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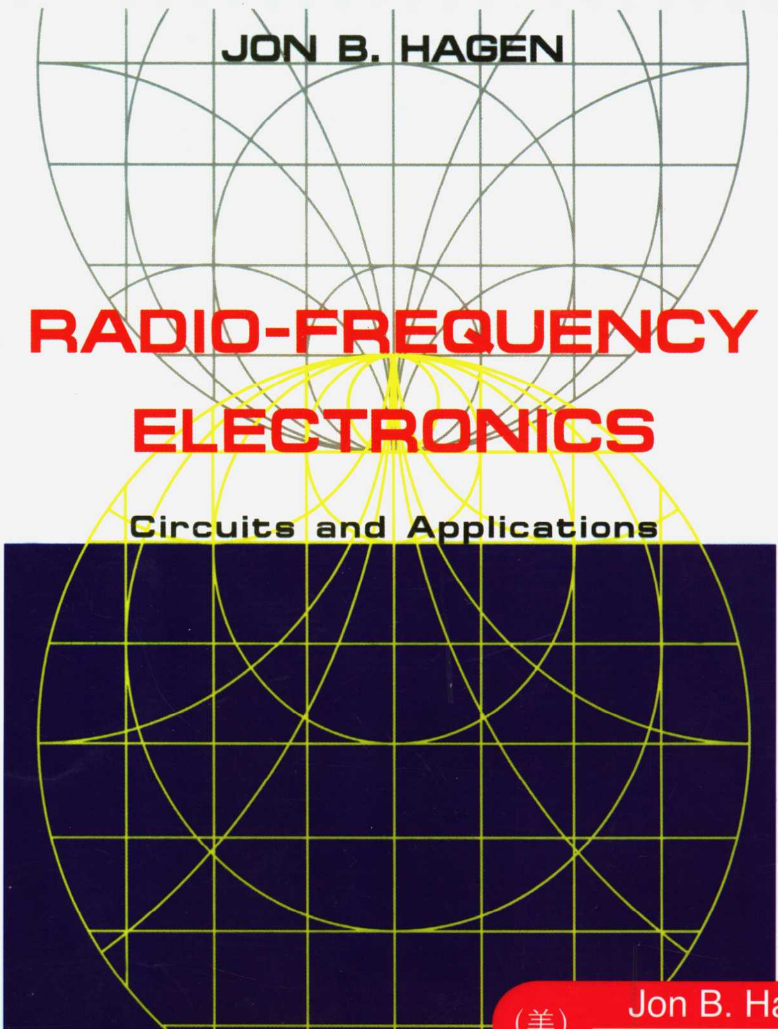
射频电子学

电路及其应用

(英文版)

JON B. HAGEN



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Circuits and Applications

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PREFACE

This book was written to prepare the reader to analyze and design radio-frequency (RF) circuits. Developed as a text for a one-semester electrical engineering course at Cornell University, it can also be used for self-study and as a reference for practicing engineers. The discussions of systems, for example television and radio astronomy, complement the detailed analyses of the basic circuit blocks. In the discussions of these basic circuits, I have tried to convey an intuitive understanding from which mathematical analysis easily follows. The scope of topics is wide, and the level of analysis ranges from introductory to advanced. This seems to suit today's students who, though unfamiliar with radio-frequency circuits, are well prepared in engineering fundamentals and have good analytical skills. The only background assumed is basic engineering mathematics and physics, linear circuit analysis, and some elementary analog electronics. Many readers will have had more digital than analog experience, so the digital aspects of switching modulators and direct digital synthesizers are given only short explanations. On the other hand, some basic analog circuit elements such as transformers are now less commonly understood and are therefore reviewed in detail.

For helpful comments and suggestions I am grateful to many students and colleagues, especially Michael Davis, Paul Horowitz, Mario Ierkic, and Wesley Swartz.

Jon B. Hagen

Ithaca, NY
October 1996

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INTRODUCTION 1

Consider the magic of radio. Portable, even hand-held, short-wave transmitters can reach thousands of miles beyond the horizon. Tiny microwave transmitters aboard space probes 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 apparatus. 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 even have hinted at wire*less* 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 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 static forces between electric charges and between current-carrying wires. The dramatic result is, of course, the experimentally known speed of light, 3×10^8 m/s. 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 (the radio waves we now take for granted) 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. Now radio also includes radar, surveillance, navigation and broadcast satellites, cellular telephones, remote control devices, and wireless data communications. Applications of radio frequency (RF) technology outside radio include microwave heaters, medical imaging systems, and cable television.

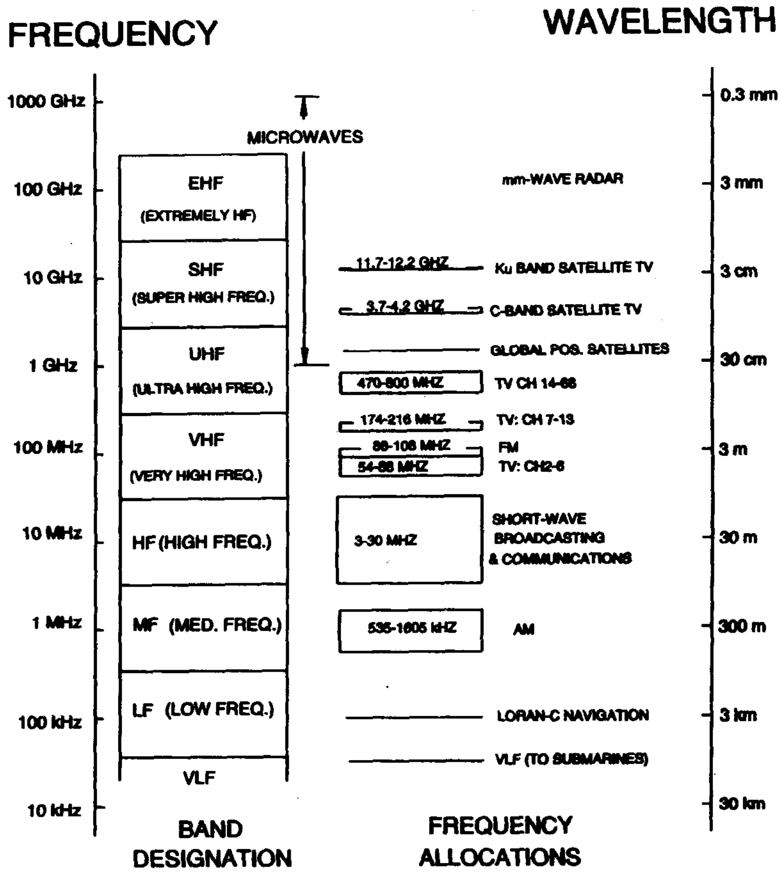

Figure 1-1. The radio spectrum.

Radio occupies about eight decades of the electromagnetic spectrum, as shown in Figure 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 multimegawatt broadcast transmitter. Again, the design principles are the same.

NARROW-BAND NATURE OF RF SIGNALS

Note that most of the RF allocations have small fractional bandwidths, that is, the bandwidths are small compared to the center frequencies. The fractional bandwidth of the signal from any given transmitter is less than ten percent – usually much less. This means that the RF voltages throughout a radio system are very nearly sinusoidal. An otherwise purely sinusoidal RF "carrier" voltage 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 carrier. 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 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 narrow-band characteristic, elementary sine wave ac circuit analysis serves for most RF work.

AC CIRCUIT ANALYSIS – A BRIEF REVIEW

The standard ac circuit theory that treats voltages and currents in linear networks is based on the linearity of the circuit elements. When a sinusoidal voltage or current generator drives a circuit, 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 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 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. Several computer programs are available to 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 COMPACT, TOUCHSTONE, and MMICAD include circuit models for strip lines, waveguides, and other RF components. You can write a simple program to analyze ladder networks (see Problem 3) that will analyze most filters and matching networks.

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 $L\ dI/dt$. If the current is $I_0e^{j\omega t}$, then the voltage is $(j\omega L)I_0e^{j\omega t}$. The impedance and admittance of an inductor are therefore respectively $j\omega L$ and $1/(j\omega L)$. The current into a capacitor is $C\ dV/dt$, 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 $1/R$, respectively. 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*.

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.