# Preface

The number of telecommunications systems is expanding at an ever increasing rate, to the extent that most people now carry or are regularly influenced by such items. These include, for example, mobile telephones, personal stereos, radio pagers, televisions and of course the associated test equipment. The expansion of wireless local area networks and multimedia transmission by microwaves is likely to further fuel this increase. Modern computer systems also clock at RF/microwave signal rates requiring high frequency design techniques. The borderline between RF and microwave systems is also less obvious in that most, if not all, of the techniques described in this book can also be applied at microwave frequencies. For example, it is now possible to obtain low cost packaged silicon devices with an $f_T$ greater than 65GHz. The skill required by the engineers working in this field is very broad and therefore an in-depth understanding of the underlying/fundamental principles used is very important.

The aim of this book is to explain the fundamentals of the basic building blocks used in RF circuit design both at the component and intermediate block level. At block level this includes low noise small signal amplifiers, both narrowband and broadband, low phase noise oscillators, mixers and power amplifiers. The components include bipolar transistors, FETs, resistors, capacitors, inductors, varactor diodes and diode detectors. Charts of performance parameters for chip components are included.

The approach is both theoretical and practical explaining the principles of operation and then applying theory (largely algebra) to show how significant insight, both linear and non-linear, can be obtained by using simplifications and approximations. Where necessary more accurate models can be derived by incorporating second order effects. The mathematics is generally included in full as it is important, when extensive CAD is used, that the initial analysis should use sufficient theory to show the required insight. This then enables more robust and longer lasting designs.

The book is an extension of the course material provided to delegates on advanced one-week intensive courses offered to industry by the University of York. These are offered either as a single course or as part of the Integrated Graduate Development Scheme (IGDS) masters degree programmes initially sponsored by the UK Engineering and Physical Sciences Research Council. This material is now also presented to our fourth year MEng students in the RF and Microwave Circuit Design course as part of the UK Radio Frequency Engineering Education Initiative (RFEEI). The material is presented over 27 lectures and three laboratory classes.

The book is based on both research and teaching material. The chapter on low phase noise oscillators is based on research carried out by my research group over the last 18 years. This chapter reviews oscillator design techniques and describes the latest techniques and publications to September 2000. As in the other chapters simple algebra is used to quantify most of the important parameters in low noise oscillator design to a high degree of accuracy. These include such parameters as the optimum coupling coefficients of the resonator to the amplifier and the noise caused by the varactor diode. This theory is then illustrated in eight designs showing accurate prediction of noise performance to within 0 to 2dB of the theory. The latest addition includes a new technique to remove flicker noise in microwave oscillators.

**Chapter 1** describes models for bipolar transistors, FETs, varactor diodes, diode detectors and passive components including resistors capacitors and inductors. Modelling of the bipolar transistor starts with the simple T model, which most closely resembles the actual device. The $\pi$ model is then developed. Both T and $\pi$ models are used for the bipolar transistor, as it is often easier to solve a problem by using their equivalence and switching between them during calculations. They also offer different insights for different circuit configurations. The Miller effect is then described generically enabling the standard approximation for roll-off in bipolar transistors caused by the feedback capacitance. This is then extended to model the effect of any feedback impedance. This is later used in Chapter 3 for broadband amplifier design with optimum input and output match over multiple octave bandwidths when the feedback capacitor is replaced by a resistor.

$S_{21}$ vs frequency and current is then derived for the $\pi$ model using only the operating current, $f_T$ and feedback capacitance. It is then shown how this can be made more accurate by incorporating the base spreading resistance and the emitter contact resistance and how this is then usually within a few per cent of the parameters given in data sheets. The accuracy is illustrated graphically for two devices operating at 1 and 10mA. This then allows intuitive design enabling the important parameters for the device to be chosen in advance, through a deeper understanding of their operation, without relying on data sheets. The harmonic and third order intermodulation distortion is then derived for common emitter and differential amplifiers showing the removal of even order terms during differential operation. The requirement for low level operation for low distortion is then illustrated in tabular form. The characteristics for FETs and varactor diodes are then described.

The operation of diode detectors is then described with a calculation of the sensitivity and illustration of the changeover between the square law and linear characteristic. The noise performance is then illustrated using the Tangential Sensitivity. Models including the parasitics and hence frequency response of chip resistors and capacitors are then described illustrating for example the effect of series resonance in capacitors and the change in impedance for resistors. This is similarly applied to inductors where empirical equations are quoted for inductors, both wound and spiral. The calculation of inductance for a toroid is then derived from first principles using Ampère's law illustrating how easy and accurate a simple fundamental calculation can be.

In **Chapter 2**, two port parameter definitions (*h*, *z*, *y* and *S*) are shown illustrating the common nature of these parameters and how a knowledge of these enables the different elements of equivalent circuit models to be deduced. Here, parameter conversion is used, for example, to deconvolve the non-linear capacitors within the device model, enabling the development of large signal models for power amplifiers. This is also used for linear models elsewhere. Transmission line characteristics are then illustrated and a simplified model for *S* parameters is derived which enables easier calculation of the forward and reverse parameters. This is then applied to a range of circuits including the bipolar transistor described elsewhere in the text.

**Chapter 3** describes small signal amplifier design using both *Y* and *S* parameters illustrating how both approaches offer further insight. The simple calculation of the resistance required to maintain stability is illustrated using the simple *S* parameter equations for the input and output reflection coefficient. These same equations are later used to illustrate and calculate the models for one port error correction. Matching is described using both tapped resonant networks and two component inductor/capacitor networks using Smith Charts with a number of design examples. The effect of loaded and unloaded *Q* on insertion loss and hence noise figure is described.

Noise measurement and calculation are described using a two temperature technique. This is a fundamental technique which is similar in concept to commercial systems and can easily be built in-house. The bipolar transistor models are extended using the concept of complex current gain to illustrate how low noise can be obtained at the same time as optimum match by using an emitter inductor. This is similar to the method described by Hayward.

Broadband amplifier design is described in detail showing the effect of the feedback resistance, the emitter resistance and the bias current. A design example is included.

Methods for passive and active biasing of devices are then discussed. Measurements illustrating device test jigs and the operation of a modern network analyser are described. The importance of calibration and hence error correction is applied with the detailed equations for one port error correction.

**Chapter 4** describes to a large extent a linear theory for low noise oscillators and shows which parameters explicitly affect the noise performance. From these analyses equations are produced which accurately describe oscillator performance usually to within 0 to 2dB of the theory. It shows that there are optimum coupling coefficients between the resonator and the amplifier to obtain low noise and that this optimum is dependent on the definitions of the oscillator parameters. The factors covered are: the noise figure (and also source impedance seen by the amplifier); the unloaded $Q$; the resonator coupling coefficient and hence $Q_L/Q_0$ and closed loop gain; the effect of coupling power out of the oscillator; the loop amplifier input and output impedances and definitions of power in the oscillator; tuning effects including the varactor $Q$ and loss resistance, the coupling coefficient of the varactor; and the open loop phase shift error prior to loop closure.

Optimisation of parameters using a linear analytical theory is of course much easier than using non-linear theories.

The chapter then includes eight design examples which use inductor/capacitor, Surface Acoustic Wave (SAW), transmission line, helical and dielectric resonators at 100MHz, 262MHz, 900MHz, 1800MHz and 7.6GHz. These oscillator designs show very close correlation with the theory usually within 2dB of the predicted minimum. It also includes a detailed design example.

The chapter then goes on to describe the four techniques currently available for flicker noise measurement and reduction including the latest techniques developed by my research group in September 2000. Here a feedforward amplifier is used to suppress the flicker noise in a microwave GaAs based oscillator by 20dB. The theory in this chapter accurately describes the noise performance of this oscillator, within the thermal noise regime, to within ½ to 1dB of the predicted minimum.

A brief introduction to a method for breaking the loop at any point, thus enabling non-linear computer aided analysis of oscillating (autonomous) systems, is described. This enables prediction of the biasing, output power and harmonic spectrum.

**Chapter 5** describes an introduction to mixers starting with a simple non-linear device and then leading on to an ideal switching mixer. The operation and waveforms of switching diode and transistor mixers are then described. Diode parameters such as gain compression and third order intermodulation distortion are then introduced.

**Chapter 6** provides an introduction to power amplifier design and includes Load Pull measurement and design techniques and a more analytic design example of a broadband, efficient amplifier operating from 130 to 180 MHz. The design example is based around high efficiency Class E techniques and includes the development of an accurate large signal model for the active device. This model is also used to enable calculation of the large signal input impedance of the device under the correct operating conditions. Although the design relates to Class E techniques the methods described can be used for all amplifier types.

**Chapter 7** describes a circuit simulator which displays in real time the waveforms, at all the nodes, while using the mouse with crosshatch and slider controls to vary the component values and frequency at the same time as solving the relevant differential equations. This then enables real time tuning of the circuit for optimum response. The techniques for entering the differential equations for the circuit are described. These differential equations are computed in difference form and are calculated sequentially and repetitively while the component values and frequency are varied. This is similar to most commercial time domain simulators, but it is shown here that it is relatively easy to write down the equations for fairly simple circuits. This also provides insight into the operation of large signal simulators. The version presented here uses Visual Basic Version 6 for a PC and enables the data to be presented in an easily readable format. A version of this program is used here to examine the response of a broadband highly efficient amplifier load network operating around 1 to 2GHz.

**Summary:** The aim therefore is to provide a book which contains both analytical and practical information enabling insight and advanced design through in-depth understanding of the important parameters.

I plan to maintain a web page with addenda, corrections and answers to any comments by readers. The URL will be a subfolder of my University of York web page: http://www.york.ac.uk/depts/elec/staff/academic/jkae.html.

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