JON B. HAGEN

Radio-Frequency Electronics

Circuits and Applications

Second Edition

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Radio-Frequency Electronics

Circuits and Applications

This second, much updated edition of the best-selling *Radio-Frequency Electronics* introduces the basic concepts and key circuits of radio-frequency systems. It covers the fundamental principles applying to all radio devices, from wireless single-chip data transceivers to high-power broadcast transmitters.

New to this edition:

- Extensively revised and expanded throughout, including new chapters on radar, digital modulation, GPS navigation, and *S*-parameter circuit analysis.
- New worked examples and end-of-chapter problems aid and test understanding of the topics covered.
- Numerous extra figures provide a visual aid to learning, with over 400 illustrations throughout the book.

Key topics covered include filters, amplifiers, oscillators, modulators, low-noise amplifiers, phase lock loops, transformers, waveguides, and antennas. Assuming no prior knowledge of radio electronics, this is a perfect introduction to the subject. It is an ideal textbook for junior or senior courses in electrical engineering, as well as an invaluable reference for professional engineers in this area.

Praise for the first edition:

This book is wonderfully informative, and refreshingly different from the usual rehash of standard engineering topics. Hagen has put his unique insights, gleaned from a lifetime of engineering and radio science, into this volume and it shows. There's an insight per page, at least for me, that makes it truly enjoyable reading, even for those of us who think we know something about the field! *Paul Horowitz, Harvard University*

Jon B. Hagen was awarded his Ph.D. from Cornell University in 1972, where he went on to gain 30 years' experience as an electronic design engineer, as well as establishing and teaching a Cornell electrical engineering course on RF electronics. Now retired, he has held positions as Principal Engineer at Raytheon, Electronics Department Head at the Arecibo Observatory in Puerto Rico, and Director of the NAIC Support Laboratory at Cornell.

Preface

This book was written to help the reader to understand, analyze, and design RF circuits. Developed as a textbook for an RF engineering course at Cornell University, it can also be used for self-study and as a reference for practising engineers. The scope of topics is wide and the level of analysis ranges from introductory to advanced. In each chapter, I have tried to convey an intuitive "how things work" understanding from which the mathematical analysis follows. The initial chapters present the amplifiers, filters, modulators, and demodulators, which are the basic building blocks of radio systems, from AM and FM to the latest digital radio systems. Later chapters alternate between systems, such as television, and radio astronomy, and theoretical topics, such as noise analysis and radio spectrometry. The book provides the RF vocabulary that carries over into microwave engineering, and one chapter is devoted to waveguides and other microwave components.

In this second edition, many chapters have been expanded. Others have been rearranged and consolidated . New chapters have been added to cover radar, the GPS navigation system, digital modulation, information transmission, and *S*-parameter circuit analysis.

The reader is assumed to have a working knowledge of basic engineering mathematics and electronic circuit theory, particularly linear circuit analysis. Many students will have had only one course in electronics, so I have included some fundamental material on amplifier topologies, transformers, and power supplies. The reader is encouraged to augment reading with problem-solving and lab work, making use of mathematical spreadsheet and circuit simulation programs, which are excellent learning aids and confidence builders. Some references are provided for further reading, but whole trails of reference can be found using the internet.

For helpful comments, suggestions, and proofreading, I am grateful to many students and colleagues, especially Wesley Swartz, Dana Whitlow, Bill Sisk, Suman Ganguly, Paul Horowitz, Michael Davis, and Mario Ierkic.

Jon B. Hagen
Brooklyn, NY
July 2008

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CHAPTER

1 Introduction

Consider the magic of radio. Portable, even hand-held, short-wave transmitters can reach thousands of miles beyond the horizon. Tiny microwave transmitters riding on spacecraft return data from across the solar system. And all at the speed of light. Yet, before the late 1800s, there was nothing to suggest that telegraphy through empty space would be possible even with mighty dynamos, much less with insignificantly small and inexpensive devices. The Victorians could extrapolate from experience to imagine flight aboard a steam-powered mechanical bird or space travel in a scaled-up Chinese skyrocket. But what experience would have even hinted at *wireless* communication? The key to radio came from theoretical physics. Maxwell consolidated the known laws of electricity and magnetism and added the famous displacement current term, $\partial D/\partial t$. By virtue of this term, a changing electric field produces a magnetic field, just as Faraday had discovered that a changing magnetic field produces an electric field. Maxwell's equations predicted that *electromagnetic waves* can break away from the electric currents that generate them and propagate independently through empty space with the electric and magnetic field components of the wave constantly regenerating each other.

Maxwell's equations predict the velocity of these waves to be $1/\sqrt{\varepsilon_0 \mu_0}$ where the constants, ε_0 and μ_0, can be determined by simple measurements of the forces between static electric charges and between current-carrying wires. The dramatic result is, of course, the experimentally-known speed of light, 3×10^8 m/sec. The electromagnetic nature of light is revealed. Hertz conducted a series of brilliant experiments in the 1880s in which he generated and detected electromagnetic waves with wavelengths very long compared to light. The utilization of Hertzian waves (electromagnetic waves) to transmit information developed hand-in-hand with the new science of electronics.

Where is radio today? AM radio, the pioneer broadcast service, still exists, along with FM, television and two-way communication. But radio now also includes digital broadcasting formats, radar, surveillance, navigation and broadcast satellites, cellular telephones, remote control devices, and wireless data communications. Applications of radio frequency (RF) technology outside

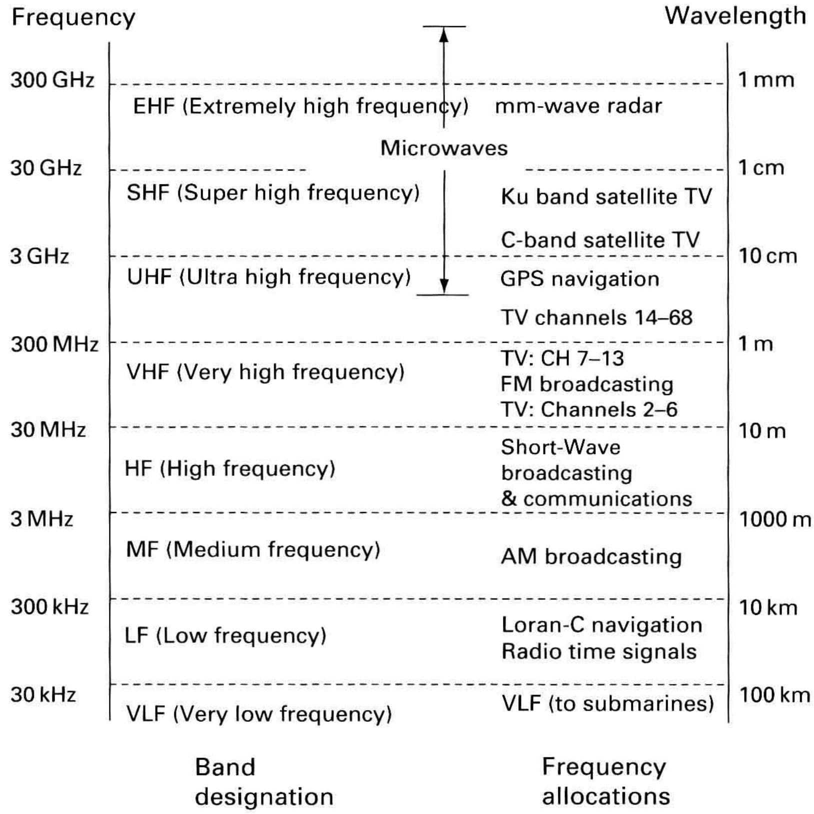

Figure 1.1. The radio spectrum.

radio include microwave heaters, medical imaging systems, and cable television. Radio occupies about eight decades of the electromagnetic spectrum, as shown in Figure 1.1.

1.1 RF circuits

The circuits discussed in this book generate, amplify, modulate, filter, demodulate, detect, and measure ac voltages and currents at radio frequencies. They are the blocks from which RF systems are designed. They scale up and down in both power and frequency. A six-section bandpass filter with a given passband shape, for example, might be large and water-cooled in one application but subminiature in another. Depending on the frequency, this filter might be made of sheet metal boxes and pipes, of solenoidal coils and capacitors, or of piezoelectric mechanical resonators, yet the underlying circuit design remains the same. A class-C amplifier circuit might be a small section of an integrated circuit for a wireless data link or the largest part of a multi-megawatt broadcast transmitter. Again, the design principles are the same.

1.2 Narrowband nature of RF signals

Note that most frequency allocations have small fractional bandwidths, i.e., the bandwidths are small compared to the center frequencies. The fractional bandwidth of the signal from any given transmitter is less than 10 percent – usually much less. It follows that the RF voltages throughout a radio system are very nearly sinusoidal. An otherwise purely sinusoidal RF "carrier" voltage[1] must be *modulated* (varied in some way) to transmit information. Every type of modulation (audio, video, pulse, digital coding, etc.) works by varying the amplitude and/or the phase of the sinusoidal RF wave, called the "carrier" wave. An unmodulated carrier has only infinitesimal bandwidth; it is a pure spectral line. Modulation always broadens the line into a spectral band, but the energy clusters around the carrier frequency. Oscilloscope traces of the RF voltages in a transmitter or on a transmission line or antenna are therefore nearly sinusoidal. When modulation is present, the amplitude and/or phase of the sinusoid changes but only over many cycles. Because of this narrowband characteristic, elementary sine wave ac circuit analysis serves for most RF work.

1.3 AC circuit analysis – a brief review

The standard method for ac circuit analysis that treats voltages and currents in linear networks is based on the linearity of the circuit elements: inductors, capacitors, resistors, etc. When a sinusoidal voltage or current generator drives a circuit made of linear elements, the resulting steady-state voltages and currents will all be perfectly sinusoidal and will have the same frequency as the generator. Normally we find the response (voltage and current amplitudes and phases) of driven ac circuits by a mathematical artifice. We replace the given sinusoidal generator by a hypothetical generator whose time dependence is $e^{j\omega t}$ rather than $\cos(\omega t)$ or $\sin(\omega t)$. This source function has both a real and an imaginary part since $e^{j\omega t} = \cos(\omega t) + j\sin(\omega t)$. Such a nonphysical (because it is complex) source leads to a nonphysical (complex) solution. But the real and imaginary parts of the solution are separately good physical solutions that correspond respectively to the real and imaginary parts of the complex source. The value of this seemingly indirect method of solution is that the substitution of the complex source converts the set of linear *differential* equations into a set of easily solved linear *algebraic* equations. When the circuit has a simple topology, as is often the case, it can be reduced to a single loop by combining obvious series and parallel branches. Many computer programs are available to

[1] There is no low-frequency limit for radio waves but the wavelengths corresponding to audio frequencies, hundreds to thousands of kilometers, make it inefficient to connect an audio amplifier directly to an antenna of reasonable size. Instead, the information is impressed on a carrier wave whose wavelength is compatible with practical antennas.

find the currents and voltages in complicated ac circuits. Most versions of SPICE will do this steady-state ac analysis (which is much simpler than the transient analysis which is their primary function). Special linear ac analysis programs for RF and microwave work such as Agilent's ADS and MMICAD include circuit models for strip lines, waveguides, and other RF components. You can write your own program to analyze ladder networks (see Problem 1.3) and to analyze most filters and matching networks.

1.4 Impedance and admittance

The coefficients in the algebraic circuit equations are functions of the complex *impedances* (V/I), or *admittances* (I/V), of the *RLC* elements. The voltage across an inductor is $L\mathrm{d}I/\mathrm{d}t$. If the current is $I_0 e^{j\omega t}$, then the voltage is $(j\omega L)I_0 e^{j\omega t}$. The impedance and admittance of an inductor are therefore respectively $j\omega L$ and $1/(j\omega L)$. The current into a capacitor is $C\mathrm{d}V/\mathrm{d}t$, so its impedance and admittance are $1/(j\omega C)$ and $j\omega C$. The impedance and admittance of a resistor are just R and $1/R$. Elements in series have the same current so their total impedance is the sum of their separate impedances. Elements in parallel have the same voltage so their total admittance is the sum of their separate admittances. The real and imaginary parts of impedance are called *resistance* and *reactance* while the real and imaginary parts of admittance (the reciprocal of impedance) are called *conductance* and *susceptance*.

1.5 Series resonance

A capacitor and inductor in series have an impedance $Z_s = j\omega L + 1/(j\omega C)$. This can be written as $Z_s = j(L/\omega)(\omega^2 - 1/[LC])$, so the impedance is zero when the (angular) frequency is $1/\sqrt{LC}$. At this *resonant frequency*, the series *LC* circuit is a perfect *short circuit* (Figure 1.2). Equal voltages are developed across the inductor and capacitor but they have opposite signs and the net voltage drop is zero.

At resonance and in the steady state there is no transfer of energy in or out of this combination. (Since the overall voltage is always zero, the power, IV, is always zero.) However, the circuit does contain *stored* energy which simply sloshes back and forth between the inductor and the capacitor. Note that this circuit, by itself, is a simple bandpass filter.

Figure 1.2. Series-resonant *LC* circuit.