Course Overview

Title:
Advanced Nonlinear Microwave Circuit Engineering
Non-Linear RF Circuits and the LSNA
Theory and Practice

Background:
Wireless has experienced an incredible growth; from cellular phones, to wireless local area networks (WLAN), portable radios have become ubiquitous. The trend is to develop RF radios with wider bandwidth (data rate) and low power dissipation for supporting new broadband services. Of particular importance is the non-linear RF front end circuits in radios which typically dissipate half the handheld power. Given that this is a rapidly changing field, students, practicing engineers and researchers need to keep themselves abreast of new developments in the field. A course presenting such novel material (theory, methodology and techniques) in non-linear circuits, in a comprehensive fashion with practical examples would be therefore valuable for engineers and researchers.

Brief Description of the Course:
With the continuous development of wireless for broadband and higher frequencies, RF engineers world wide are challenged to develop low-cost, linear and power efficient RF electronics. To address these challenges, RF engineers needs to keep up with developments in large-signal measurement techniques, modelling, and nonlinear circuit design theory which have taken place in the last 5 years. This course will review emerging paradigms for a comprehensive approach to non-linear circuit design. First we will discuss novel measurement techniques which have become available with the introduction of the large-signal network analyzer (LSNA). The LSNA permits the vector calibrated measurement of the device voltage and currents (fundamental & harmonics) up to 50 GHz for CW, modulated or pulsed RF excitations. Next we will explore the direct extraction of device models from the RF dynamic large-signal loadlines and show how memory effects (self-heating, traps) can be characterized with modulated RF measurements. Alternatively, bypassing modelling, we can use non-linear measurements for the direct interactive design of non-linear RF circuits such as power amplifiers of various classes and oscillators using a new ultra-fast multi-harmonic active load-pull approach implemented with the LSNA. The course will also show how the output power and phase noise properties of oscillators can be optimized using the measured device line. Then, switching to the system level, we will see how a frequency selective predistorter can be developed to linearize PAs using multi-carrier Volterra/Wiener filters. Finally the linearization of RFIC mixers using the polyphase up-converter topology will be presented an option for realizing wide-band software defined radio.
List of Topics

1. Introduction

This chapter will discuss the trends of wireless communication systems and standards for cellular, WLAN, WPAN. The PARP, EVM metrics and other spectral requirements associated with digital modulation such as OFDM, CDMA will be discussed together with the challenges they cause in the development of low-cost, linear and power efficient RF electronics.

1.1 Modern wireless communications
1.2 Digital modulation and air interface metrics
1.3 Overview of present and emerging design & testing methodologies

2. Large Signal Vector Measurement Techniques with the LSNA

This chapter will introduce some of the vector large-signal measurement techniques which have been developed and the variety of measurements which they make possible.

2.1 Principle of operation of vector large signal measurements
2.2 Relative, power and harmonic phase calibrations
2.3 Modulated measurements and IF calibration
2.4 Dynamic load-line, dynamic AM/AM AM/PM, dynamic IMD3
2.5 EVM and EMI measurement for digital communications
2.6 Pulsed IV- pulsed RF small and large signal measurements
2.7 Measurements of broadband modulated RF signals

3. Model Extraction of Transistor from Large Signal Load-lines

This chapter will review the various model topologies used for large-signal RF device modelling. A new methodology allowing for the direct extraction of device model parameters from the RF dynamic large-signal load-lines at various frequencies will be presented for the accelerated development of non-linear RF models.

3.1 Large-signal model topologies
3.2 Closed-form and table-base representation
3.4 Direct capacitances extraction from large-signal load-lines
3.5 Extraction of parasitics using multi-frequency load-lines
3.6 Modelling verification for 45 nm CMOS.
4. **Characterisation and Modelling of Memory Effects in RF Power Transistors**

This chapter will discuss the leading memory effects (self-heating, traps, parasitic bipolar effect) affecting RF devices. Distributed and transient thermal models will be presented. Novel large signal measurement techniques for characterizing memory effects in transistors using pulsed-biased and modulated RF large-signal measurements will be presented.

4.1 Importance of memory effects in RF devices
4.2 Pulsed-IV and pulsed-RF measurements for device modeling
4.3 Distributed and transient models for self-heating in power transistors
4.4 Trap modelling in transistors
4.5 Parasitic bipolar effects in IV kinks in SOI technology
4.6 Characterization of self-heating and traps with pulsed and modulated large-signal RF measurements

5. **Interactive Load-line Based Design of Power RF Amplifiers**

This chapter will first review the operation of power amplifiers in various classes (A-F). A multi-harmonic real-time active load-pull for acquiring and synthesizing the transistor load-line and associated current and voltage waveforms will be presented together with its application to power amplifier design of various classes.

5.1 Review of power amplifiers of various classes (A-F)
5.2 Multi-harmonic real-time active load-pull
5.3 Applications to the design of high efficiency class E and F amplifiers
5.4 Doherty, Envelope tracking and Pulse Load Modulation amplifiers

6. **Kurokawa Theory of Oscillator Design and Advanced Phase-Noise Theory**

This chapter will review the non-linear envelope circuit theory developed by Kurokawa for the design of oscillator while accounting for non-linear effects, operating point stability, injection locking and noise. The experimental vector measurement of the non-linear device line under variable harmonic termination will be demonstrated using real-time active loadpull and supportive Volterra behavioural modelling using X and V parameters for harmonic balance simulations. Next an advanced phase noise theory for both white and flicker noise accounting for amplitude and phase noise correlation will be introduced. Applications to RFIC oscillators will be discussed next.

6.1 Kurokawa theory of oscillator design
6.2 Vector measurement of device line
6.3 Non-linear Volterra modelling of oscillators
6.4 Advanced phase noise theory for white noise
6.5 Advanced phase noise theory for flicker noise
6.6 RFIC oscillator design examples
6.7 Joint additive phase noise and large signal measurements
7. Behavioral Modeling of Power RF Amplifiers with Memory

This chapter will first discuss Volterra behavioural models for RF power amplifiers for the multi-harmonic response of CW signals including X and V parameters. Next envelope behavioural models for the inband (fundamental) response of RF power amplifier for modulated signals are presented.

7.1 Multi-Harmonic Behavioral modelling of Power Amplifiers:
- X and V parameters

7.2 Envelope Volterra modelling of Power Amplifiers
- Memory polynomial approximation
- B-spline model

7.3 Vector measurement of differential memory effects
7.4 Two-band modelling of Power Amplifiers

8. Frequency Selective Linearization of Power RF Amplifiers with Memory

This chapter will first review predistortion linearization and demonstrate in both simulation and measurement how the linearization is affected by electrical and self-heating memory effects. A frequency selective multi-band predistorter based on a Volterra/Wiener filter will then be demonstrated for a multi-carrier PA.

8.1 Predistortion linearization and the impact of memory effects
8.2 Frequency selective analog predistorter using Volterra/Weiner filter
8.3 Digital implementation of Volterra/Weiner predistorter
8.4 Experimental results for 2-band frequency selective digital predistorter
8.5 Crest factor reduction
8.6 Adaptive implementation of linearization

9. Characterization and Linearization of IQ Modulators

This chapter will first discuss the linear vector characterization of IQ modulator and its application to IQ modulator balancing. Joint balancing of cascaded up-converter and down-converter will then be presented. The theory and implementation of the poly-phase up-converter will then be presented as an option for wide-band software defined radio. This chapter will then conclude with the introduction of the poly-harmonic predistorter for the linearization of the polyphase up-converter.

9.1 Vector characterization of mixer and IQ modulator
9.2 Joint balancing of cascaded up-converter and down-converter
9.3 Poly-phase up-converter theory and implementation
9.4 Poly-harmonic predistortion linearization of the poly-phase up-converter