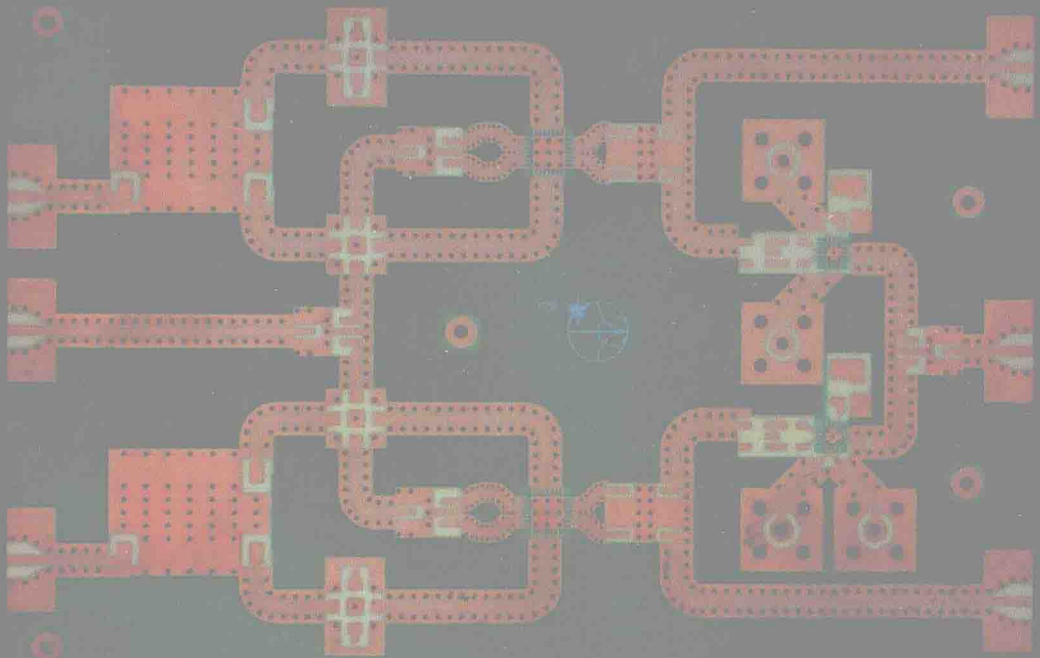


Microwave and Millimetre-Wave Design for Wireless Communications

Ian Robertson

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MICROWAVE AND MILLIMETRE-WAVE DESIGN FOR WIRELESS COMMUNICATIONS

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Ian Robertson
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Mitchai Chongcheawchamnan
April 2016

Preface

This book is aimed primarily at final year undergraduates and Masters students. It will also be invaluable as background reading for PhD students and as a primer for practising engineers in industry. Its primary purpose is to explain concepts in clear terms, with an emphasis on modern industry practice, with references for further reading given to provide more detailed information and background theory.

The book describes a full range of contemporary techniques for the design of transmitters and receivers for communications systems operating in the range from 1 through to 300 GHz. Within this frequency range there are many technologies that need to be employed, with silicon integrated circuits at the core but, compared to other electronic systems, with a much greater need for specialist devices and components for high performance – for example, low-loss passive components and low-noise and high-power compound semiconductor devices. Millimetre-waves (frequencies from 30 to 300 GHz) have rapidly been adopted for a wide range of consumer applications such as wireless high-definition video for virtual and augmented reality, 5G mobile systems, and automotive radars. It has taken many years to develop low-cost technologies for suitable transmitters and receivers, so previously these frequencies have been employed only in expensive military and space applications. This really does represent a new era in the use of the millimetre-wave part of the electromagnetic spectrum. The next 20 years will see explosive growth in the use of the frequency range from 30 to 300 GHz, and this requires engineers to be able to understand and apply the techniques of traditional microwave engineering, as well as the newer technologies such as silicon germanium and gallium nitride devices and integrated circuits. These are then assembled into sophisticated multichip modules and system-in-package products with integrated antenna arrays.

The book starts with an emphasis on the applications of microwave and millimetre-wave systems, in Chapter 1, followed by a description of the wide range of modern transmitter-receiver architectures in Chapter 2. The use of quadrature modulation schemes and modern direct-conversion transceivers, that are at the heart of nearly all wireless communication systems, are covered. Chapter 3 introduces *S*-parameters so that they can be used in Chapter 4 on Lumped Element Filters. This introduces Bode plots, transfer functions, poles and zeros and the *s*-domain, followed by design techniques for low-pass, high-pass, band-pass and bandstop filters. However, a key conclusion of this chapter is that lumped elements often suffer from serious limitations in high-frequency design, which is why transmission lines are needed for many circuits.

Chapter 5 introduces the main principles of transmission lines, including the telegrapher's equation, signal flowgraphs, standing waves, impedance transformation along a line and the

Smith chart. This is followed by Chapter 6 on transmission line components, which is focused on the practical aspects of the main transmission line types – coaxial lines, rectangular waveguide, microstrip and various others, including coplanar waveguide (CPW) and substrate integrated waveguide (SIW). The emphasis is on those transmission line media that are used for circuit design, looking at their propagation characteristics, technologies and materials, discontinuities and modelling. A number of key standard components are introduced, such as the Wilkinson power divider, Lange coupler, branch-line coupler and rat-race hybrid.

Having covered the key transmission line media, Chapter 7 returns to the subject of filters. A succinct coverage of distributed filters is given, covering those topologies most commonly encountered in modern microwave and millimetre-wave design. The mathematical conversion from lumped element filters to distributed elements, followed by network transformation to produce realisable practical filters, is described.

Chapter 8 introduces the key semiconductor devices – both discrete low-noise and high-power transistors and those used for integrated circuits. The chapter summarises the key features of silicon, silicon-germanium, GaAs, GaN and InP transistors. Chapter 9 explains the importance of impedance matching, with particular reference to amplifier design. The use of the Smith chart is introduced and a number of common matching techniques is described. Chapter 10 builds on this by describing amplifier design techniques, starting with the classical gain and stability analysis using S -parameter and Mason's rule analysis. The key topologies used in GaAs MMIC and silicon RFIC design are introduced. Distortion and intermodulation in power amplifiers is explained, followed by a summary of key classes of operation (A, AB, C, D, E, F, etc.) and a brief treatment of the main techniques employed for power-combining and linearising power amplifiers.

Chapter 11 introduces the fundamentals of oscillators, followed by coverage of the main oscillator circuit topologies. The importance of resonator Q -factor and phase noise are explained. Phase-locked loop techniques are covered, giving an introduction to integer- N and fractional- N frequency synthesis. Mixers are the core component for up- and down-conversion of signals, including use in 'IQ' direct conversion transceivers. Chapter 12 focuses on the most common mixer design techniques, including the Gilbert cell mixer technique, now adopted even beyond 100 GHz.

Chapter 13 describes radiofrequency microelectromechanical systems (MEMS), which are an important niche technology that can substantially change the architecture of modern transceivers. RF MEMS are of increasing interest as adaptive antennas, and multiband transceivers become key to future communications systems. Switches, phase shifters and reconfigurable circuits are also covered.

Chapter 14 gives an overview of the basics of antennas and propagation since, in order to understand the challenge of exploiting the millimetre-wave part of the electromagnetic spectrum, it is necessary to study the propagation characteristics in the range 1 to 1000 GHz. Millimetre-waves give the very significant advantage of small, high-gain antennas, and modern communications systems are relying more than ever on adaptive and multiple-beam antennas in order to combat propagation effects and increase the capacity of systems. The chapter therefore introduces the key concepts such as multiple input/multiple output (MIMO) systems.

Modern communications systems nearly always use direct conversion architectures, and it is important that RF engineers have some understanding of the digital part of the system. Consequently, Chapter 15 provides an introduction to some of the digital signal processing (DSP) techniques used for communications transceivers. The chapter also provides a tutorial

on the key principles of analogue-to-digital and digital-to-analogue converters and DSP techniques. This is important so that RF engineers understand how DSP is used to combat signal impairments and realise functions such as beam forming.

The final three chapters describe how all the devices, components and circuits covered in the previous chapters are assembled, simulated and measured. Chapter 16 describes the main technologies and design techniques for microwave circuit assemblies and multichip modules, as well as emerging 3-D system-in-package and 'system-on-substrate' technologies. Chapter 17 covers electronic design automation (EDA), describing the most common design tools used by designers. The aim here is that the reader will fully understand the role and limitations of different simulation techniques, including linear, time-domain nonlinear, harmonic balance, modulation domain, planar electromagnetic, 3-D electromagnetic and system-level simulation. Finally, Chapter 18 covers measurement techniques, including vector network analyser calibration methods. A wide range of test equipment for measuring individual devices and components through to complete transmitters and receivers is described, using Keysight Technologies equipment as examples.

We sincerely hope that you find this book useful. Microwave and millimetre-wave design is a fascinating subject, and is possibly unique in the way it blends electronic circuits into works of art – such is the importance of their physical form in determining function. That, combined with the amazing potential for wireless communications to transform every aspect of human endeavour, makes RF engineering one of the most rewarding careers of all.

Ian Robertson
Nutapong Somjit
Mitchai Chongcheawchamnan
April 2016

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