Engineering Applications of Electromagnetic Theory

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Samuel Y. Liao

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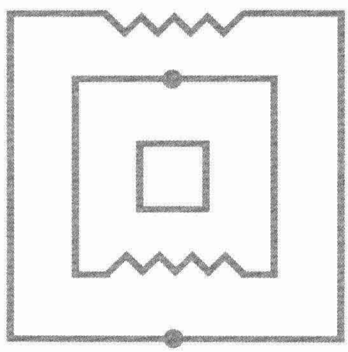

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Engineering Applications of Electromagnetic Theory

For their valuable collective contributions, I dedicate this book to my wife, Lucia Hsiao-Chuang Lee, and my children, Grace in bioengineering, Kathy in electrical engineering, Gary in electronics engineering, and Jeannie in teacher education.

Preface

This book is intended to serve primarily as a text for courses on engineering applications of electromagnetic theory at the senior or beginning graduate level in electrical engineering. The contents of the book grew out of lecture notes that I used in a one-semester course for several years. I assume that students have had previous courses in electrical circuit analysis and electromagnetic theory, including Maxwell's equations. Because the book is largely self-contained, it can also be used as a textbook for physical science students and as a reference book by electronics engineers working in the areas of electromagnetic energy transmission and measurements.

In most universities and four-year colleges, two basic courses in electromagnetic theory and applications are required for all electrical engineering students in the junior or senior year. The first deals with electromagnetic field theory and the second addresses the engineering applications of field theory to transmission lines, waveguides, and antennas. Many good textbooks present either the two courses combined or the theory course alone; only a couple of texts cover the engineering applications course, and they are out of print. This book is intended to serve as a text for the applications course only.

In accordance with the traditional subjects of the second course on electromagnetic theory, this book contains three main parts: transmission lines, waveguides, and antennas. Much new material was incorporated into each part in order to make the book as current as possible.

Part One contains Chapters 1–4 and deals with transmission lines:

Chapter 1 describes transmission lines.

Chapter 2 presents transmission-line matching techniques, such as single-stub matching and double-stub matching.

Chapter 3 covers striplines, such as microstrip lines, parallel striplines, and coplanar striplines.

Chapter 4 discusses digital transmission lines, such as pulse digital lines, superconducting lines, and optical-fiber lines.

Part Two contains Chapters 5–8 and deals with waveguides:

Chapter 5 discusses TE and TM modes in rectangular waveguides and waveguide characteristics.

Chapter 6 analyzes TE and TM modes in circular waveguides and waveguide characteristics.

Chapter 7 investigates optical-fiber waveguides, such as step-index fibers, graded-index fiber, and resonators.

Chapter 8 describes dielectric planar waveguides, such as parallel-plate, dielectric-slab, and coplanar waveguides.

Part Three contains Chapters 9–12 and deals with antennas:

Chapter 9 discusses antenna parameters and characteristics, such as antenna gain, bandwidth, impedance matching, and so on.

Chapter 10 presents dipole antennas and slot antennas.

Chapter 11 covers broadband antennas and array antennas, such as log-periodic antennas, phased-array antennas, Yagi–Uda antennas, and antenna-measurement techniques.

Chapter 12 analyzes an electromagnetic energy transmission system, including antenna temperature, electric-field measurements, and computations.

Instructors have choices in the selection or order of topics to fit either a one-semester or a one-quarter course. Most example problems and field patterns are solved both by conventional calculations and computer methods. The computer solutions are intended to help the student to write computer programs for solving transmission-line problems with complex quantities and hyperbolic functions, determining the modes in waveguides, and plotting electric-field patterns or radiation-power patterns of various antennas. Problems at the end of each chapter are intended to further the student's understanding of the subjects discussed in that chapter. Instructors may obtain a solutions manual from the publisher.

I would like to thank the following reviewers for their many helpful suggestions:

Dr. Ken James, *California State University, Long Beach*; Dr. J. B. Knorr, *Naval Postgraduate School*; Dr. Paul E. Mayes, *University of Illinois at Urbana–Champaign*; Dr. Harold Mott, *University of Alabama*; Dr. Keith D. Paulsen, *University of Arizona*; Dr. Farhad Radpour, *University of Oklahoma*; Dr. Sembian Rengarajan, *California State University, North Ridge*; Dr. David Stephenson, *Iowa State University*; and Dr. V. K. Tripathi, *Oregon State University.*

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S. Y. L.

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APPENDIXES

Chapter 0

Introduction

0-1 ELECTROMAGNETIC ENERGY TRANSMISSION

The purpose of this book is to present the engineering applications of electromagnetic (EM) field theory to transmission lines, waveguides, and antennas. A course in the engineering applications of electromagnetic energy transmission is a fundamental course in the undergraduate or beginning graduate study of electrical engineering.

A radio frequency (RF) energy transmission system consists of a transmitter, a transmission line, and/or a waveguide, a transmitting antenna, a propagation medium or free space, a receiving antenna, a receiver transmission line, and/or a waveguide, and finally a receiver. The entire circuit between the transmitter output terminals and the receiver input terminals, represented by a "black box" in Fig. 0-1-1, is the subject that we describe, analyze, and discuss extensively in this book.

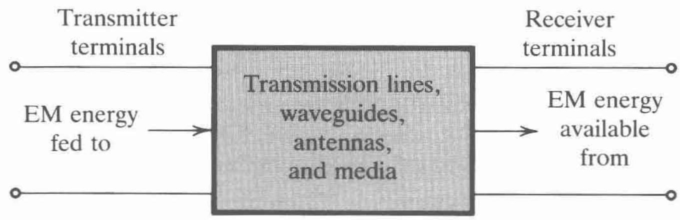


Figure 0-1-1 Block diagram of EM energy transmission.

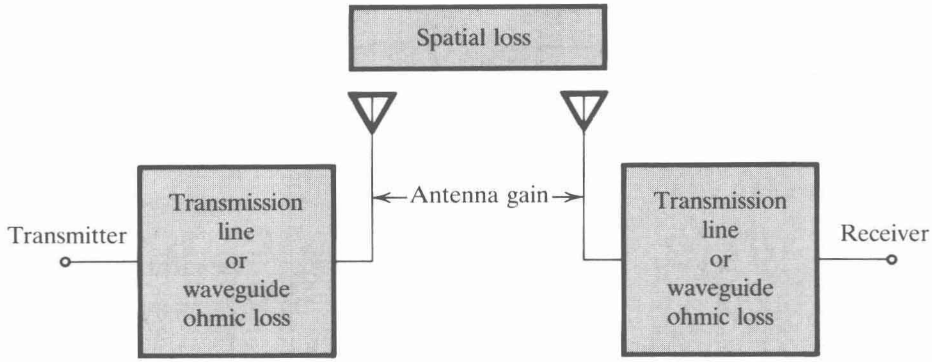


Figure 0-1-2 Losses and gains in an energy transmission system.

As electromagnetic energy travels from the transmitter terminals through various links to the receiver terminals, the energy is amplified and/or attenuated along the way. However, for reasons that will become apparent later, electromagnetic energy should be transmitted at maximum efficiency. Thus the power loss and gain in the links between the transmitter and receiver are the main concern of this book. We can relate power loss and gain to the "black-box" elements in Fig. 0-1-1, as shown in Fig. 0-1-2.

The four major elements in an RF system are:

Transmission Lines. The transmission line remains one of the primary types of energy carrier, because its frequency range extends from zero to a very high value. If a line is properly matched, maximum efficiency can be reached at a very high frequency. We can conveniently analyze the line in terms of voltage, current, and impedance by the distributed circuit theory. If the spacing between conductors is greater than or comparable to the wavelength of the signal being transmitted, we have to analyze the transmission line as a waveguide.

Waveguides. Waveguides are used primarily in the microwave region. In waveguides, the electric and magnetic fields are confined to the space within the guides. Hence, no power is lost through radiation, nor is dielectric loss of any practical importance, because the guides are normally air-filled. We can analyze waveguides, which are sometimes referred to as another type of transmission line, only by electromagnetic field theory.

Antennas. The antenna is another type of transmission line by which electromagnetic energy can be transmitted over a wide range of frequencies. Because of the directivity or gain of any antenna, the use of antennas in the microwave region has expanded rapidly in recent decades. We cannot utilize ordinary simple circuit theory for determining the characteristics of an antenna because of the high frequency at which the antenna operates. Hence, we have to analyze the antenna by electromagnetic field theory. After discussing the electromagnetic energy radiated by an antenna, we address the problem of wave propagation in free space.

Media. The medium is usually free space or the dielectric substrate.

Electromagnetic energy transmission systems have been used increasingly in such diverse applications as power transmission, television distribution, long-distance telephone transmission, computer links, radio astronomy, space navigation, radar systems, medical equipment, missile systems, satellite communications, and military command and control.

0-2 FREQUENCY

The frequency limitations of transmission lines, waveguides, and antennas are different. We can analyze lines using distributed circuit theory. However, we must use electromagnetic field theory in order to analyze waveguides and antennas.

0-2-1 Frequency Ranges

It seems appropriate to list here the frequency bands, since we refer to frequency ranges throughout this book. In the electronics industry and academic institutions, the Institute of Electrical and Electronics Engineers, Inc. (IEEE) frequency bands, as shown in Table 0-2-1, are commonly used.

Table 0-2-1 IEEE frequency bands

Band Number	Designation	Frequency	Wavelength
2	ELF (Extreme low frequency)	30–300 Hz	10–1 Mm
3	VF (Voice frequency)	300–3000 Hz	1–0.1 Mm
4	VLF (Very low frequency)	3–30 kHz	100–10 km
5	LF (Low frequency)	30–300 kHz	10–1 km
6	MF (Medium frequency)	300–3000 kHz	1–0.1 km
7	HF (High frequency)	3–30 MHz	100–10 m
8	VHF (Very high frequency)	30–300 MHz	10–1 m
9	UHF (Ultrahigh frequency)	300–3000 MHz	100–10 cm
10	SHF (Superhigh frequency)	3–30 GHz	10–1 cm
11	EHF (Extreme high frequency)	30–300 GHz	1–0.1 cm
12	Decimillimeter	300–3000 GHz	1–0.1 mm
	P band	0.23–1 GHz	130–30 cm
	L band	1–2 GHz	30–15 cm
	S band	2–4 GHz	15–7.5 cm
	C band	4–8 GHz	7.5–3.75 cm
	X band	8–12.5 GHz	3.75–2.4 cm
	Ku band	12.5–18 GHz	2.4–1.67 cm
	K band	18–26.5 GHz	1.67–1.13 cm
	Ka band	26.5–40 GHz	1.13–0.75 cm
	Millimeter wave	40–300 GHz	7.5–1 mm
	Submillimeter wave	300–3000 GHz	1–0.1 mm

The frequency designations based on World War II radar security considerations had never been officially sanctioned by any industrial, professional, or government organization until 1969. In August 1969, the U.S. Department of Defense (DoD), Office of the Joint Chiefs of Staff directed all the armed services to use the frequency bands shown in Table 0-2-2. On May 24, 1970, the DoD adopted yet another frequency-band designation, as shown in Table 0-2-3. These three band designations are compared in Table 0-2-4.

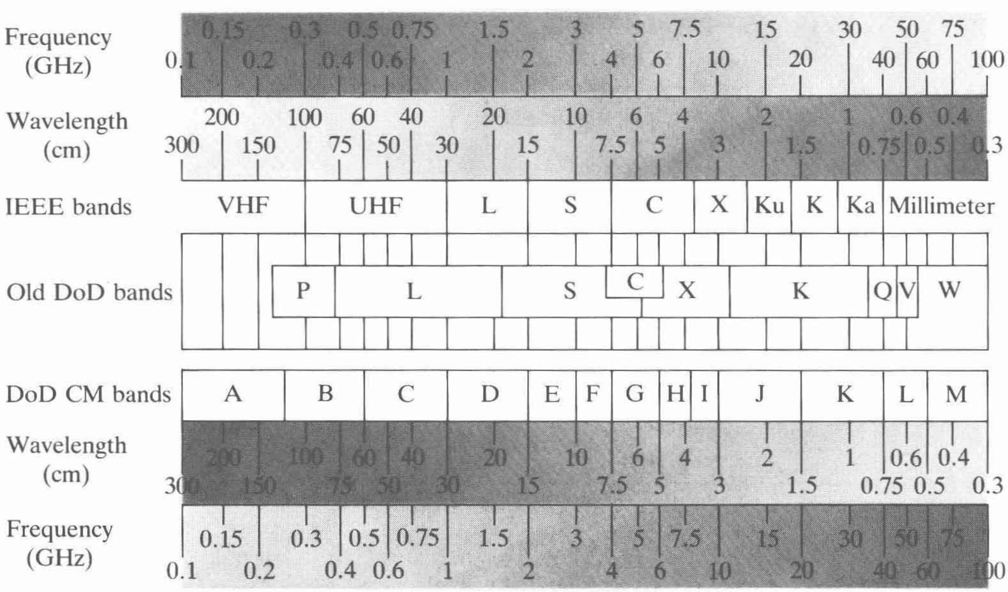
Table 0-2-2 Old DoD frequency bands

Designation	Frequency Range, GHz
P-band	0.225– 0.390
L-band	0.390– 1.550
S-band	1.550– 3.900
C-band	3.900– 6.200
X-band	6.200– 10.900
K-band	10.900– 36.000
Q-band	36.000– 46.000
V-band	46.000– 56.000
W-band	56.000–100.000

Table 0-2-3 DoD ECM frequency bands

Designation	Frequency Range, GHz
A-band	0.100– 0.250
B-band	0.250– 0.500
C-band	0.500– 1.000
D-band	1.000– 2.000
E-band	2.000– 3.000
F-band	3.000– 4.000
G-band	4.000– 6.000
H-band	6.000– 8.000
I-band	8.000– 10.000
J-band	10.000– 20.000
K-band	20.000– 40.000
L-band	40.000– 60.000
M-band	60.000–100.000

Table 0-2-4 Comparison of IEEE bands, old DoD bands, and new DoD ECM bands



0-2-2 MKS Units and Physical Constants

We use the rationalized meter–kilogram–second (MKS) system of units—the International System of Units—throughout this book unless otherwise indicated. The most commonly used MKS units are listed in Table 0-2-5. The physical constants commonly used in this book are listed in Table 0-2-6.

Table 0-2-5 MKS units

Quantity	Unit	Symbol
Angstrom	10^{-10} meter	Å
Capacitance	Farad = Coulombs per volt	F
Charge	Coulomb: Ampere-seconds	Q
Conductance	Mho or Siemen	℧
Current	Ampere $= \frac{\text{Coulombs}}{\text{Second}}$	A
Frequency	Cycles per second	Hz
Energy	Joule = Watt-second	J
Field (electric)	Volts per meter	E
Field (magnetic)	Amperes per meter	H
Flux linkage	Weber = volt-seconds	ψ
Inductance	Henry $= \frac{\text{V-s}}{\text{A}}$	H
Length	Meter	m
Micron	10^{-6} meter	μm
Power	Watt = Joules per second	W
Resistance	Ohm	Ω
Time	Second	s
Velocity	Meters per second	v
Voltage	Volt	V

Table 0-2-6 Physical constants

Constant	Symbol	Value
Boltzman constant	k	1.381×10^{-23} J/°K
Electron volt	eV	1.602×10^{-19} J
Electronic charge	q	1.602×10^{-19} C
Electronic mass	m	9.109×10^{-31} Kg
Ratio of charge to mass of an electron	e/m	1.759×10^{11} C/Kg
Permeability of free space	μ_0	$4\pi \times 10^{-7}$ H/m
Permittivity of free space	ε_0	8.854×10^{-12} F/m
Planck's constant	h	6.626×10^{-34} J-s
Velocity of light in vacuum	c	2.998×10^{8} m/s