CHAPTER 1

INTRODUCTION

Wireless systems, including communication, networking, and sensing systems, play a critical role in our information-age society in many areas, from public service and safety, consumer, industry, sports, gaming, and entertainment, asset and inventory management, medicine, banking to government and military operations. The key to enabling effective wireless communications, sensing and networking is radio-frequency (RF) integrated circuits (ICs).

Radio-frequency integrated circuits (RFICs) typically refer to RF monolithic ICs fabricated on silicon (Si) substrates using complementary metal oxide semiconductor (CMOS) or BiCMOS technology. From a general perspective, however, RFICs are not and should not be limited to only Si-based CMOS and BiCMOS circuits; others like microwave monolithic integrated circuits (MMICs) using III–V semiconductors such as GaAs MMICs can also be classified as RFICs. Nevertheless, in this book, to emphasize the main objective of the book and to distinguish Si-based RFICs from other non-Si based RFICs, we will use the term RFIC to indicate Si-based CMOS/BiCMOS RFIC. The readers should, however, keep in mind that the presented materials are not limited to Si-based RFICs; they are also applicable to non-Si based RFICs such as GaAs MMICs.

The frequencies used to indicate the RF range, in general, and for RFICs, in particular, are not strictly defined in practice. To some extent, particularly in the past, the frequencies in the RF range are known as a few kilohertz to a few gigahertz and, hence, RF is clearly distinct from microwave. Since the frequencies for radio waves are normally known as between 3 KHz and 300 GHz, to a broader extent, the frequencies in the RF range can be considered from 3 KHz to 300 GHz. As the name RF implies, however, these frequencies should not be limited to below 300 GHz. In this book, we will consider all the RFs in the electromagnetic (EM) spectrum up to terahertz (THz) as RF — in other words, we view the RF range as including all frequencies from 3 KHz to microwave, millimeter-wave and sub-millimeter-wave frequencies. Therefore, RF, as it is practiced or should be practiced now, is not different from microwave, millimeter-wave and sub-millimeter-wave frequencies. The boundary between RF and microwave, millimeter-wave and sub-millimeter-wave indeed no longer exists or should not exist. As the technologies for RFICs advance toward the terahertz region of the RF spectrum, it is expected that RFICs will find many useful applications in both the commercial and the defense sectors at terahertz — for instance, medical imaging or personal-health

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monitoring in the medical field and extremely wide bandwidth and ultrahigh data-rate for wireless communications.

Over the past several decades, RF components and systems in the microwave, millimeter-wave and sub-millimeter-wave ranges have been dominated with circuits employing III–V compound semiconductor devices, such as GaAs metal semiconductor field effect transistor (MESFET), high electron mobility transistor (HEMT), InP HEMT, GaAs heterojunction bipolar transistor (HBT), and InP HBT, etc. due to their superior performance as compared to Si-based technologies. RFICs based on III–V semiconductors, however, are expensive and have limited integration capability for single-ship systems. Exploding demand for low cost, low power, compactness, and high integration ability, far exceeding those provided by the III–V semiconductor technologies, has led the wireless industry to focus on better Si-based technologies capable of operating in the RF range. Si-based RF technologies have advanced significantly during the past few decades and are increasingly important for wireless communications, sensing, and networking due to their low cost, low power, and excellent integration ability, notably CMOS, that facilitates various applications requiring miniature, low cost, low power systems with high volume throughput. Presently, Si-based technologies can offer good performance up to the millimeter-wave regime with much lower cost and better integration capability than their non-silicon based counterparts, hence opening up many opportunities in wireless communications, sensing and networking.

Various RFICs, including single components and single-chip subsystems and systems, have been successfully developed with good performance up to millimeter-wave frequencies, demonstrating the potential capability of RFICs and their possible applications in the higher end of the RF spectrum. As an example, Figure 1.1 shows the schematic and microphotograph of a single-chip millimeter-wave RFIC transmitter operating concurrently in two frequency bands at 24.5 ± 0.5 GHz and 35 ± 0.5 GHz using a 0.18-μm SiGe BiCMOS process, showing the integration of several RF components. RFICs have played a significant role in advancing the state of the art of RF circuits and systems for various applications from sensing and imaging to communications across a few hundred MHz to millimeter-wave frequencies, and potentially beyond. It is foreseen that RFICs and systems with 3D (vertical and horizontal) integrations can perform at very high frequencies in the RF range in the future. RFIC is now inevitable in RF systems, and it is expected that it will dominate the RF territory, particularly for commercial applications, just like III–V semiconductors based MMICs have done, but with much lower costs and better abilities for direct integration with digital ICs. Although the performance of many Si-based RFICs still presently does not match that of RFICs implemented using III–V compound semiconductor devices, particularly in the higher frequency end of the RF spectrum such as millimeter-wave frequencies, due to lower f_T and $f_{\max}$, higher substrate loss, more noise, and so on of current CMOS/BiCMOS devices, they have lower cost and better abilities for direct integration with digital ICs (and hence better potential for complete system-on-chip). RFICs are also small and low power, making them suitable for battery-operated wireless communication, sensing and networking devices and systems. RFICs are thus attractive for systems and, in fact, the principal choice for commercial wireless markets.

Typical RFIC design based on traditional analog design approach is not very suitable at high frequencies of the RF range that is currently practiced. As the RF spectrum moves toward the multi-GHz realm, the need of incorporating microwave design techniques into analog circuits and systems becomes increasingly important and is, in fact, inevitable. Consequently, the knowledge of EM and microwave engineering becomes vital for RFIC engineers in order to understand and design RFICs properly. This is a fact that is recognized by RF researchers and engineers in both academia and industry. High frequencies in the RF range, especially those approaching the frequency limits of CMOS/BiCMOS technology, make RFIC design challenging. The design of RFICs at high frequencies poses further challenging as circuits and devices become extremely small and the interactions between elements within a circuit or between circuits in an integrated system become so immense. Typical RFICs, especially those at low frequencies, use exclusively lumped elements. While lumped elements are useful for RF circuitry and, in some cases, mandatory (e.g., resistive terminations, bias bypass capacitors), it is difficult to realize a truly lumped element in lossy silicon substrates at high frequencies because of significant parasitics to ground associated with Si substrates and high frequency EM effects. At these frequencies, the need of incorporating transmission lines, distributed elements (e.g., transmission-line components) and microwave design techniques, besides lumped elements and (low frequency) analog design

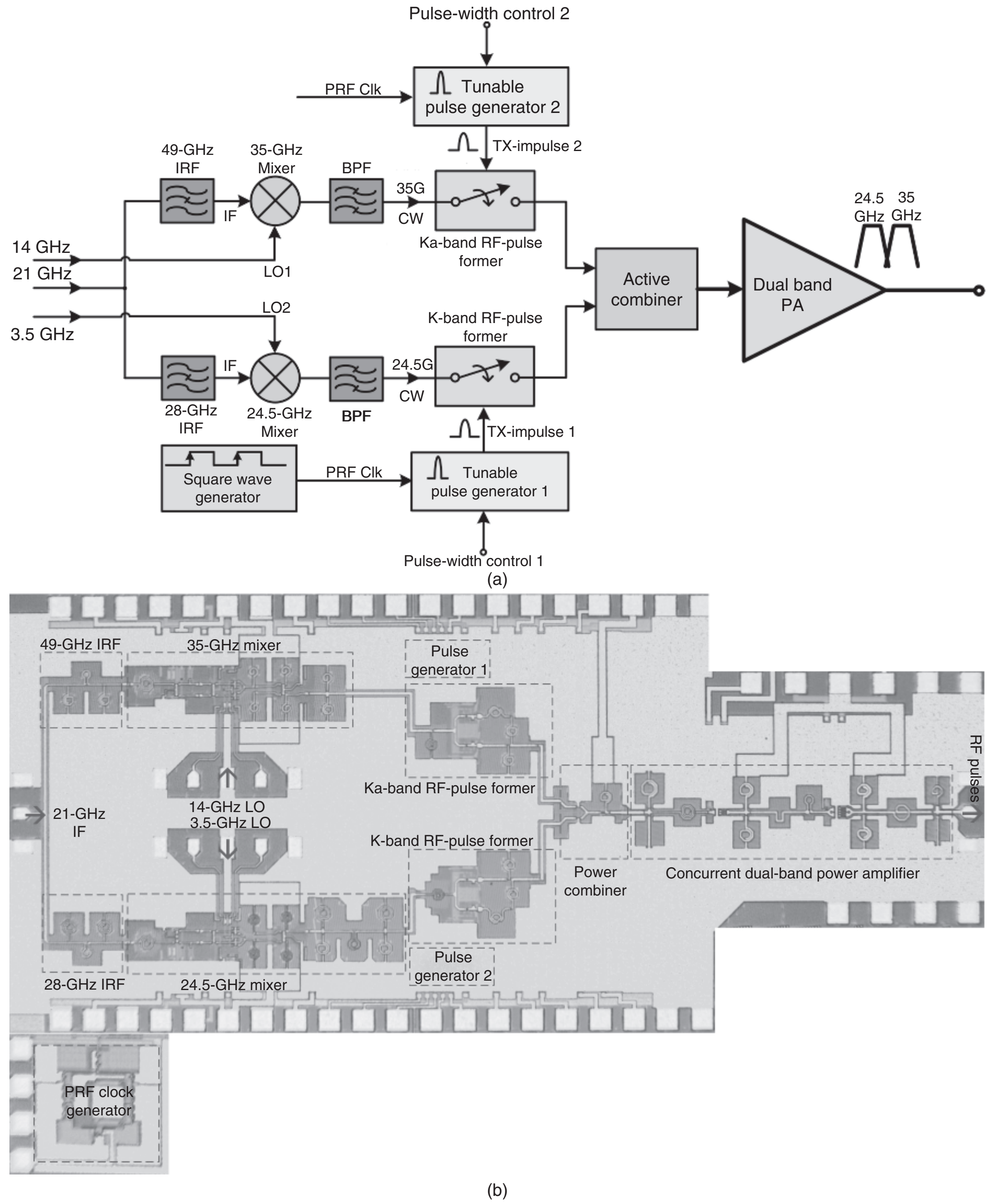

Figure 1.1. Schematic (a) and microphotograph (b) of a single-chip 0.18-μm SiGe BiCMOS millimeter-wave transmitter operating concurrently at two bands around 24.5 and 35 GHz. IRF: image-reject filter; BPF: band-pass filter; PA: power amplifier; TX: transmitter; RX: receiver; PRF: pulse repetition frequency; Clk: clock.

techniques, into RFICs becomes essential. Furthermore, besides circuit simulation, EM simulation needs to be effectively utilized to accurately model all effects occurring at these high frequencies. In view of these, it is crucial that the design of RFIC needs to be approached from the microwave design point of view. The design of Si-based RFICs is in general similar to the design of GaAs MMICs; the main difference is the use of Si instead of GaAs as the processing means. In other words, the design of RFICs is essentially executed using the microwave design principles in Si-based "analog" environment.

This book revolves around the philosophy that RFIC engineers need knowledge in EM and microwave engineering, passive RFICs, active RFICs, RFIC analysis and design techniques, and RF systems. To that end, the book is aimed to address the theory, analysis, and design of passive and active RFICs using Si-based CMOS and BiCMOS technologies, in particular, and other non-silicon based technologies, in general, at high frequencies beyond those in the traditionally considered RF range. It intends to provide a comprehensive coverage for RFICs from passive to active circuits with particular emphasis on using microwave analysis and design techniques, which distinguishes itself from other RFIC books. It attempts to present the materials in details with a self-contained concept to allow graduate students and engineers with basic knowledge in RF and circuits to understand RFICs and their design. The book also includes problems for each chapter so readers can reinforce and practice their knowledge. Some of the problems are rather difficult and time-consuming and they can also be used as class projects for students. An important remark, yet may be redundant to RF engineers, is that many RF applications and systems are generally based on the same fundamentals and similar RF components. Knowledge of an RF system (e.g., pulsed system) and its RF components (e.g., mixer) for one application (e.g., sensing) can be used for the design of other systems (e.g., frequency-modulated continuous wave (FMCW) system) and for other applications (e.g., wireless communications.)

The book is organized into 16 chapters blending analog and microwave engineering with particular emphasis on the microwave engineering approach for RFICs, which is essential but not implemented in typical RFIC books. Chapter 2 provides the fundamentals of EM theory needed for RF engineers to understand basic yet relevant EM principles and effects on RFICs. Chapter 3 covers the design and analysis of on-chip lumped elements typically used in RFICs, including inductors, capacitors and resistors. Chapter 4 discusses the fundamentals of transmission lines for both single and multiconductor transmission lines including transmission-line equations and important transmission-line parameters, as well as synthetic transmission lines and commonly used printed-circuit transmission lines. Chapter 5 covers the analysis and design of both lumped-element and distributed resonators. Chapter 6 presents some fundamental design techniques for impedance-matching networks. Chapter 7 presents the formulation and characteristics of the scattering parameters as well as important parameters related to them. Chapter 8 presents the analysis and design of various basic RF passive components including directional couplers, hybrids, power dividers, and filters. Chapter 9 provides the fundamentals of CMOS transistors that are useful for the design of CMOS RFICs. Chapter 10 presents an analysis of stability for RFICs employing transistors. Chapter 11 covers the fundamentals and design of RF amplifiers, low noise amplifiers, power amplifiers (PAs), balanced amplifiers, and broad-band amplifiers. Chapter 12 discusses the fundamentals of oscillators, the theory of phase noise, and the design of both single-ended and balanced oscillators for RFICs. Chapter 13 presents the fundamentals of mixers, their topologies, analysis, and design for RFICs. Chapter 14 discusses the fundamentals and analyses of switches, and the design of SPST (single pole single throw) and T/R switches for RFICs. It also addresses ultra-wideband distributed switches, ultrahigh isolation switches, and switches implementing filtering functions. Chapter 15 presents the simulation, layout, and measurement for RFICs, as well as the calibration and de-embedding for on-wafer measurement. Chapter 16 addresses the commonly used pulsed and FMCW systems along with the widely used receiver architectures of homodyne and super-heterodyne as a way to introduce RF systems. Finally, the Appendix presents the design of an RFIC double-balanced mixer based on the Gilbert cell as an example to illustrate the design process of RFICs.

It is particularly noted that, in this book, for the sake of simplicity, we will use the term CMOS RFIC often but this, by no means, implies that the book only addresses CMOS RFICs. The design of other Si-based RFICs such as BiCMOS RFICs (and in fact the design of other non-silicon RFICs like GaAs MMICs as stated earlier) is equally applicable.

PROBLEMS

The objective of these problems is to familiarize readers with some of the current and potential applications/systems of RFICs and systems.

1.1 Search the 802.11b wireless Local Area Network (WLAN) applications. Describe the IEEE 802.11b standards, some systems currently employed and components used in these systems, their applications, performance, operating frequencies, and CMOS/BiCMOS technologies used, etc.

1.2 Repeat Problem 1.1 for un-licensed ultra-wideband (UWB) applications from 3.1 to 10.6 GHz.

1.3 Repeat Problem 1.1 for Bluetooth.

1.4 Repeat Problem 1.1 for millimeter-wave (MMW) radio applications including 60 GHz and E-band (71–76 GHz and 81–86 GHz bands).

1.5 Search for current Si-based CMOS and BiCMOS processes and compile on a table the following: (i) device technology (i.e., 30, 45, 90, 130, 180, and 250 nm), (ii) f_T (the cut-off frequency or the frequency of unity gain), (iii) $f_{\max}$ (the maximum frequency of oscillation or the frequency at which the maximum available gain is 0 dB), (iv) foundry, and (v) other pertinent information.

1.6 Describe current and potential applications of Si-based RFICs and systems (from microwave to millimeter wave frequencies). What do you think are the future trends and applications and at what frequencies?