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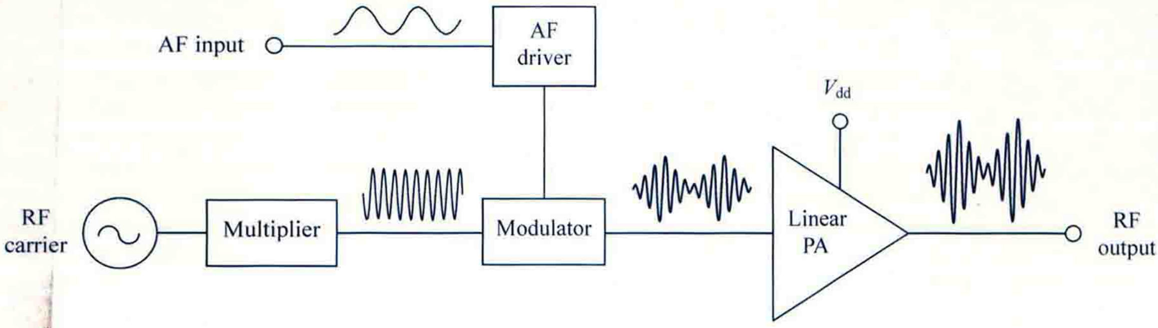
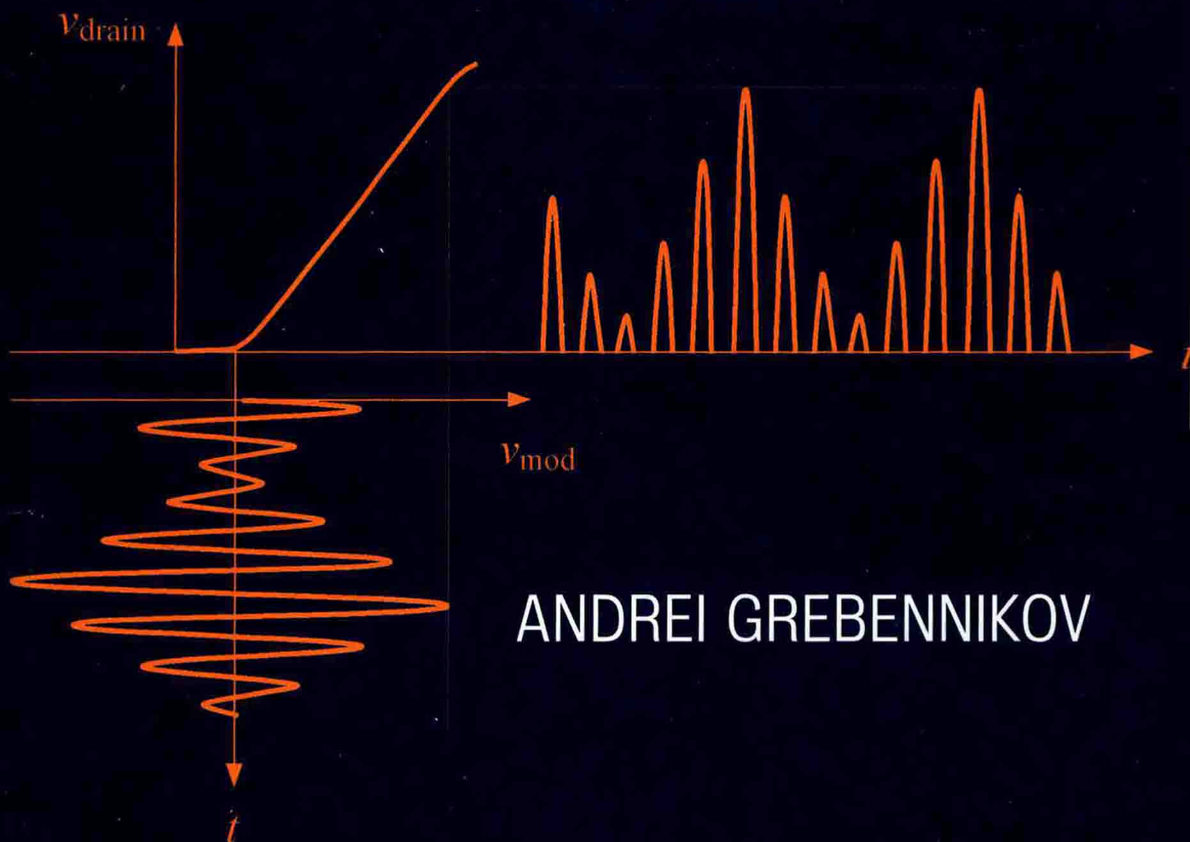


RF AND MICROWAVE TRANSMITTER DESIGN



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WILEY

RF AND MICROWAVE TRANSMITTER DESIGN

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KAI CHANG, Editor
Texas A&M University

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PREFACE

The main objective of this book is to present all relevant information required to design the transmitters in general and their main components in particular in different RF and microwave applications including well-known historical and recent novel architectures, theoretical approaches, circuit simulation results, and practical implementation techniques. This comprehensive book can be very useful for lecturing to promote the systematic way of thinking with analytical calculations and practical verification, thus making a bridge between theory and practice of RF and microwave engineering. As a result, this book is intended for and can be recommended to *university-level professors* as a comprehensive material to help in lecturing for graduate and postgraduate students, to *researchers and scientists* to combine the theoretical analysis with practical design and to provide a sufficient basis for innovative ideas and circuit design techniques, and to *practicing designers and engineers* as the book contains numerous well-known and novel practical circuits, architectures, and theoretical approaches with detailed description of their operational principles and applications.

Chapter 1 introduces the basic two-port networks describing the behavior of linear and nonlinear circuits. To characterize the nonlinear properties of the bipolar or field-effect transistors, their equivalent circuit elements are expressed through the impedance Z-parameters, admittance Y-parameters, or hybrid H-parameters. On the other hand, the transmission $ABCD$-parameters are very important for the design of the distributed circuits such as a transmission line or cascaded elements, whereas the scattering S-parameters are widely used to simplify the measurement procedure. The design formulas and curves are given for several types of transmission lines including stripline, microstrip line, slotline, and coplanar waveguide. Monolithic implementation of lumped inductors and capacitors is usually required at microwave frequencies and for portable devices. Knowledge of noise phenomena such as noise figure, additive white noise, low-frequency fluctuations, or flicker noise in active or passive elements is very important for the oscillator modeling in particular and entire transmitter design in general.

In Chapter 2, all necessary steps to provide an accurate device modeling procedure starting with the determination of the device small-signal equivalent circuit parameters are described and discussed. A variety of nonlinear models for MOSFET, MESFET, HEMT, and BJT devices including HBTs, which are very prospective for modern microwave monolithic integrated circuits, are given. In order to highlight the advantages or drawbacks of one over another nonlinear device model, a comparison of the measured and modeled volt–ampere and voltage–capacitance characteristics, as well as a frequency range of model application, are analyzed.

The main principles and impedance matching tools are described in Chapter 3. Generally, an optimum solution depends on the circuit requirements, such as the simplicity in practical realization, frequency bandwidth and minimum power ripple, design implementation and adjustability, stable operation conditions, and sufficient harmonic suppression. As a result, many types of the matching networks are available, including lumped elements and transmission lines. To simplify and visualize the matching design procedure, an analytical approach, which allows calculation of the parameters of the matching circuits using simple equations, and Smith chart traces are discussed. In addition, several examples of the narrowband and broadband power amplifiers using bipolar or MOSFET devices are given, including successive and detailed design considerations and explanations.

Chapter 4 describes the basic properties of the three-port and four-port networks, as well as a variety of different combiners, transformers, and directional couplers for RF and microwave power applications. For power combining in view of insufficient power performance of the active devices, it is best to use the coaxial-cable combiners with ferrite core to combine the output powers of RF power amplifiers intended for wideband applications. Since the device output impedance is usually too small for high power level, to match this impedance with a standard 50-Ω load, it is necessary to use the coaxial-line transformers with specified impedance transformation. For narrowband applications, the N-way Wilkinson combiners are widely used due to the simplicity of their practical realization. At the same time, the size of the combiners should be very small at microwave frequencies. Therefore, the commonly used hybrid microstrip combiners including different types of the microwave hybrids and directional couplers are described and analyzed.

Chapter 5 introduces the basic types of RF and microwave filters based on the low-pass or high-pass sections and bandpass or bandstop transformation. Classical filter design approaches using image parameter and insertion loss methods are given for low-pass and high-pass *LC* filter implementations. The quarterwave-line and coupled-line sections, which are the basic elements of microwave transmission-line filters, are described and analyzed. Different examples of coupled-line filters including interdigital, combline, and hairpin bandpass filters are given. Special attention is paid to microstrip filters with unequal phase velocities, which can provide unexpected properties because of different implementation technologies. Finally, the typical structures, implementation technology, operational principles, and band performance of the filters based on surface and bulk acoustic waves are presented.

Chapter 6 discusses the basic features of different types of analog modulation including amplitude, single-sideband, frequency, and phase modulation, and basic types of digital modulation such as amplitude shift keying, frequency shift keying, phase shift keying, or pulse code modulation and their variations. The principle of operations and various schematics of the modulators for different modulation schemes including Class S modulator for pulse-width modulation are described. Finally, the concept of time and frequency division multiplexing is introduced, as well as a brief description of different multiple access techniques.

A basic theory describing the operational principles of frequency conversion in receivers and transmitters is given in Chapter 7. The different types of mixers, from the simplest based on a single diode to a balanced and double-balanced type based on both diodes and transistors, are described and analyzed. The special case is a mixer based on a dual-gate transistor that provides better isolation between signal paths and simple implementation. The frequency multipliers that historically were a very important part of the vacuum-tube transmitters can extend the operating frequency range.

Chapter 8 presents the principles of oscillator design, including start-up and steady-state operation conditions, noise and stability of oscillations, basic oscillator configurations using lumped and transmission-line elements, and simplified equation-based oscillator analyses and optimum design techniques. An immittance design approach is introduced and applied to the series and parallel feedback oscillators, including circuit design and simulation aspects. Voltage-controlled oscillators and their varactor tuning range and linearity for different oscillator configurations are discussed. Finally, the basic circuits and operation principles of crystal and dielectric resonator oscillators are given.

Chapter 9 begins with description of the basic phase-locked loop concept. Then, the basic performance and structures of the analog, charge-pump, and digital phase-locked loops are analyzed. The basic loop components such as phase detector, loop filter, frequency divider, and voltage-controlled oscillator are discussed, as well as loop dynamic parameters. The possibility and particular realizations of the phase modulation using phase-locked loops are presented. Finally, general classes of frequency synthesizer techniques such as direct analog synthesis, indirect synthesis, and direct digital synthesis are discussed. The proper choice of the synthesizer type is based on the number of frequencies, frequency spacing, frequency switching time, noise, spurious level, particular technology, and cost.

Chapter 10 introduces the fundamentals of the power amplifier design, which is generally a complicated procedure when it is necessary to provide simultaneously accurate active device modeling, effective impedance matching depending on the technical requirements and operation conditions, stability in operation, and simplicity in practical implementation. The quality of the power amplifier design is evaluated by realized maximum power gain under stable operation condition with minimum amplifier stages, and the requirement of linearity or high efficiency can be considered where it is needed. For a stable operation, it is necessary to evaluate the operating frequency domains where the active device may be potentially unstable. To avoid the parasitic oscillations, the stabilization circuit technique for different frequency domains (from low frequencies up to high frequencies close to the device transition frequency) is discussed. The key parameter of the power amplifier is its linearity, which is very important for many wireless communication applications. The relationships between the output power, 1-dB gain compression point, third-order intercept point, and intermodulation distortions of the third and higher orders are given and illustrated for different active devices. The device bias conditions, which are generally different for linearity or efficiency improvement, depend on the power amplifier operation class and the type of the active device. The basic Classes A, AB, B, and C of the power amplifier operation are introduced, analyzed, and illustrated. The principles and design of the push–pull amplifiers using balanced transistors, as well as broadband and distributed power amplifiers, are discussed. Harmonic-control techniques for designing microwave power amplifiers are given with description of a systematic procedure of multiharmonic load–pull simulation using the harmonic balance method and active load–pull measurement system. Finally, the concept of thermal resistance is introduced and heatsink design issues are discussed.

Modern commercial and military communication systems require the high-efficiency long-term operating conditions. Chapter 11 describes in detail the possible circuit solutions to provide a high-efficiency power amplifier operation based on using Class D, Class F, Class E, or their newly developed subclasses depending on the technical requirements. In all cases, an efficiency improvement in practical implementation is achieved by providing the nonlinear operation conditions when an active device can simultaneously operate in pinch-off, active, and saturation regions, resulting in nonsinusoidal collector current and voltage waveforms, symmetrical for Class D and Class F and asymmetrical for Class E (DE, FE) operation modes. In Class F amplifiers analyzed in frequency domain, the fundamental-frequency and harmonic load impedances are optimized by short-circuit termination and open-circuit peaking to control the voltage and current waveforms at the device output to obtain maximum efficiency. In Class E amplifiers analyzed in time domain, an efficiency improvement is achieved by realizing the on/off active device switching operation (the pinch-off and saturation modes) with special current and voltage waveforms so that high voltage and high current do not concur at the same time.

In modern wireless communication systems, it is very important to realize both high-efficiency and linear operation of the power amplifiers. Chapter 12 describes a variety of techniques and approaches that can improve the power amplifier performance. To increase efficiency over power backoff range, the Doherty, outphasing, and envelope-tracking power amplifier architectures, as well as switched multipath power amplifier configurations, are discussed and analyzed. There are several linearization techniques that provide linearization of both entire transmitter system and individual power amplifier. Feedforward, cross cancellation, or reflect forward linearization techniques are available technologies for satellite and cellular base station applications achieving very high linearity levels. The practical realization of these techniques is quite complicated and very sensitive to both the feedback loop imbalance and the parameters of its individual components. Analog predistortion linearization technique is the simplest form of power amplifier linearization and can be used for handset application, although significant linearity improvement is difficult to realize. Different types of the feedback linearization approaches, together with digital linearization techniques, are very attractive to be used in handset or base station transmitters. Finally, the potential semidigital and digital amplification approaches are discussed with their architectural advantages and problems in practical implementation.

Chapter 13 discusses the circuit schematics and main properties of the semiconductor control circuits that are usually characterized by small size, low power consumption, high-speed performance, and operating life. Generally, they can be built based on the *p–i–n* diodes, silicon MOSFET, or GaAs MESFET transistors and can be divided into two basic parts: amplitude and phase control circuits. The control circuits are necessary to protect high power devices from excessive peak voltage or dc current conditions. They are also used as switching elements for directing signal between different transmitting paths, as variable gain amplifiers to stabilize transmitter output power, as attenuators and phase shifters to change the amplitude and phase of the transmitting signal paths in array systems, or as limiters to protect power-sensitive components.

Finally, Chapter 14 describes the different types of radio transmitter architectures, history of radio communication, conventional types of radio transmission, and modern communication systems. Amplitude-modulated transmitters representing the oldest technique for radio communication are based on high- or low-level modulation methods, with particular case of an amplitude keying. Single-sideband transmitters as the next-generation transmitters could provide higher efficiency due to the transmission of a single sideband only. Frequency-modulated transmitters then became a revolutionary step to improve the quality of a broadcast transmission. TV transmitters include different modulation techniques for transmitting audio and video information, both analog and digital. Wireless communication transmitters as a part of the cellular technologies provide a worldwide wireless radio access. Radar transmitters are required for many commercial and military applications such as phased-array radars, automotive radars, or electronic warfare systems. Satellite transmission systems contribute to worldwide transmission of any communication signals through satellite transponders and offer communication for areas with any population density and location. Ultra-wideband transmission is very attractive for their low-cost and low-power communication applications, occupying a very wide frequency range.

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ANDREI GREBENNIKOV

CONTENTS

INTRODUCTION

A vacuum-tube or solid-state radio transmitter is essentially a source of a radio-frequency (RF) signal to be transmitted through antenna in different radio systems such as wireless communication, television (TV) and broadcasting, navigation, radar, or satellite, the information format and electrical performance of which should satisfy the corresponding standard requirements. The transmission of radio signals is produced by modulation of different types, with different output power and transmission mode, and in different frequency ranges, from high frequencies to millimeter waves. Transmitters in which the power output is generated directly by the modulated source are considered as possessing high-level modulation systems. In contrast, arrangements in which the modulation takes place at a power level less than the transmitter output are referred to as low-level modulation systems.

Figure I.1 shows the simplified block diagram of a conventional radio transmitter intended to operate at radio and microwave frequencies, which consists of the following: the source of the information signal, which is usually amplified, filtered, or transformed to the intermediate frequency; the local oscillator and frequency multiplier, which establish the stabilized carrier frequency or some multiple of it; the RF modulator or mixer, which combines the signal and carrier frequency components to produce one of the varieties of the RF modulated waves; the power amplifier to deliver the RF modulated signal of required power level to the antenna; the antenna duplexer to separate and isolate transmitting and receiving paths. The power amplifier usually consists of cascaded gain stages, and each stage should have adequate linearity in the case of transmitting signal with variable amplitude corresponding to amplitude-modulated or multicarrier signals. In practice, there are many variations in transmitter architectures depending on the particular frequency bandwidth, output power, or modulation scheme.

Dr. Lee De Forest was an inventor who changed the world with electronics by inventing the vacuum tube, which he called the *audion*. In January 1907, De Forest filed a patent for an oscillation detector based on a three-electrode device representing a vacuum tube [1]. His pioneering innovation was the insertion of a third electrode (grid) in between the cathode (filament) and the anode (plate) of the previously invented diode. However, it was not until 1911 that De Forest built the first vacuum-tube amplifier based on three audions as amplifiers [2]. The original audion was capable of slightly amplifying received signals, but at this stage could not be used for more advanced applications such as radio transmitters. The inefficient design of the original audion meant that it was initially of little value to radio, and due to its high cost and short life it was rarely used. Eventually, vacuum-tube design was improved enough to make vacuum tubes more than novelties. Beginning in 1912, various researchers discovered that properly constructed (i.e., according to scientific and engineering principles) vacuum tubes could be employed in electrical circuits that made radio receivers and amplifiers thousands of times more powerful, and could also be used to make compact and efficient radio transmitters, which for the first time made radio broadcasting practical.

In 1914, the first vacuum-tube radio transmitters began to appear—a key technical development that would lead to the introduction of widespread broadcasting. Both amateurs and commercial firms started to experiment with the new vacuum-tube transmitters, employing them for a variety of purposes. Six years after suspending his efforts to make audio transmissions, when he had unsuccessfully

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