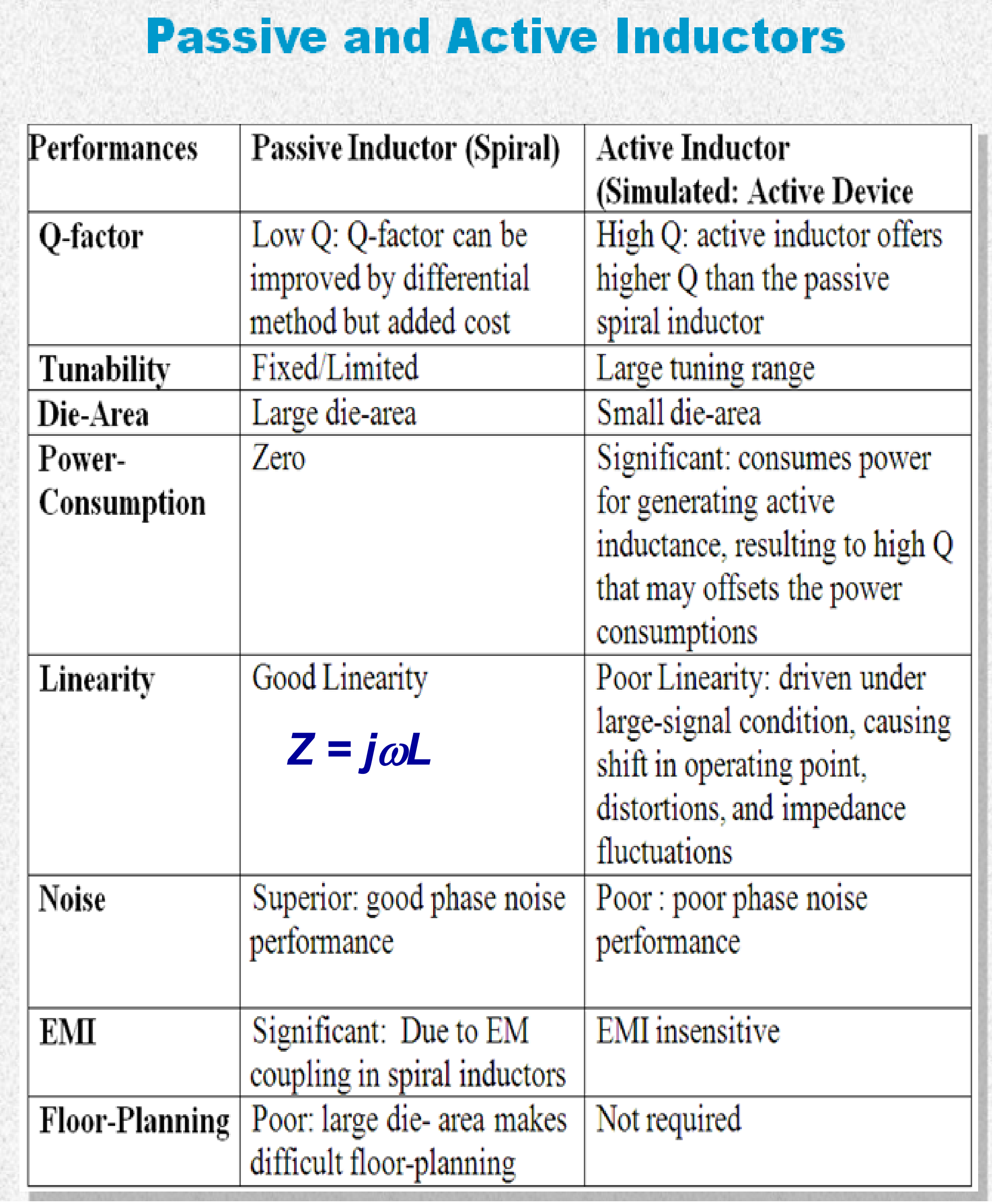
PHYSICAL SIZE OF SPIRAL INDUCTOR, cont'd.

Physical size of spiral inductor



Why we avoid the use of on-chip inductors!

COMPARISION: PASSIVE and ACTIVE INDUCTORS



Passive and Active Inductors

Performances	Passive Inductor (Spiral)	Active Inductor (Simulated: Active Device
Q-factor	Low Q: Q-factor can be improved by differential method but added cost	High Q: active inductor offers higher Q than the passive spiral inductor
Tunability	Fixed/Limited	Large tuning range
Die-Area	Large die-area	Small die-area
Power-Consumption	Zero	Significant: consumes power for generating active inductance, resulting to high Q that may offsets the power consumptions
Linearity	Good Linearity $Z = j\omega L$	Poor Linearity: driven under large-signal condition, causing shift in operating point, distortions, and impedance fluctuations
Noise	Superior: good phase noise performance	Poor : poor phase noise performance
EMI	Significant: Due to EM coupling in spiral inductors	EMI insensitive
Floor-Planning	Poor: large die- area makes difficult floor-planning	Not required

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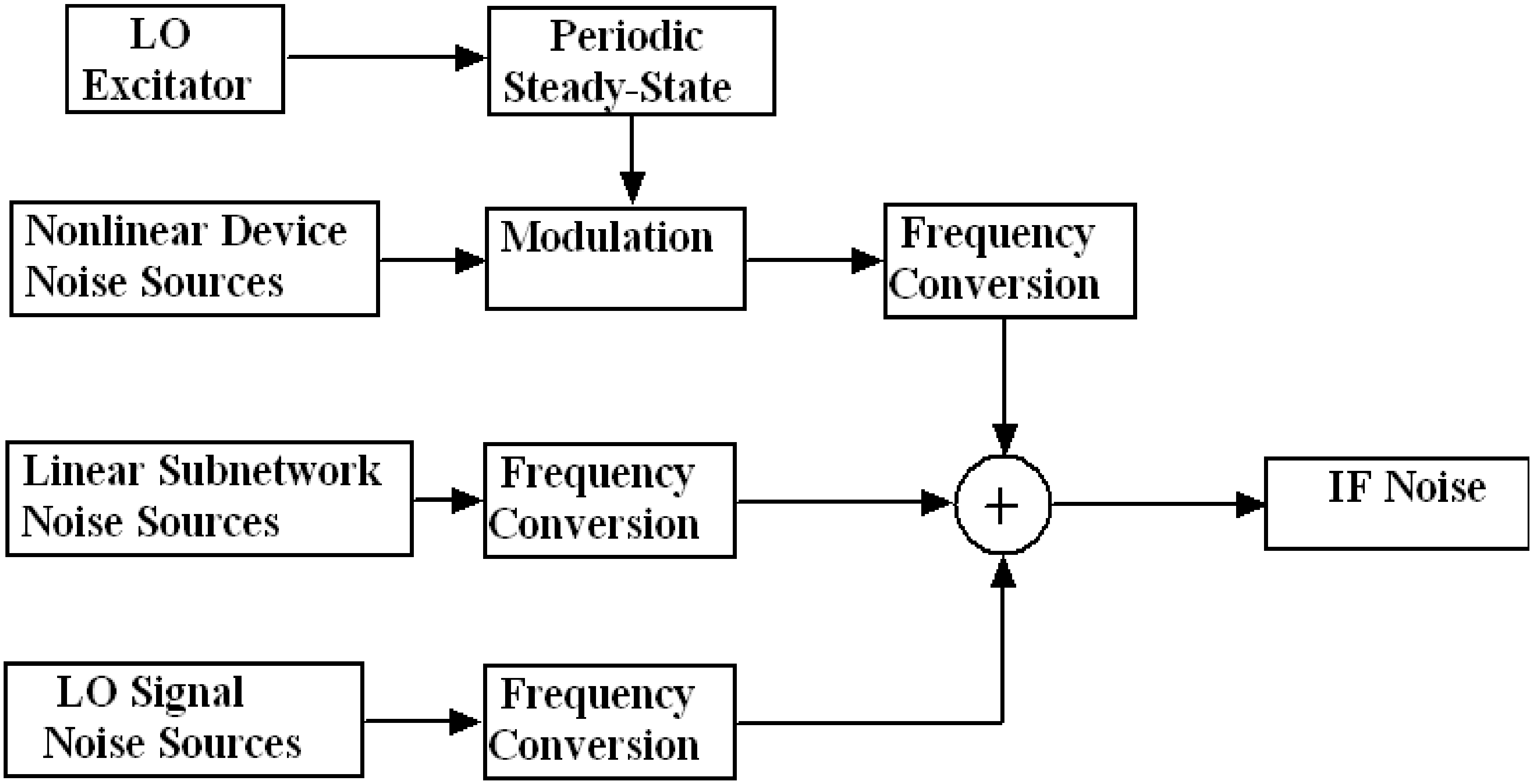
NOISE SOURCES IN THE OSCILLATOR

Noise sources of an oscillators being mixed on the carrier



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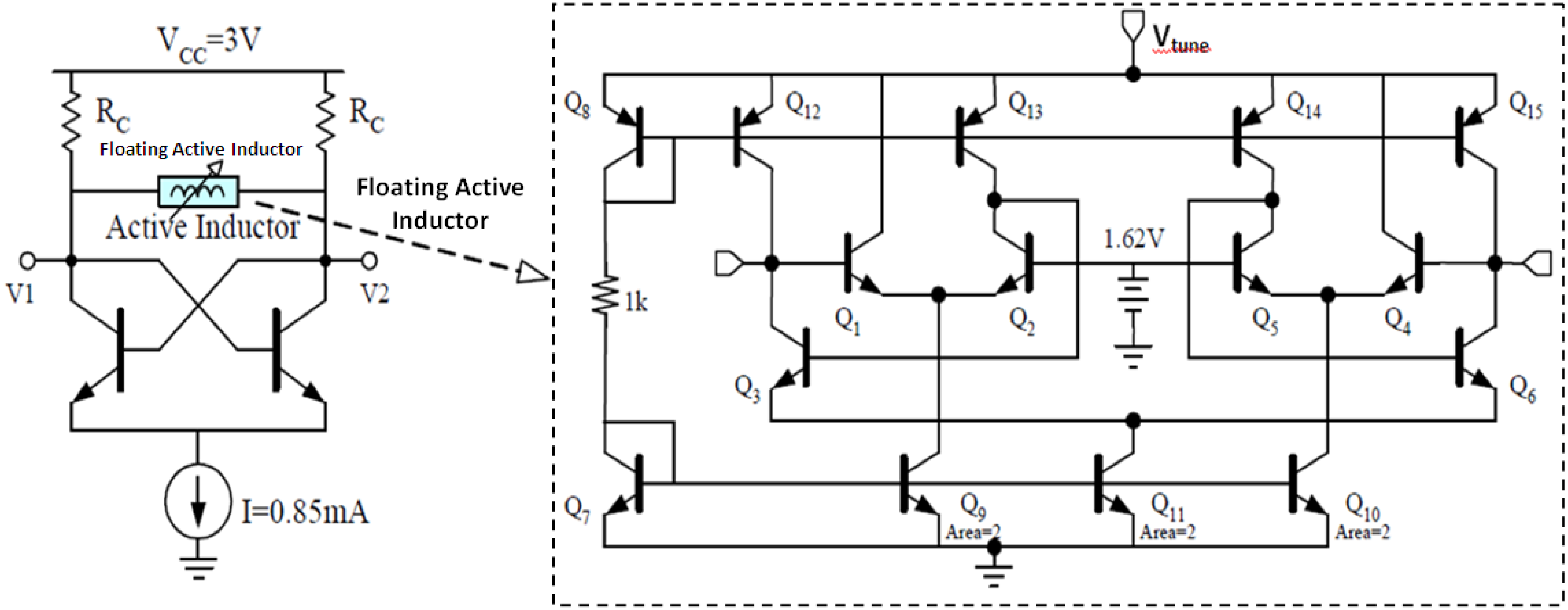
INTRODUCTION: ACTIVE INDUCTOR OSCILLATOR

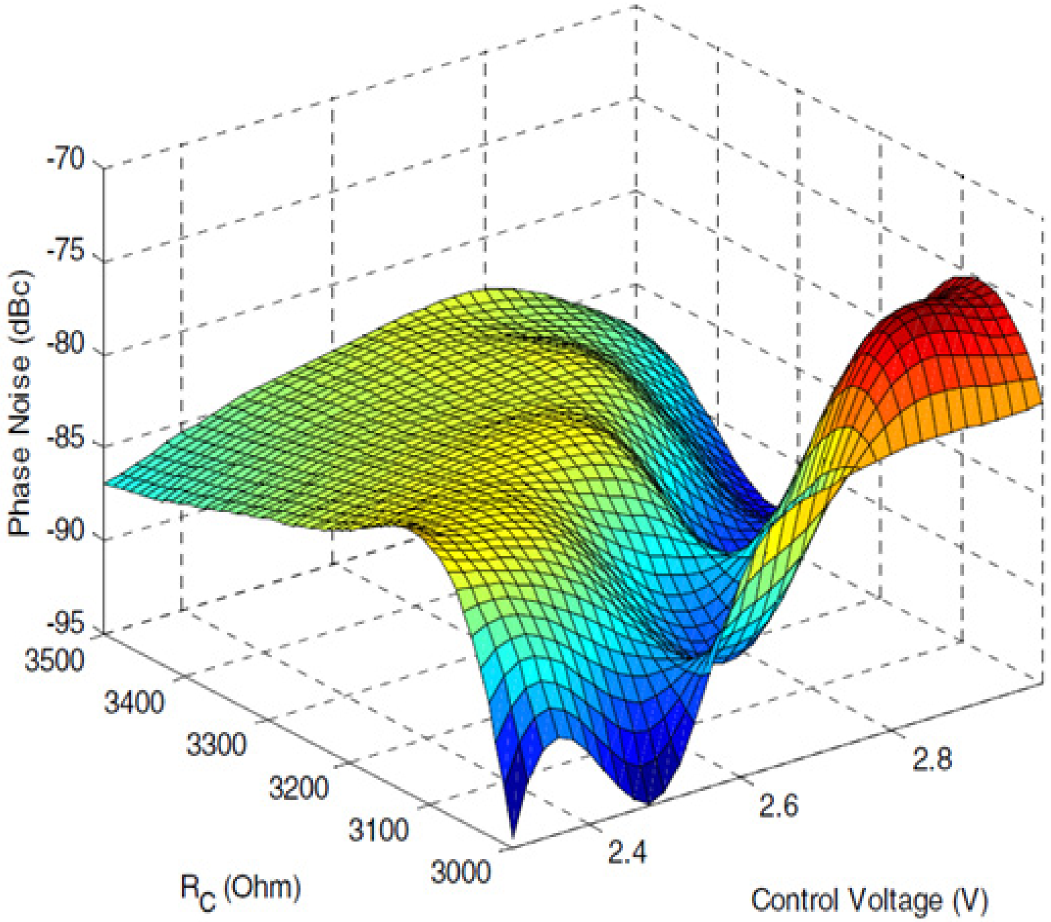
This Active Inductor Oscillator (AIO) includes a stable active inductor within a conventional integrated LC oscillator



ACTIVE INDUCTOR OSCILLATOR PHASE NOISE

Phase Noise Plots

Surface of phase noise @ 1MHz offset from the carrier



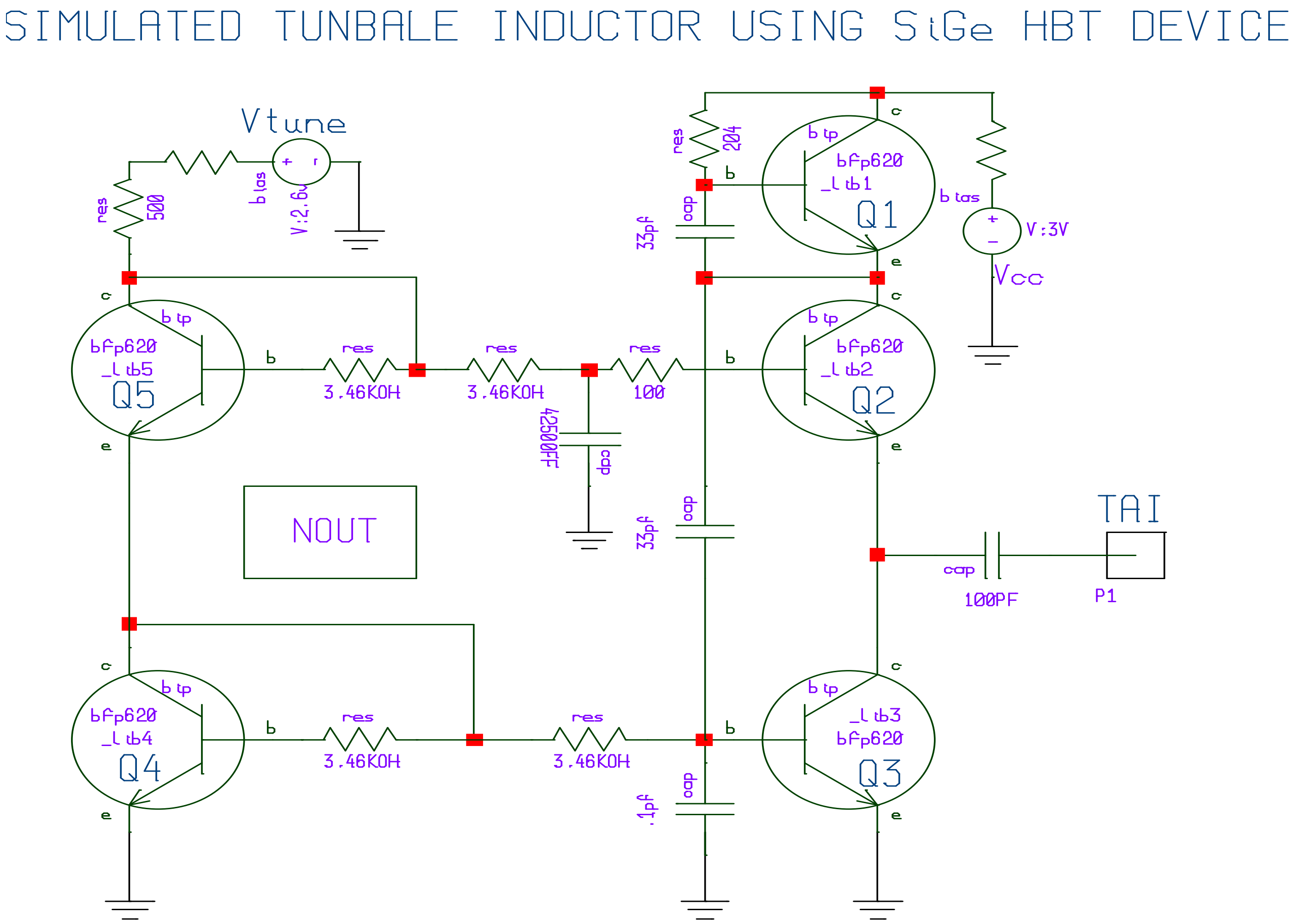
Advantages:

1. Broadband VCO Operation (Tuned L)
2. Multi-Band VCO Operation (Switched L)

Drawbacks:

1. DC Power Consumption
2. Poor Phase Noise Performances
3. Limited Large Signal Performances

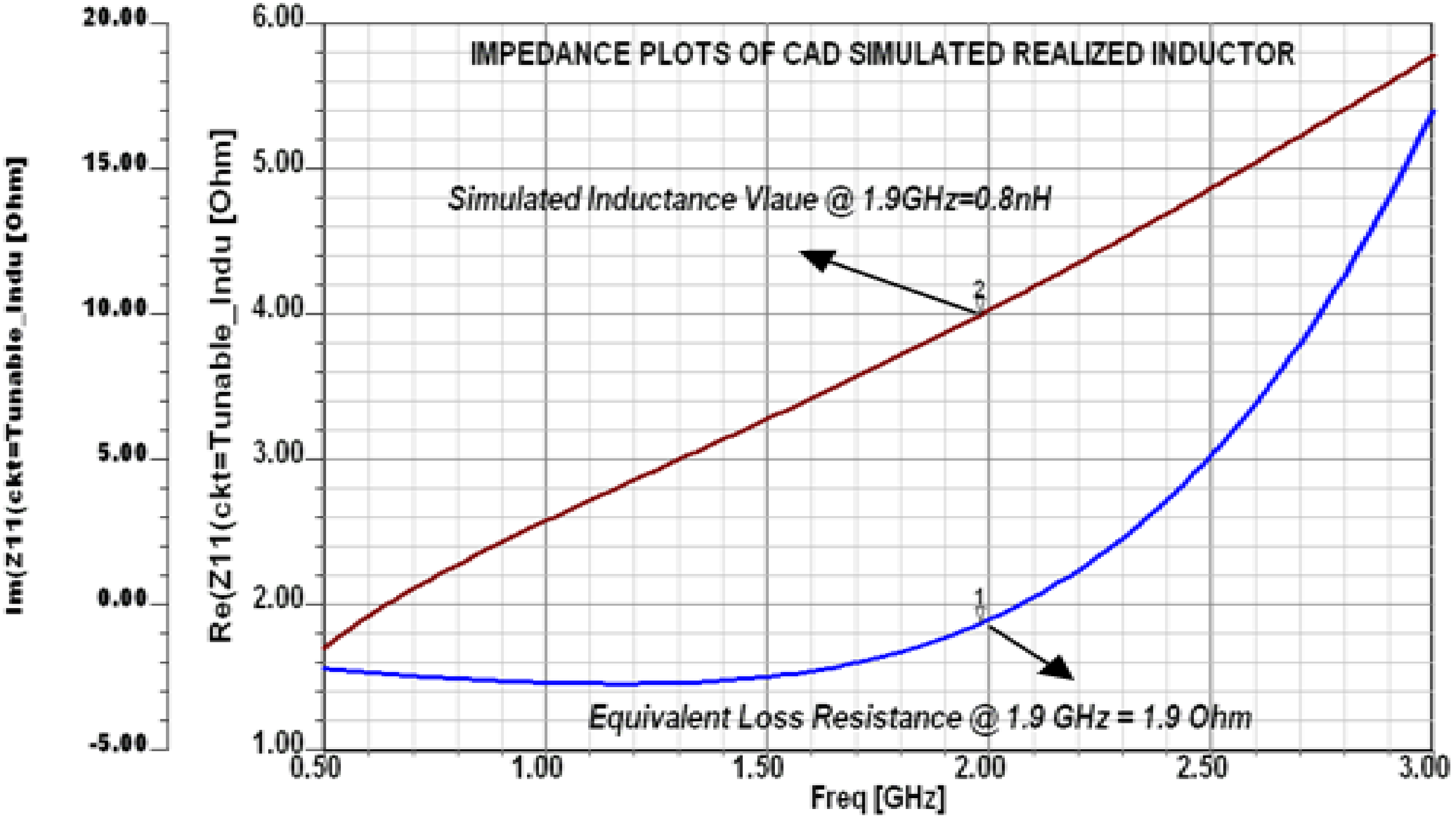
SYNTHESIZED INDUCTOR CIRCUITS



This Figure shows a schematic of a transistorized inductor using SiGe HBT (BFP 620) from Infineon . The reason for using a high cut-off frequency (ft=75 GHz) SiGe HBT transistor is to minimize the package parasitic effects and allow comparative evaluations of the 1.9GHz varactor-tuned and synthesized inductor-tuned LC oscillator using discrete components for experimental validations.

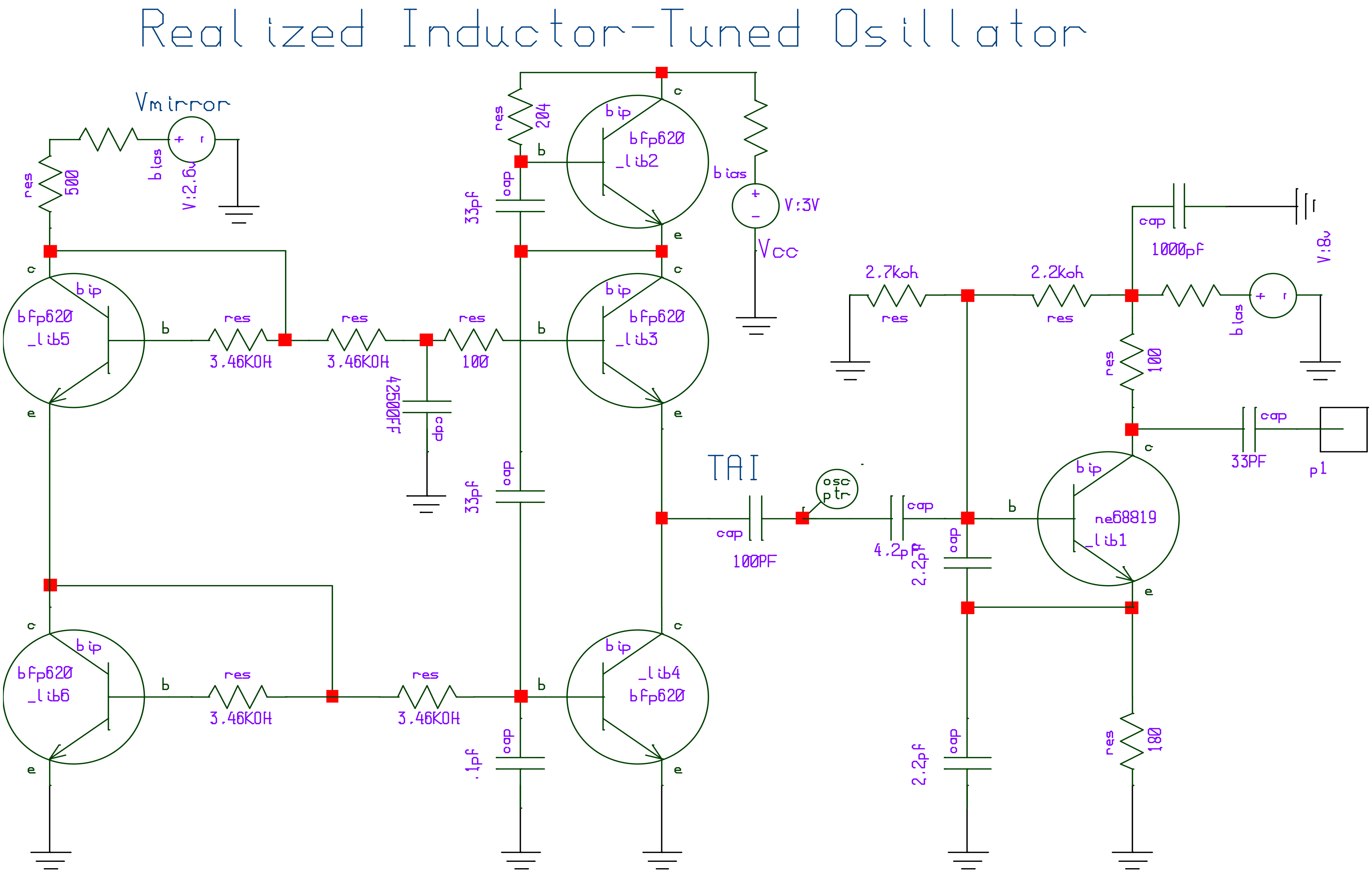
SYNTHESIZED TUNABLE INDUCTANCE , cont'd.

This Figure shows the typical plot of reactance and equivalent loss resistance of the synthesized inductor using high cut-off frequency SiGe HBTs.



As shown in Figure, the value of the realized inductance and associated equivalent loss resistance are 0.8nH and 1.9Ω at 1.9 GHz for the operating DC bias condition (3V, 1.8mA) and V_{tune} (2.5V). The operating DC bias and V_{tune} are adjusted in such a way that realized equivalent noise resistance must be positive to avoid the multi-mode oscillations caused by the regenerative effect (if the simulated loss resistance associated with realized inductor is negative in value).

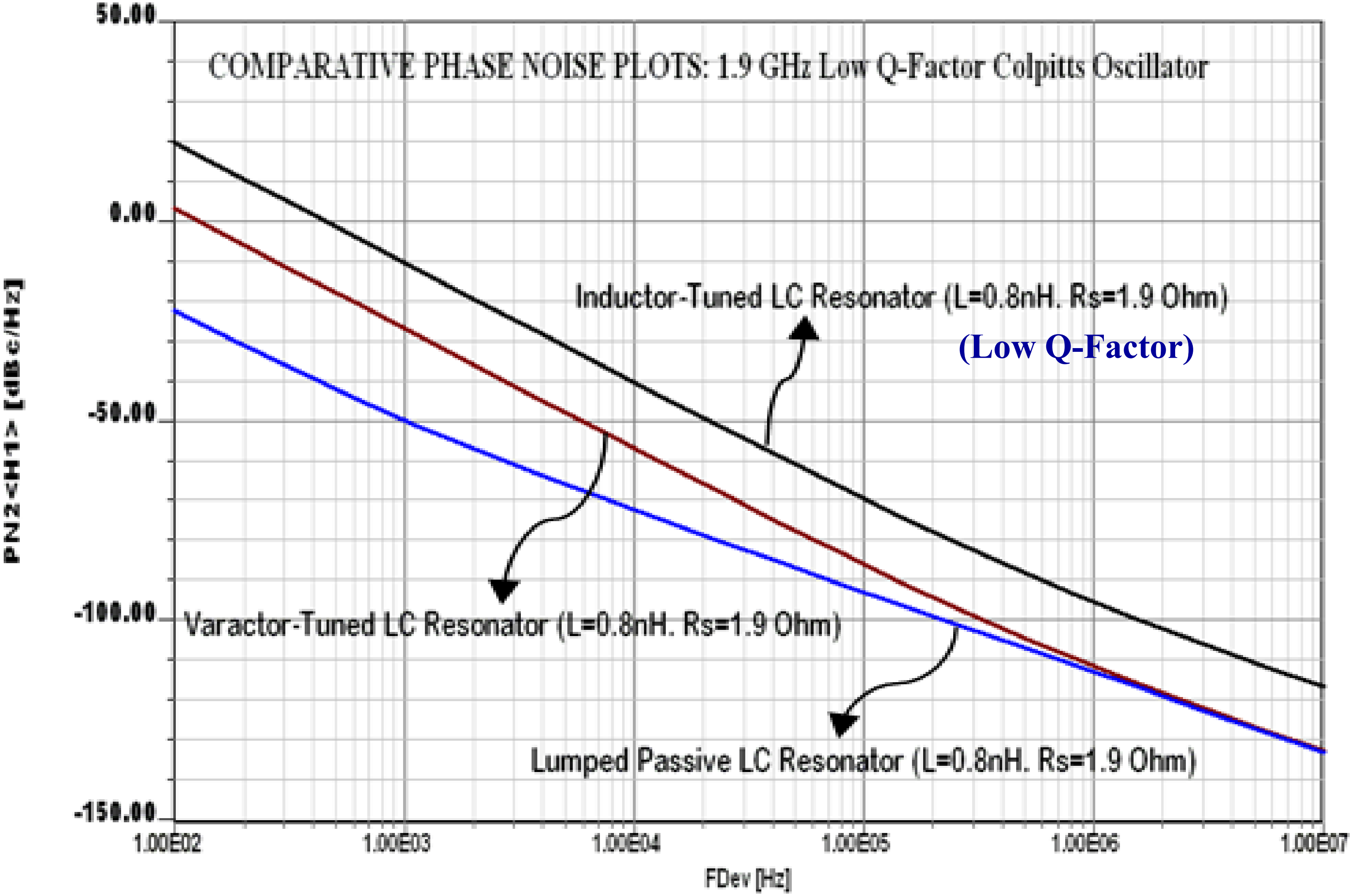
SYNTHESIZED TUNABLE INDUCTOR OSCILLATOR



Schematic of the Colpitts oscillator circuits using CAD simulated inductor (0.8nH, 1.9Ω)

OUTLINE

SYNTHESIZED INDUCTOR-TUNED OSCILLATOR PHASE NOISE

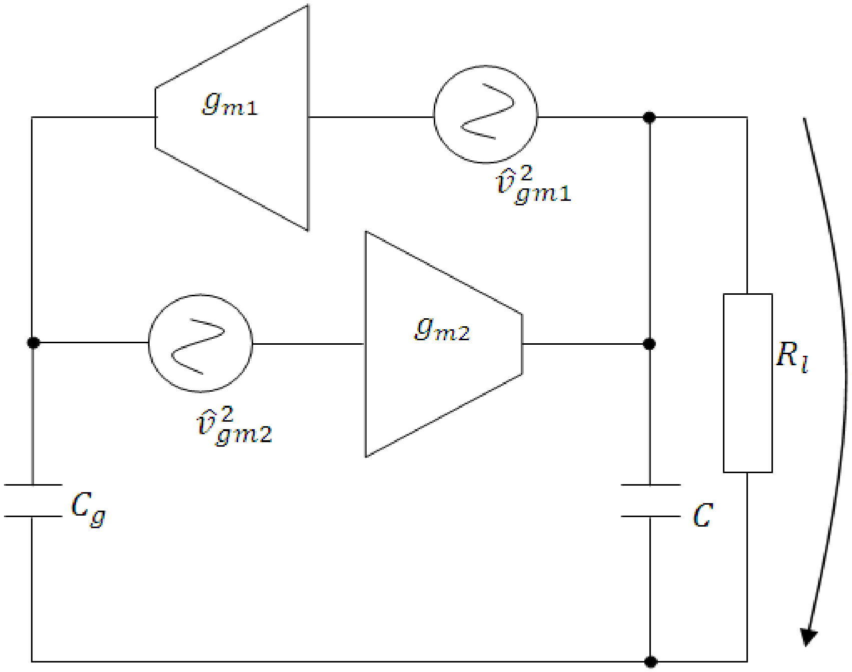


This plot shows the comparative phase noise plots for the LC Colpitts oscillator using the passive lumped LC resonator, the varactor-tuned passive lumped LC resonator and the synthesized inductor-tuned resonator network for identical inductance value and loss resistance (0.8nH with series loss resistance 1.9Ω).

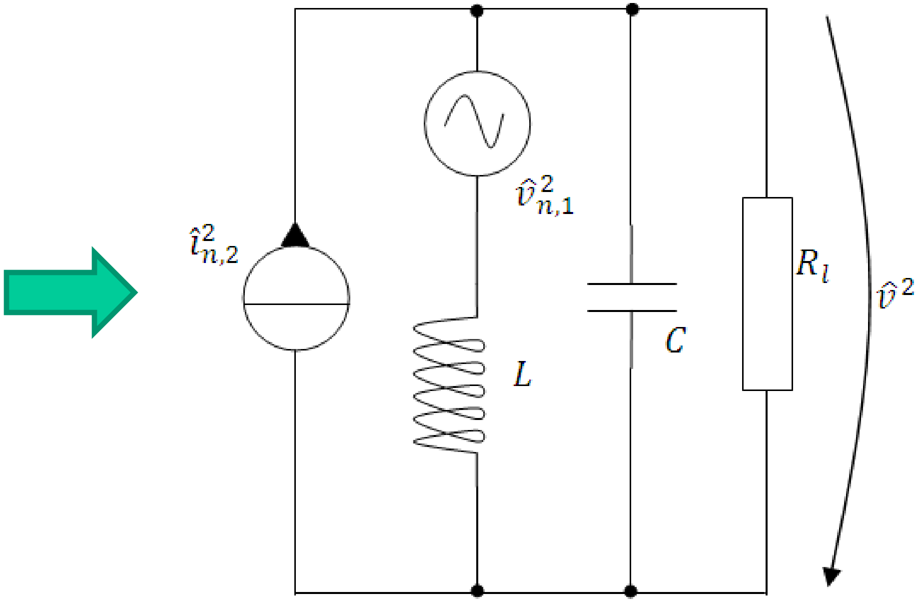
OUTLINE

ACTIVE INDUCTOR NOISE

Capacitor loaded gyrator based active inductor resonator with noise source



A simplified circuit of active inductor resonator with noise sources



$$\hat{v}^2_{n,1} = \hat{v}^2_{gm1} \cong \frac{4kT\lambda}{g_m}$$

$$\hat{\imath}^2_{n,2} = \hat{g}^2_{gm2}\hat{v}^2_{gm2} = 4kT\lambda g_m$$

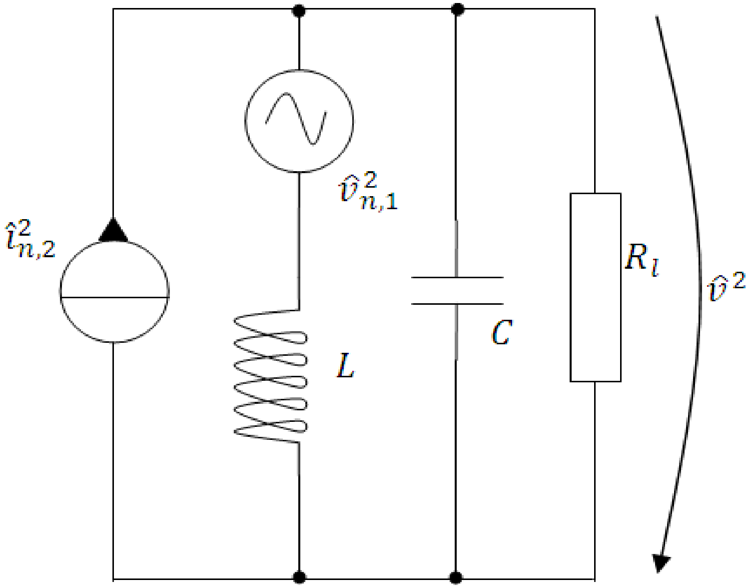
V_{gm1} and V_{gm2} are the equivalent noises from the transconductances of the Gyrators

ACTIVE INDUCTOR NOISE, cont'd.

Since

$$\hat{v}_n^2 \cong 4kTr_n|R|, \quad \hat{\imath}_n^2 \cong 4kTg_n|G|$$

where *R* and *G* are the negative resistance and conductance values, and the coefficients r_n and g_n are frequency dependent relative noise resistance and conductance (these give a comparative value of how much noise the active negative resistor produces compared to a passive resistor of the same value).



The total noise voltage spectral density of the active inductor resonator is

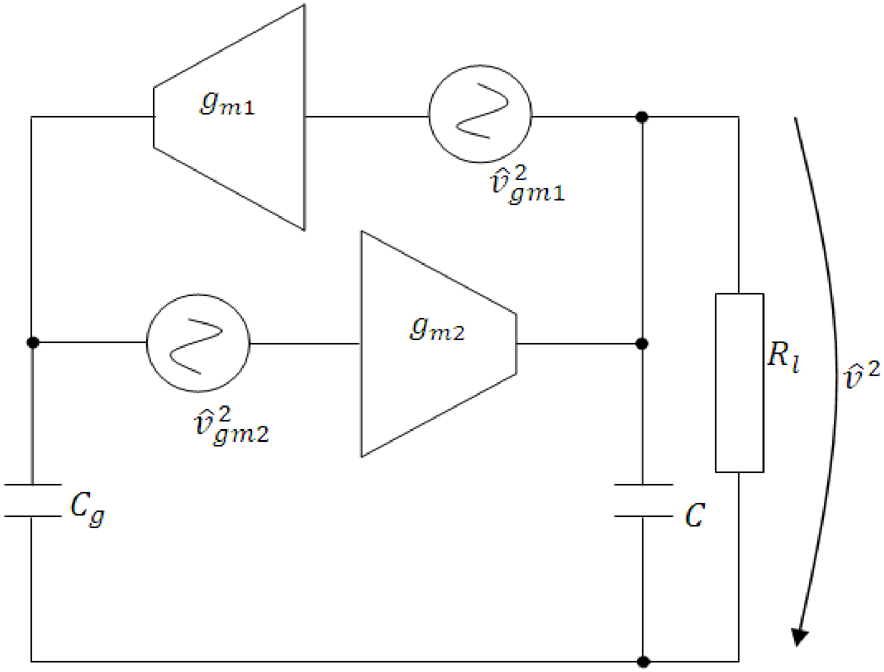
$$\hat{v}^2 = \frac{\hat{v}^2_{gm1} + \hat{v}^2_{gm2} g^2_{m2} \omega^2 L^2}{\omega^2 L^2 G_l^2 + (\omega^2 LC - 1)^2} \Rightarrow \hat{v}^2\big|_{\omega\to\omega_0} = Q_l^2\left(\hat{v}^2_{g_{m1}} + g^2_{m2}\hat{v}^2_{g_{m2}}\omega^2 L^2\right) = 4kT\lambda Q_l^2\left(\frac{1}{g_{m1}} + \frac{g_{m2}}{\omega_0^2 C^2}\right)$$

The time average Q-factor of active inductor is

$$\frac{\omega_0(1 + r_n, g_n)}{\lambda g_{m2}\left(\frac{1}{C} + \frac{1}{C_g}\right)}$$

ACTIVE INDUCTOR NOISE, cont'd.

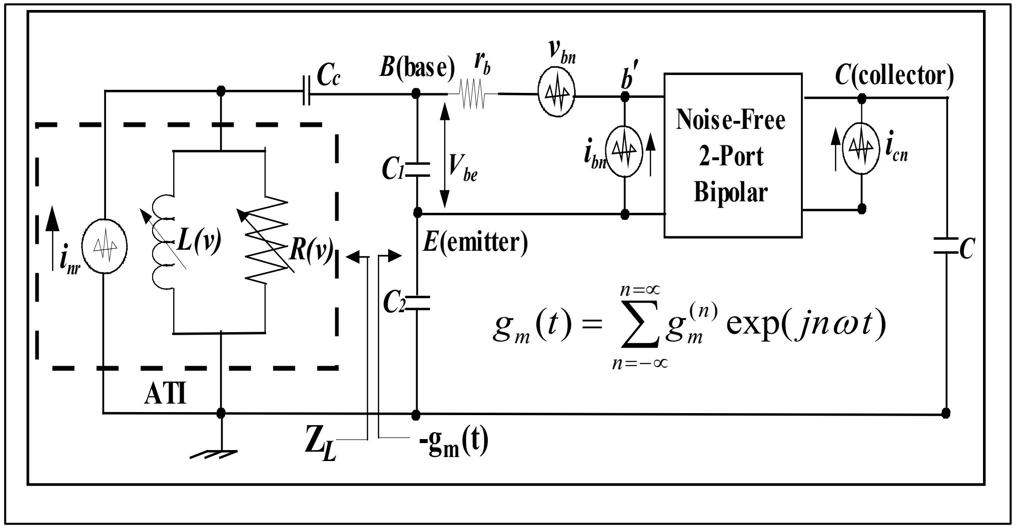
The time average normalized noise power of an active inductor resonator can be determined by



$$\overline{v^2} = \int_0^{\infty} \hat{v}^2 df = \frac{\hat{v}^2_{gm1}}{2\pi}\omega_o \int_0^{\infty} \frac{d\omega}{[(\omega^2 LC - 1)^2 + \omega^2 L^2 G_l^2]} + \frac{\hat{g}^2_{gm2}\hat{v}^2_{gm2}}{2\pi}\int_0^{\infty} \frac{\omega^2 L^2 d\omega}{[(\omega^2 LC - 1)^2 + \omega^2 L^2 G_l^2]}$$

$$\overline{v^2} \approx \frac{kT\lambda}{C} Q_l \left(\frac{g_{m2}}{g_{m1}}\right)^{1/2} \left[\left(\frac{C_g}{C}\right)^{1/2} + \left(\frac{C}{C_g}\right)^{1/2}\right] = \frac{kT\lambda}{C} Q_l \frac{\omega_O}{g_{m1}} (C + C_g)$$

ACTIVE INDUCTOR OSCILLATOR PHASE NOISE



The total noise voltage power within 1 Hz bandwidth can be described by

$$\left|\overline{e_n^2(\omega)}\right|_{\omega=\omega_0} = \overline{[e_n^2(\omega_0)]_{-gm1}} + \overline{[e_n^2(\omega_0)]_{-gm2}}$$

The first term is related to the active inductor noise due to the active inductor and the second term is related to negative resistance generative active device.

After some lengthy calculations and approximations, adding shot noise, flicker noise and the loss resistor, the equivalent expression of the phase noise is given by

$$\left|\overline{e_{gm2}^2(\omega)}\right|_{\omega=\omega_0} = [4kTR] + \left[\frac{4qI_{c0}g_{m2}^2 + \dfrac{4K_f I_b^{AF}}{\omega} g_{m2}^2}{\omega_0^2 C_1^2 [\omega_0^2 (\beta^+)^2 C_2^2 + g_{m2}^2 \dfrac{C_2^2}{C_1^2}]}\right]$$

$$g_{m2} = [Y_{21}^+]\left[\frac{C_1}{C_2}\right]^q$$

$$\beta^+ = \left[\frac{Y_{21}^+}{Y_{11}^+}\right]\left[\frac{C_1}{C_2}\right]^p$$

$$g_m(t) = \sum_{n=-\propto}^{n=\propto} g_m^{(n)} \exp(jn\omega t)$$

The values of p and q depend upon the drive level.

ACTIVE INDUCTOR OSCILLATOR PHASE NOISE

After some lengthy calculations and approximations, adding shot noise, flicker noise and the loss resistor, the equivalent expression of the phase noise is given by

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

$$k_0 = \frac{kTR}{\omega^2\,\omega_0^2 C_2^2 L_{active-inductor}^2 V_{cc}^2} \qquad k_1 = \frac{qI_c g_{m2}^2 + \frac{K_f I_b^{AF}}{4\omega} g_{m2}^2}{\omega^2\,\omega_0^4 L_{active-inductor}^2 V_{cc}^2} \qquad k_2 = \omega_0^4 (\beta^+)^2 \qquad k_3 = \omega_0^2 g_{m2}^2$$

$$k = \frac{k_3}{k_2 C_2^2} \qquad L_{active-inductor} = \frac{C_1 C_2}{[C_1 + C_2] g_{m1}^2} \qquad g_m(t) = \sum_{n=-\infty}^{n=\infty} g_m^{(n)} \exp(jn\omega t)$$

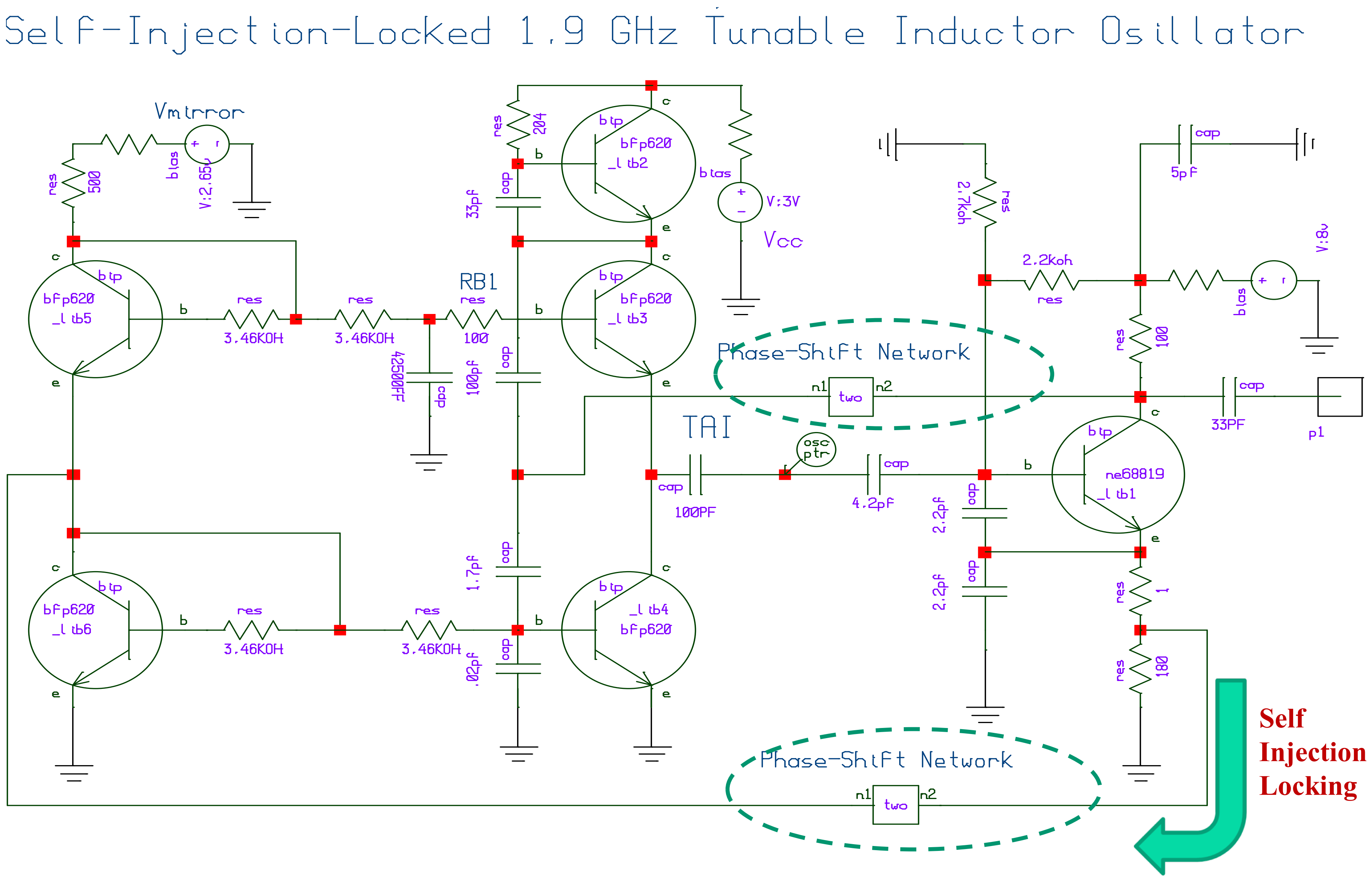
$$g_{m2} = \left[Y_{21}^+\right]\left[\frac{C_1}{C_2}\right]^q \qquad \beta^+ = \left[\frac{Y_{21}^+}{Y_{11}^+}\right]\left[\frac{C_1}{C_2}\right]^p \qquad y = \frac{C_1}{C_2}$$

The values of p and q depend upon the drive level.

OUTLINE

- What is an Oscillator
- Oscillator Basics
- Typical Microwave Oscillator (Colpitts Oscillator)
- Oscillator Transistors Large Signal Operations
- Frequency Variation of the Oscillator
- Introduction of the Spiral Inductor
- Introducing the Gyrator
- Surface area of the Passive Inductor
- Noise sources in the Oscillator
- Active Inductor Based Oscillator
- Active Inductor Oscillator Phase Noise
- Calculation of the Active Inductor Noise
- Validation Circuits
- Summary

ATI OSCILLATOR VALIDATION EXAMPLE

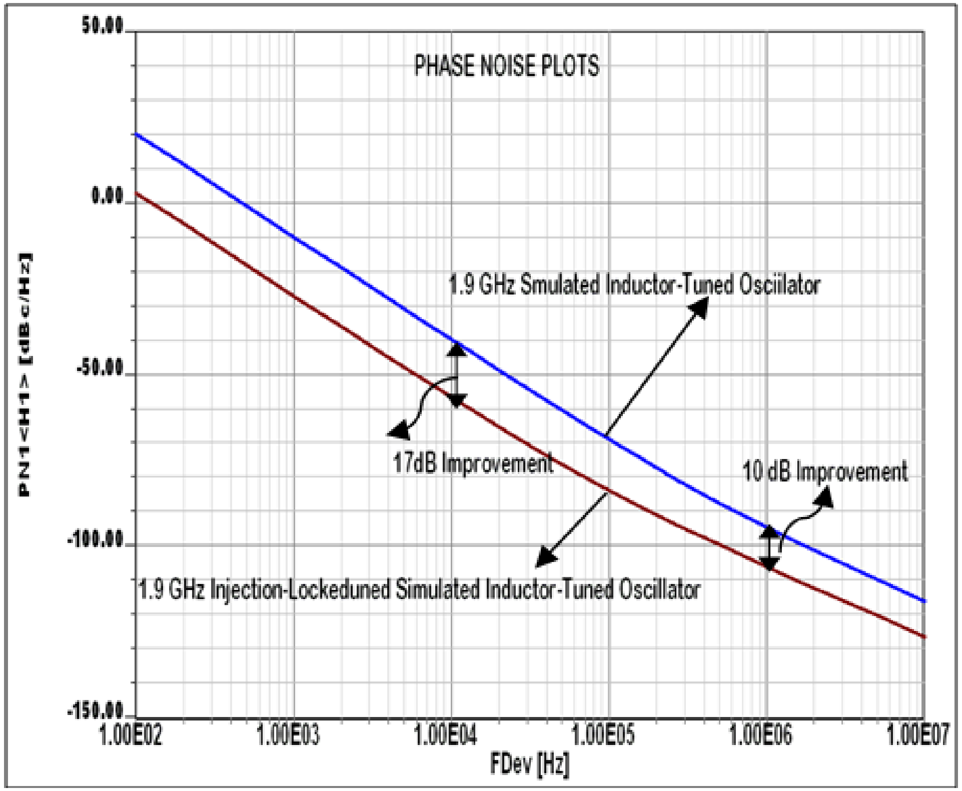


Self Injection Locking

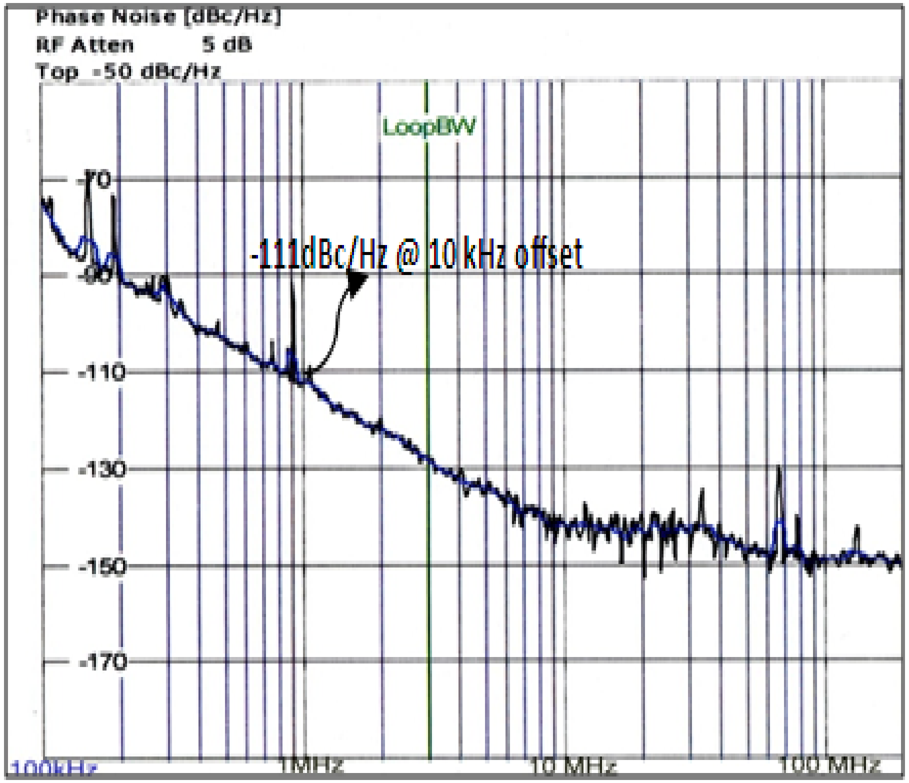
This Figure shows the schematic of self-injection-locked inductor-tuned Colpitts oscillator realized by incorporating phase shifter network in the feedback path, which improves the 1/*f* noise, including linearization of the large signal drive-level characteristics of the synthesized inductor circuits.

ACTIVE INDUCTOR OSCILLATOR PHASE NOISE PLOTS

CAD simulated phase noise plot



Measured phase noise plot (Injection-Locked)



Figures show the CAD simulated and measured phase noise plot of injection locked 1.9 GHz TAI, which shows the 8-10 dB improvement in the phase noise performances.

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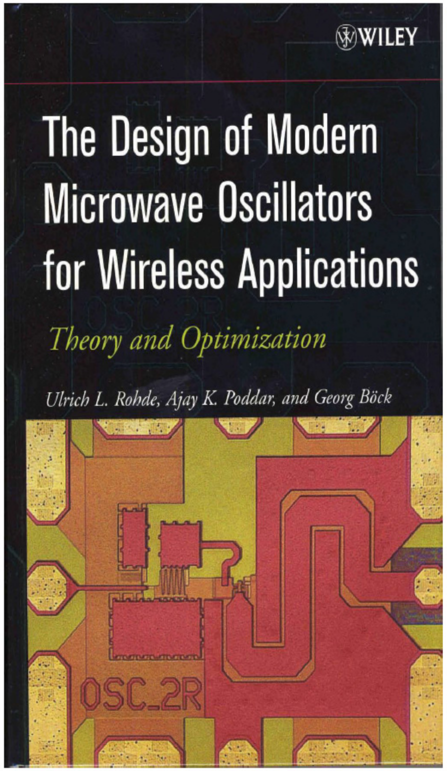
SUMMARY

- ✓ **This research work demonstrates the state-of-the-art in designing tunable inductor based VCO**
- ✓ **Use of TAI resonator is relatively new and its application to replace tuning diodes in VCOs have recently begun to be explored**
- ✓ **Closed form noise models for TAI VCOs involved complex mathematical treatment due to the convergence problems at large drive-level**
- ✓ **Limitation in the dynamic range may restricts the applications in high performance tunable filters, nevertheless by incorporating my novel techniques one can improve the dynamic range up to an accepted limit**

SUMMARY

- ✓ The behavior of the active inductor oscillator was studied and verified with practical examples.
- ✓ Intensive studies were conducted to find the optimum configuration for the constant phase noise over the tuning range, and a US Patent application was filed.
- ✓ The extension of the research work is to increase the operating frequency by employing injection mode coupling in monolithic IC technology.
- ✓ I expect to see continued research in this field and the use of TAI based transformers for RF circuit like the oscillator

REFERENCES: FURTHER READINGS



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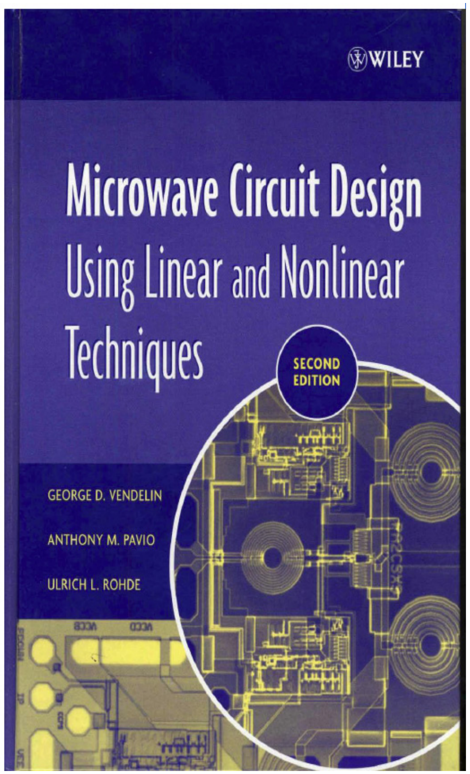
The Design of Modern Microwave Oscillators for Wireless Applications

Theory and Optimization

Ulrich L. Rohde, Ajay K. Poddar, and Georg Böck



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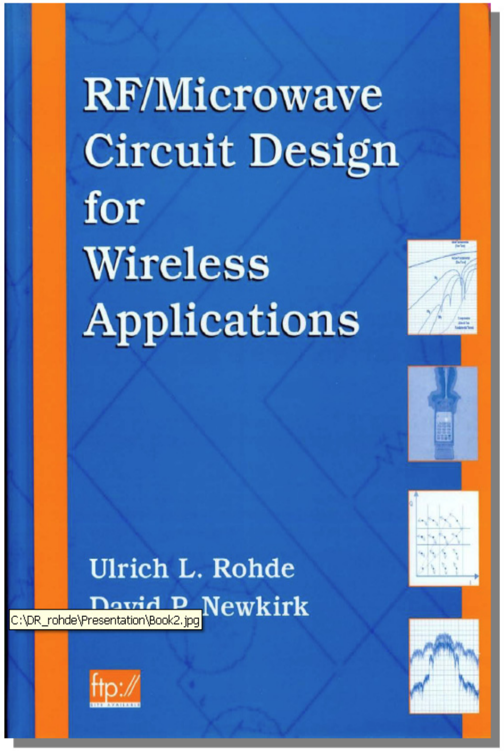

RF/Microwave Circuit Design for Wireless Applications

Ulrich L. Rohde

David P. Newkirk

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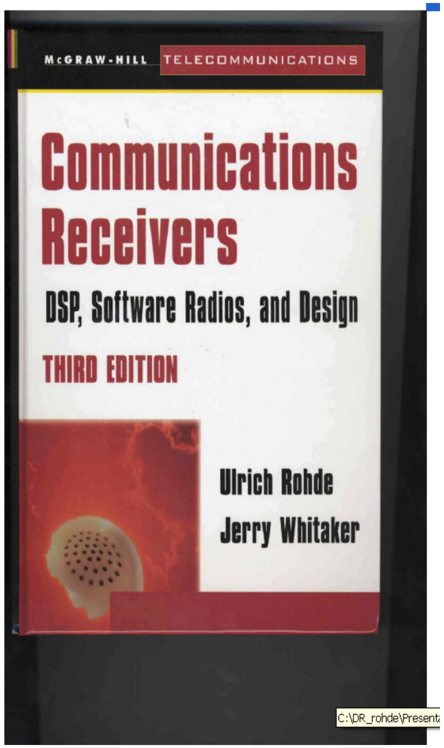

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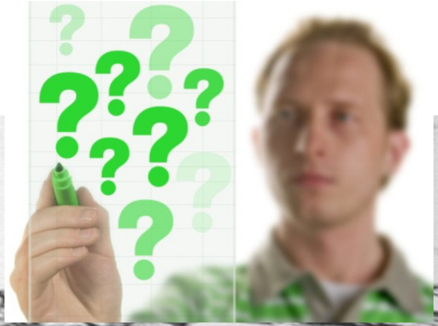

QUESTIONS?