Second Edition

HIGH-FREQUENCY and MICROWAVE CIRCUIT DESIGN

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Preface to Second Edition

The first edition of *High-Frequency and Microwave Circuit Design* was aimed at enabling graduating electrical engineering students to design stable amplifiers using potentially unstable transistors. The book was rather brief and assumed a better background in undergraduate topics than can still, at this date, often be depended upon. This author presented impedance matching using irises in waveguides and found that the length of WR 90 he brandished aloft was the first waveguide many had ever seen. Thus, it seemed advisable to add Chapter 2, "Waveguides," before bringing up irises. It was then reasonable to do impedance matching in Chapter 3.

The first edition covered stability circles in the first chapter. This part of the presentation made use of scattering coefficients, which are not commonly taught in any standard undergraduate texts on distributed circuits. We needed scattering coefficients even before they had been introduced. So, Chapter 4 introduces scattering coefficients and then examines the topic of stability. Chapters 5 and 6 were the original Chapters 3 and 4, on tuned circuits and oscillators and modulation circuits. Chapter 7 deals with the origin and control of noise powers. Chapter 8, on antennas, takes a somewhat different, qualitative approach than the previous edition; its exercises relate antenna performance to the requirements of digital communication systems. Throughout, the author has endeavored to offer practical homework problems.

Preface to the First Edition

"All right, Dr. Nelson," the potential reader may be thinking or saying, "what unfulfilled need does this book aim to fill?" Well, I say, every year we expect B.S. graduates in electronics engineering to have learned something that we formerly saved for graduate work. The material in this book is like that. The curriculum at this non-Ph.D.-granting institution requires a year of active circuit design from a book such as Microelectronic Circuits by Sedra and Smith. Thus, the student's exposure to high frequency effects in electronics will stop with the hybrid-pi high frequency equivalent circuit, leaving him or her to be most astonished and feeling helpless when they encounter a spec sheet which states scattering coefficients. Also, even though the curriculum might require an electromagnetics course treating wave behavior, the topics in electromagnetics books, even though they may treat standing waves and impedance matching, often do not mention that one's knowledge of the impedance to be matched may actually be stated in terms of scattering coefficients. Thus, a concise introduction to scattering coefficients that is understandable to undergraduates is a key aim of this book.

If there were one somewhat specialized audience at which this book is aimed, it would be those engineers who are or will be working to provide the world with the vast number and types of communication apparatus which will be needed at the beginning of the twenty-first century. These devices will have various digital functions and features, yet there will also need to be in them various aspects of analog design. The engineering graduate who thinks he or she will be able to confine herself, or himself, to either analog or digital design will quickly find that one has voluntarily limited one's usefulness to an employer. The author hopes to "demystify" some of the useful techniques that future communication engineers may need. He hopes that he can emphasize that many concepts have not changed and that the newer concepts and perspectives easily grew out of the traditional. One of his major aims has been not to startle the reader with many totally new or unfamiliar techniques.

Resonant circuits are a topic to which the student may have been introduced in both network analysis and active circuits courses. Yet, those presentations may both have been rather academic and totally lacking in relation to practical needs. The author hopes to motivate study of this topic by examples and exercises, which are applied to transmitters, receivers, and other applications requiring selectivity in the signals which are passed or rejected.

Chapter 1 begins at medium frequencies and quickly arrives at what are generally considered microwaves. It calculates the easily obtained distributed parameters in coaxial lines and determines their propagation constants and low and high frequency characteristic impedance. It moves on to the design of microstrip lines for specified characteristic impedance. Reflection coefficients and their effect on input impedances of lines are next derived, as well as the effects of attenuation on input impedance. Use of the Smith chart is reviewed. Finally, we arrive at scattering coefficients as two-port parameters for transistors. We are introduced to stability considerations and conditions for simultaneous conjugate impedance matching at input and output.

In Chapter 2, we begin the task of impedance matching by considering using L-sections of lumped impedance. We move on to quarter-wavelength and near-quarter-wavelength transmission lines for impedance matching; how and when we may use a matching section, which is not exactly a quarter-wavelength, is a straightforward procedure that is not commonly taught. Then we consider how one shunt or series reactance may match the transmission line if it is placed at the correct location. Finally, we see how the required reactance may be provided by an appropriate length of short or open-circuited transmission line, called a "stub." For completeness, we have also included irises for the matching of waveguides.

In Chapter 3, we begin with bandpass amplifiers using LRC circuit design and crystal filters. We apply these concepts to the needs of receivers and calculate performance limitations. We look at what are the requirements for a successful oscillator and illustrate it with perhaps conceptually the simplest oscillator, the phase shift oscillator. We move on to the increasing complexity of the Colpitts, the Hartley, and the crystal-controlled variety. Finally, we consider how one might design a voltage-controlled oscillator, as may be found in phase-locked loops.

Chapter 4 looks first at the most elementary ways of producing and detecting amplitude and frequency modulation. Synchronous detectors are the first demodulators considered, then later, the less expensive envelope detector. Finally, we look at the basics of the most common forms of digital modulation and demodulation.

Noise can be a very complex and theoretical topic. The approach here in Chapter 5 is simply to state the results using as given constants the arcane symbols of statistical mechanics. We define noise factor and noise figure in functional ways and look at the general way in which noise is added as we cascade amplifiers. Having established that overall noise performance depends mainly upon both the gain and the noise factor of the first stage, we learn how to draw amplifier noise and gain circles so as to have a systematic way to make such tradeoffs. We finish by seeing the high noise performance of FM and the markedly higher performance of systems of digital modulation.

Chapter 6 aims to lift, at least a little, the veil of mystery which has for many years hidden from young engineers some rather straightforward characteristics of antennas. The principles are introduced in such a way that a minimum amount of theory leads to a number of important performance characteristics. An aspect of this chapter as a capstone for the book is to use antenna gains, transmitter power, distance, carrier frequency, and bit rate in the evaluation of the optimum communication systems.

The computer revolution has also made available very powerful calculators which can do complex algebra, for reasonable prices. Appendix A gives a few helpful formulas which enable much of the impedance match problem to be soluble directly on the calculator.

Einstein was quoted that we should make complex things as "simple as possible, but no simpler." It is fondly hoped that this book can make the areas of high frequency design as clear as possible to the graduate electrical engineer.

About the Author

Charles G. Nelson, Ph.D., was born in Northport, Michigan. He received all his primary education in a tiny school district and graduated as co-valedictorian of his class. All of his academic degrees are in electrical engineering, including the bachelor of science from Michigan State University and the master of science and doctor of philosophy degrees from Stanford University. His doctoral research involved conversion efficiency of a klystron using varying profiles of magnetic field to hold the electron beam together. A summary was published in the Transactions on Electron Devices of IEEE. Other publications were in the Annual Convention on Engineering in Medicine and Biology and periodic and final reports to the California Department of Transportation (CALTRANS).

This is his first textbook to be published, although his students have for years used his photocopied notes as the only textbook for two or three subjects.

His military service was with the Research Lab of the Ordnance Missile Labs at Redstone Arsenal, Huntsville, AL, where his primary assignment was the study of a communication system using pulse position modulation with only discrete positions allowed, thus exhibiting some of the advantages and limitations of digitization. He had industrial experience with Zenith Radio Research Corporation of Menlo Park, CA, working on extending the operation frequency of the electron beam parametric amplifier, and summer research with NASA at Ames Research Labs, doing early studies of phase modulation of a light beam in lithium niobate. His research interests continue to be in fields and waves and communication systems, and in sound and noise pollution.

Dr. Nelson has taught electrical engineering at California State University, Sacramento since February 1965. He served as chair of the department of electrical and electronics engineering from 1965 to 1967 and from 1979 to 1986. He has been active in various areas of faculty governance for many years. He has been registered by the State of California as a Safety Engineer. He is a member of Tau Beta Pi, Pi Mu Epsilon, and Sigma Xi, and a life member of the IEEE.

Dr. Nelson has been married to Nina Volkert-Nelson since 1967. They have two adult children, a son educated as a computer scientist and a daughter who has her master's degree in cello performance. In his leisure, Dr. Nelson enjoys reading both fiction and nonfiction, from James Thurber to John LeCarre to Robert Woodward. He loves listening to a variety of instrumental and vocal music, is considered to be an opera buff, and he sings at the level of the better church choirs. He also enjoys the Pacific surf and wildlife and the tranquility of the shores of Lake Michigan.

1 From Lumped to Distributed Parameters

1.1 EXPECTED AND UNEXPECTED RESULTS FROM THE NETWORK ANALYZER

One very useful instrument for studying high-frequency behavior of circuits is called the *vector network analyzer*; an example of one is pictured in Figure 1.1. Measurements can be made of impedance connected to either port 1 or port 2, or of the amount of signal gain and phase shift from one port to the other, when an amplifying or attenuating two-port is connected between the ports. One first selects a frequency range of interest between 0.3 and 3000 Mhz, and then calibrates the instrument for that range and for the type of measurement planned. As an example of what is possible, the machine was calibrated from 0.3 to 100 Mhz for measurements of the impedance connected to port 1. After calibration, a type N-to-BNC coaxial adapter was connected to port 1, and a BNC-to-binding-post adapter was connected to the first adapter, after which a nominal 47 pF capacitor was connected to the binding posts without shortening the original capacitor leads. The reactances measured are shown in Table 1.1.

Now, these data are not too startling at the lower frequencies, although one observes a modest bit of jumping around. The next thing done was to disconnect the capacitor and make measurements of the impedances of just the adapters that were added after calibration. Again, the data did some jumping around, but we could say the adapters provided a fairly consistent 6.0 pF. Hence, since the capacitances of the adapters and the capacitor being measured are effectively in parallel, they add, and we can probably say with good accuracy that the "official" capacitor provides very close to 46 pF, which is certainly well within 10% of the nominal value. But now we ask, "What on earth is going on at high frequency?" and we must suspect that the long leads are having an effect. Indeed, the total negative reactance is decreasing at high frequency faster than it would for constant capacitance, until eventually the reactance goes positive, that is, inductive, so we must conclude that the long leads provide some inductance, the reactance of which cancels some of the capacitive reactance, giving a lower net reactance. Every little segment of wire contributes some inductance, so we say inductance is *distributed* uniformly along the leads. The "smart" but naive machine calculates a single equivalent circuit element, which is a capacitor higher than the nominal value, until one reaches the frequency where the inductive reactance in the leads takes over and makes the total impedance inductive.

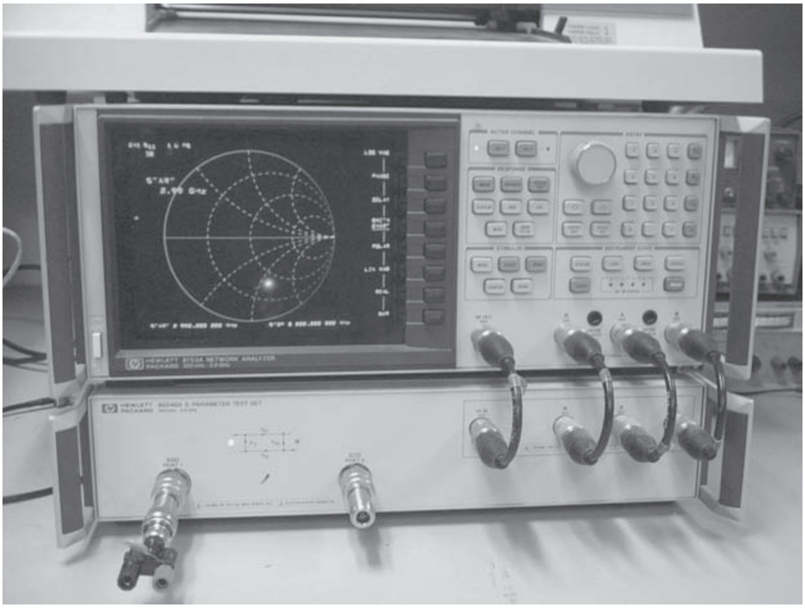

FIGURE 1.1 Network analyzer with adapters and unknown capacitor connected.

TABLE 1.1
Reactances

Frequency (Mhz)	Reactance	Eq. Circuit Element
1.0	$-j3050$	52.2 pF
2.0	$-j1535$	51.8 pF
5.0	$-j606$	52.5 pF
10	$-j302$	52.7 pF
20	$-j144.6$	55.05 pF
50	$-j38.18$	83.3 pF
100	$+j21.6$	34.4 nH

Example 1.1

The author once heard and has for years been quoting a rule of thumb that one can expect component leads to inject a nanohenry of inductance for each millimeter of wire. Let's play with our data a bit and see how well this rule checks out. The reactances we obtained above were each the average of 16 individual measurements, so we will assume they were accurate and calculate the corresponding admittance (which is called *susceptance*). We will assume that the adapters add 6.0 pF and subtract that susceptance from the total. We convert the new susceptance back to impedance and subtract the reactance corresponding to 46.0 pF. We will attribute the difference to inductive reactance and calculate the lead inductance from that. We will do this at 20 MHz and leave the numbers at 50 and 100 MHz for the exercises.

Solution: $-1/j144.6 = j6.93 \times 10^{-3}$.

Now, 6.0 pF yields $Y = j7.54 \times 10^{-4}$ at 20 MHz. Subtracting gives $Y = j6.16 \times 10^{-3}$, or an impedance of $Z = -j162$. At 20 Mhz, 46.0 pF yields an impedance of $-j173$. Therefore, a subtraction gives the result that the inductance is adding $j11$ ohms, which at 20 Mhz yields an inductance of 87.5 nH. Since the lead lengths totaled about 55 mm, our result says to expect about 1.5 nH/mm of lead length.

Exercise 1.1

Repeat the calculations above for 50 and 100 Mhz. What inductance do you get?

Answers: You should get 87.9 and 86.5 nH, respectively.

The results above represent a departure from the type of circuit modeling the student of electrical engineering or electronics technology first sees, in which the circuit parameters are assumed, with good justification, to be "lumped" in a fairly obvious location. The capacitor in the example above appeared physically as a lump of dielectric material with leads sticking out of two ends. One is normally taught that these leads are basically short circuits, not contributing any resistance or other impedance. What we found out was that the leads contributed small amounts of inductance, but that at high frequencies the impedance of the inductance became higher than the impedance of the intended capacitance. Sometimes the frequency at which the reactances are equal is called the *frequency of self-resonance*.

1.2 INTERWIRE CAPACITANCE IN AN INDUCTOR

Once one begins thinking about accidental circuit parameters that may appear, one might wonder, "Suppose we set out with wire and a coil form to wind an inductor. Can we expect every bit of wire to contribute capacitance to every other bit of wire?" The answer is, "Yes, indeed." We will in fact provide a "recipe" for the RF (radio frequency) engineer to fabricate handmade inductors because this is one component that may commonly need to be connected to two terminals of an integrated circuit in which many functions have already been provided. The procedure is discussed in *Reference Data for Radio Engineers*, published in 1956 by the Howard Sams Co. We illustrate several aspects of such design in the following example.

Example 1.2 Winding a Coil for Specified Inductance

The author was hoping to wind a coil with inductance close to 0.5 μH. He took AWG #12 wire because he had some and wanted to keep resistance as low as possible, hence Q high. Also, the wire was stiff enough to avoid any accidental short circuits between adjacent turns of the wire. The temporary coil form was a ballpoint pen. Ten turns were wound. The resulting coil was 3 cm long with a diameter of 1 cm. The handbook mentioned in the paragraph above predicts for a solenoidal coil, an inductance given in microhenries by

$$L = n^2 dF,$$