ECE 521 Lecture #17 Nov. 16, 2016

Note Title 11/16/2016

HW # 4 part 2 Due by Thu 5pm

Project proposals Due Monday in class

Exam Monday Nov. 21 2-3:50pm

more on it later

HW # 3 - Part 1 graded handed back

## BJT Colpitts oscillator

## Asymptotic Waveform Evaluation (AWE)

$$F(s) = \underline{m_0} + \underline{m_1} s + \underline{m_2} s^2 + - - - m_n s^n + -$$

moments

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## General Method

$$(G + sC)x = b$$
$$y = \ell^T x$$

$$\underline{x} = \underline{m_0} + \underline{m_1} s + \underline{m_2} s^2 + -$$

Impulse response $b = 1$

$$(G + sC)(m_0 + m_1 s + m_2 s^2 + - - -) = b$$

$$G m_0 = b$$

$$(G m_1 + C m_0) = 0$$

$$\vdots$$

$$(G m_i + C m_{i-1}) = 0$$

Solve for $m_0$ by LU Factoring G and doing forward/back solves

$$Gm_i = -Cm_{i-1}$$

$m_i$ can be determined by forward/back solves

$$m_0 = G^{-1}b$$

$$m_1 = -G^{-1}CG^{-1}b$$

$$\vdots$$

$$m_i = (G^{-1})^{i+1}C^{i}\,b$$

$(G^{-1})^{i}$ can be very ill conditioned

AWE is limited to about 10 poles because of numerical ill conditioning

A robust method is PVL (Padé via Lanczos)

(paper posted on website)

## Problem with Padé approximation (unstable reduced systems)

$$H(s) = \frac{K_1}{s-p_1} + \frac{K_2}{s-p_2} \quad ; \quad H_{0,1} = \frac{K}{s-p}$$

$$= \frac{-K_1}{p_1}\,\frac{1}{1-\frac{s}{p_1}} + \frac{-K_2}{p_2}\,\frac{1}{1-\frac{s}{p_2}}$$

$$= \frac{-K_1}{p_1}\left[1 + \frac{s}{p_1} + \frac{s^2}{p_1^2} + \cdots\right] - \frac{K_2}{p_2}\left[1 + \frac{s}{p_2} + \frac{s^2}{p_2^2} + \right]$$

$$H_{0,1}(s) = \frac{K}{s-p} = \frac{-K}{p}\left[1 + \frac{s}{p} + \frac{s}{p^2} + \cdots\right]$$

$$\left.\begin{aligned} \frac{K}{p} &= \frac{K_1}{p_1} + \frac{K_2}{p_2} \\ \frac{K}{p^2} &= \frac{K_1}{p_1^2} + \frac{K_2}{p_2^2} \end{aligned}\right\} \Rightarrow p = \frac{\frac{K_1}{p_1} + \frac{K_2}{p_2}}{\frac{K_1}{p_1^2} + \frac{K_2}{p_2^2}}$$

Suppose $K_1 = 3,\ K_2 = -8,\ p_1 = -1,\ p_2 = -2$

$$p = \left[\left(3/{-1}\right) + \left(\frac{-8}{-2}\right)\right] \Big/ \left(\frac{3}{1} + \frac{-8}{4}\right) = 1$$

**Exam** closed book/"closed" notes

2-page of notes 8½" x 11" paper

Use the sample exam as a guide

Topics: → Nodal or MNA Stamps

→ Solution of nonlinear eqns

(Newton method)

nonlinear component → companion network model

$$f(x) = 0$$

$$J x^{k+1} = J x^{k} - f(x^{k})$$

until convergence

Stamping of nonlinear elements

→ Transient analysis

- given an integration method of order k, step p

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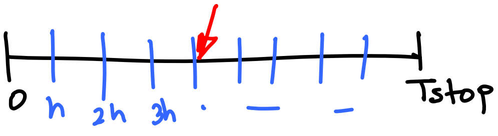
- Exactness constraints
- Local Error
- Stability of the method & regions of absolute stability

Application to circuits:

- Companion network at timepoint $t_n$

linear/nonlinear component



$$\dot{x}_n = \underline{\alpha} x_n + \underline{\beta}$$

implicit method

inductors, capacitors → Linear

nonlinear capacitors (charge based formulation)

# Simulation of Radio Frequency Integrated Circuits

**Based on:**

**“Computer-Aided Circuit Analysis Tools for RFIC Simulation: Algorithms, Features, and Limitations,”** ***IEEE Trans. CAS-II*****, April 2000.**

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## Outline

- **Introduction**
- **Analyses required for RF circuits**
- **SPICE analyses and limitations**
- **Algorithms for RF simulation**
  - Time-domain methods
  - Harmonic-balance method
  - Mixed time-frequency methods
  - Envelope method
  - Linear time varying analysis
- **RF noise**
- **Commercial tools**

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## Introduction

- **RF blocks are a big challenge in the design process**
- **Typical blocks that are analyzed**
  - Amplifiers
  - Mixers
  - Oscillators, Voltage Controlled Oscillators (VCOs)
  - Phase-Locked Loops (PLLs)
  - Filters (CT, SC, SAW)
- **SPICE is not adequate for circuit level analysis of most RF blocks**
- **Lack of computer-aided analysis tools aggravates design problems**

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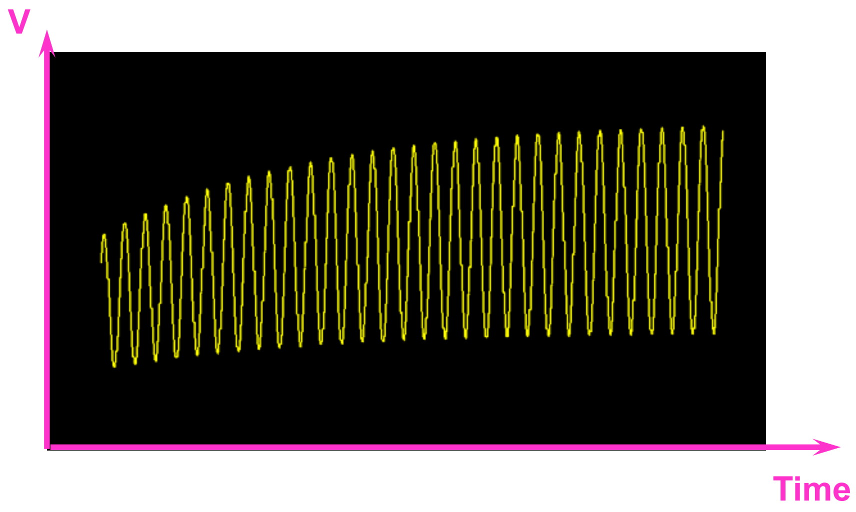
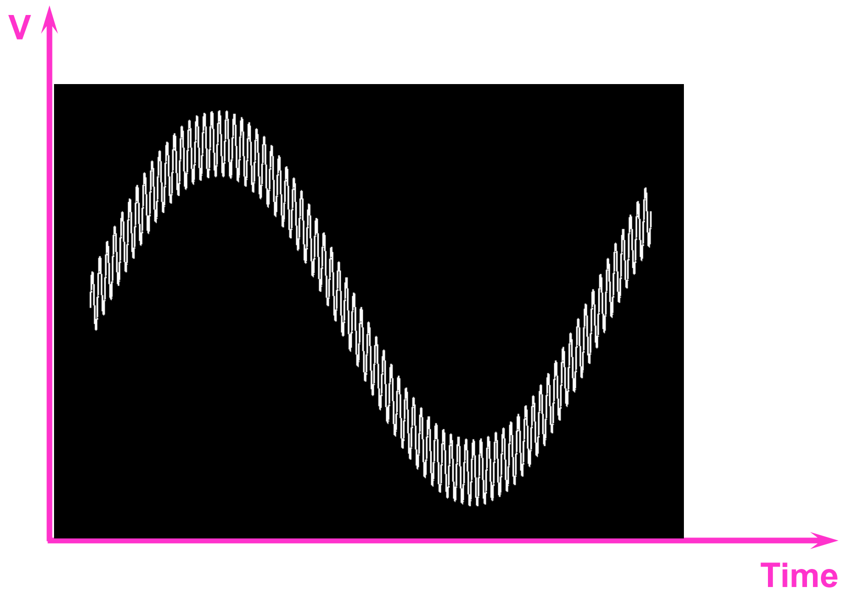
## Analyses Required for RF Circuits

- **Rapid simulation of the periodic or quasi-periodic steady state**
- **Accurate simulation of harmonic and intermodulation distortion**
- **Simulation of noise up/down conversion due to circuit nonlinearities**
- **Phase noise/jitter simulation**
- **Simulation of oscillator turn-on transient**
- **Simulation of the capture process of PLLs**
- **Distributed element simulation**

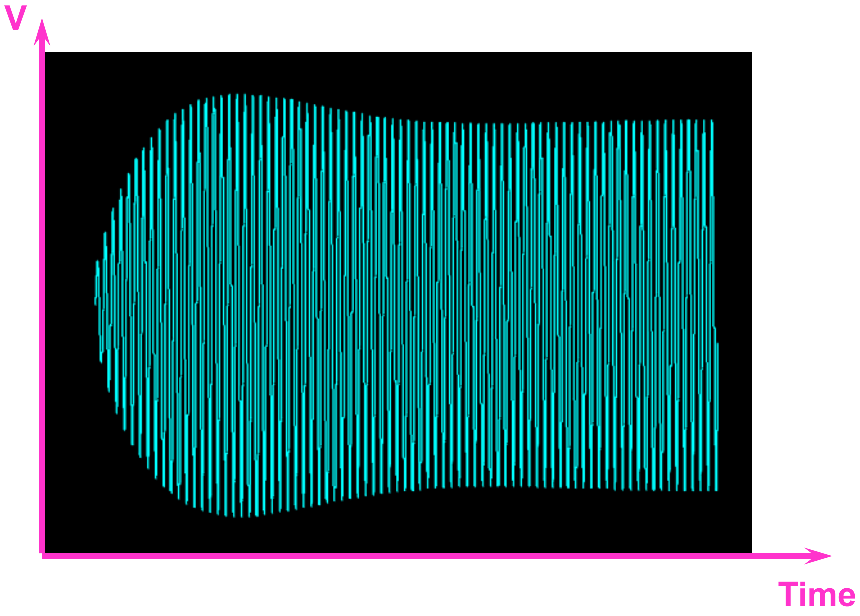
## RF Amplifier Periodic Steady State



## Mixer Quasi-Periodic Steady State



## Oscillator Turn-On and Steady State



## SPICE Analyses and Applications

- **DC**
  - – .op, .dc
  - – Dc operating point, dc transfer curves
  - – Can be used for all circuits
- **Small-signal AC**
  - – .ac, .noise, .disto
  - – Frequency response of linearized circuits
  - – Can be used for amplifiers

## SPICE Analyses and Applications

- **Transient**
  - .tran, .four
  - Large-signal time-domain analysis
  - Can be used for
    - Amplifiers
    - Oscillators
    - Mixers
    - PLLs
    - A/D, D/A converters

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## SPICE Limitations

- **Noise analysis at a dc operating point**
  - Cannot simulate noise mixing in mixers
  - Cannot simulate phase noise/jitter
- **Long transient analyses required for**
  - Periodic/quasi-periodic steady state
  - Turn-on transients of high-Q oscillators and capture process of PLLs
  - Can accumulate significant numerical error

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## SPICE Limitations

- **Fourier analysis**
  - Requires periodic steady state and fundamental frequency
  - Multiple tones must be commensurate
  - IM3 simulation is difficult
  - Subject to interpolation and aliasing errors
  - Tighter tolerances required to resolve small harmonics
  - Fourier integral gives reliable results
- **Elements and models**
  - Transmission line is the only distributed element
  - Models may possess discontinuities in higher-order derivatives => spectral contamination

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## Periodic Steady-State Simulation

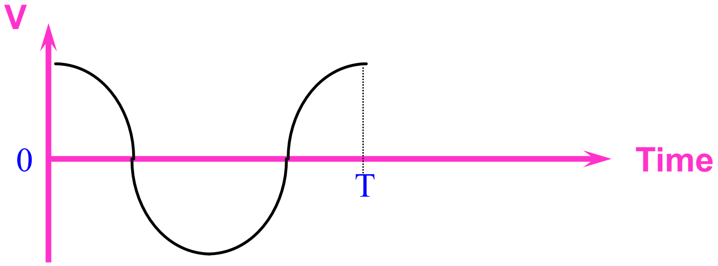
- **Time-domain methods**
- **Harmonic-balance method**
- **Mixed time-frequency methods**

- **Traditionally limited to small circuits**
- **Recent advances allow simulation of much larger circuits**

## Time-Domain Method

- Impose periodicity constraint

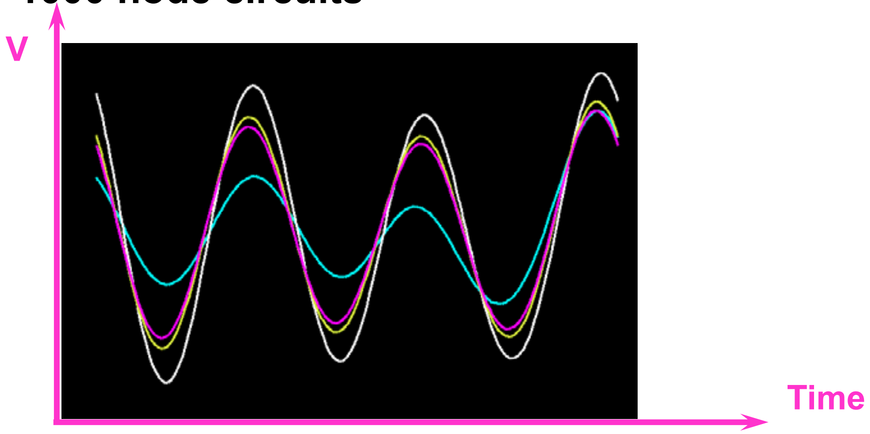
  v(0) = v(T)



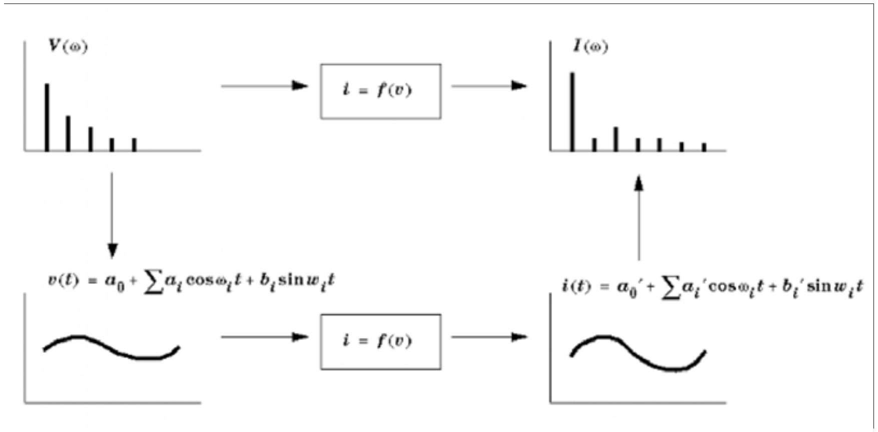
- For a driven circuit period T is known
- For an oscillator T is an unknown

## Time-Domain Method

- A popular method is the shooting method
- Requires dense matrix solutions
- Matrix-free methods allow simulation of ~1000 node circuits

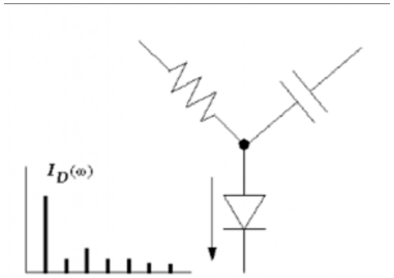


## Non-Linear Frequency Domain Analysis



- Low distortion signals require few Fourier series coefficients
- Smooth device models are essential for RF

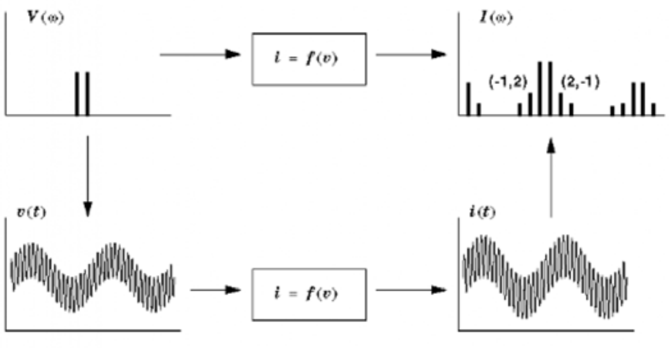
## Harmonic Balance



- “Balance” the frequency spectrum at each node

- Time-derivatives (capacitors) become multiplication in frequency domain
- Handle distributed elements in freq. domain

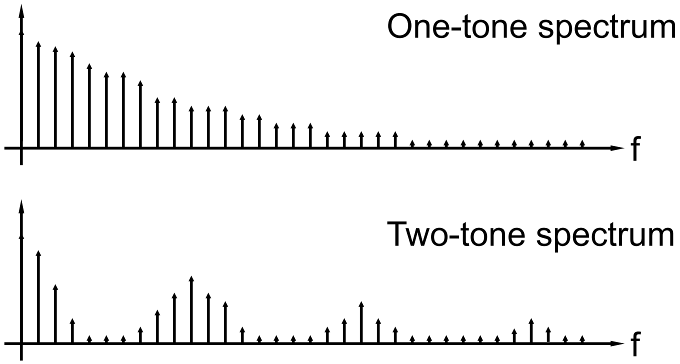
# Multi-Tone Frequency Domain Analysis



- **Minimum number of "time-domain" samples dictated by the number of significant Fourier coefficients, not by the Nyquist rate**

# Frequency Truncation

- Harmonic truncation
  - keep a finite number of frequencies containing significant energy

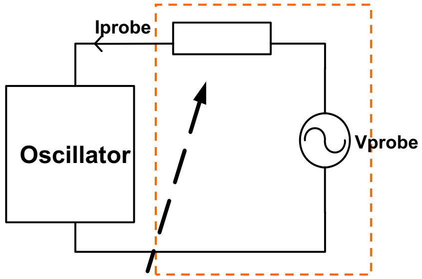


# Oscillator Simulation with HB

- **Problems**
  - Unknown period of oscillation
  - Arbitrary time origin
- **Solutions** (K. Kundert, 1990)
  - Frequency as an additional unknown
  - Additional equation to fix phase

  - Direct implementation ⇒ convergence problems

# Use Voltage Probe



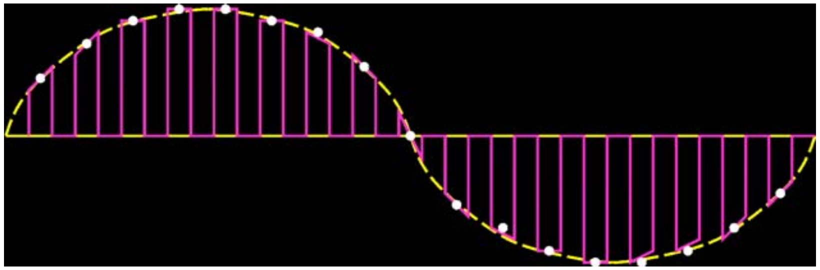
- **Convergence criterion**
  - **Probe current equals zero**
- **Advantages**
  - **Autonomous circuit ⇒ forced circuit**

$$Z(\omega)=\begin{cases}0, & \omega=\omega_f\\ \infty, & \omega\neq\omega_f\end{cases}$$

**E.Ngoya, *Int.J. Microw. Milim.-wave CAE,*1995**

# Mixed Time-Frequency Methods

- **For circuits with both mild and strongly nonlinear behavior**
  - Examples: switching mixer, switched-capacitor circuits



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# Mixed Time-Frequency Methods

- **Represent the envelope waveform with few Fourier series terms**
  - Few points needed to represent envelope
  - Can find them with a few transient simulations of the fast cycle

- **New methods**
  - Based on multi-rate partial differential equations
  - Uses bi-variate representations for efficient computation

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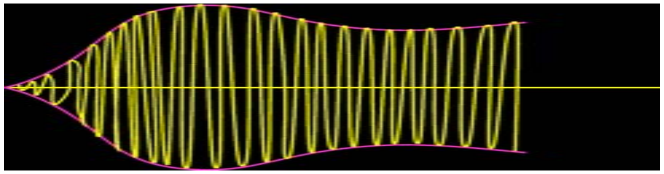
# Envelope Method

- **Slow information signal over fast carrier**
- **Startup transients of circuits with fast signals**
- **AGC circuits, PLLs**



- **Direct calculation of envelope without tracing the fast cycles**
  - Solve differential equation in the envelope
  - Inner loop is harmonic balance

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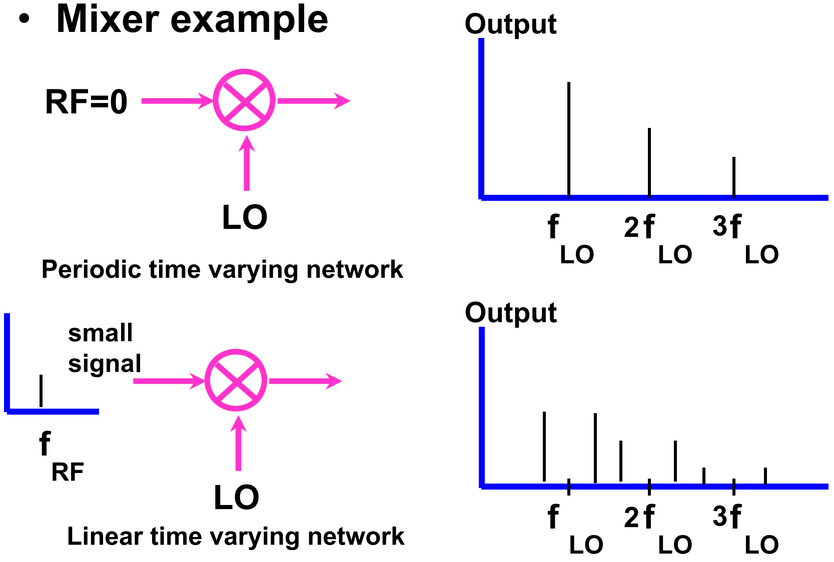
# Linear Time Varying Analysis

- **Mixer example**



# Analysis Methods - Summary

| | Time-Domain Methods | Frequency-Domain Methods | Mixed Time Freq. Method | Envelope Method | Linear Time Varying Method |
|---|---|---|---|---|---|
| **Amplifiers (MNL)** | X | X | | | |
| **Amplifiers (HNL)** | X | | | | |
| **Mixers (CT)** | X | X | X | | X* |
| **Mixers (NCT)** | | X | X | | X* |
| **Oscillators** | X | X | | X | |
| **PLLs, AGCs** | | | | X | |
| **SC Circuits** | X | | X | | X* |

* Small signal

MNL = mildly nonlinear

HNL = highly nonlinear

CT = commensurate tones

NCT = noncommensurate tones

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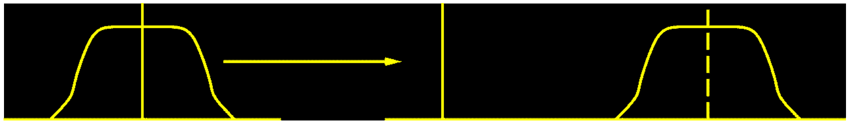
# Mixing Noise

- **Up/down conversion of noise due to mixing**



- **SPICE noise analysis does not work**
- **Cyclostationarity/frequency correlation important**
- **Monte Carlo or stochastic methods**

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# Phase Noise

- **Important for adjacent channel interference, data recovery, and sampled data systems**
- **Most analyses are of specific oscillators under simplifying assumptions**
- **Methods for proper phase noise calculation available in commercial simulators**

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# Commercial RFIC Circuit Simulators

- **Commercial simulators for RFIC design gaining maturity**
- **Simulators developed from two different fronts**
  - Microwave design
    - **ADS from Agilent/EEsof**
    - **Harmonica from Ansoft**
  - Analog IC design
    - **Spectre-RF from Cadence**
    - **ELDO-RF from Mentor**

## Conclusions

- SPICE-like analyses not suitable for RFIC circuit simulation
- Fast and efficient RFIC simulation available in commercial simulators
- Available tools lack system on chip solutions
- Simulators need to be benchmarked for accuracy and performance

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## Summary

- Harmonic balance for
  - High dynamic range weakly-nonlinear systems
    - RF front-ends (LNA, Mixer)
    - IQ modulators
    - LC and crystal oscillators
  - Circuits with distributed components
    - Transmission lines, S-parameter models
- Time-domain PSS for
  - Strongly nonlinear circuits
    - Ring oscillators
    - Frequency dividers
    - DC-DC converters
  - Input signals with sharp transitions