MICROWAVE AND FIBER OPTICS COMMUNICATIONS

ARTHUR F. WICKERSHAM

MICROWAVE AND FIBER OPTICS COMMUNICATIONS

ARTHUR F. WICKERSHAM

PRENTICE HALL
Englewood Cliffs, N.J. 07632

Library of Congress Cataloging-in-Publication Data

Wickersham, Arthur F.
Microwave and fiber optics communications/Arthur F. Wickersham.
p. cm.
Includes index.
ISBN 0-13-582099-5
1. Microwave communication systems. 2. Fiber optics. 3. Optical communications. I. Title.
TK7876.W496 1988
621.38'0413—dc 19
87-29286
CIP

Editorial/production supervision: Editing, Design & Production, Inc.
Cover design: Lundgren Graphics, Ltd.
Manufacturing buyer: Lorraine Fumoso

Smith charts courtesy of Phillip H. Smith. Charts may be obtained from Analog Instrument Co., Box 808, New Providence, NJ 07974.
Fig. 7-12 courtesy of Hewlett Packard, Inc. Used with permission.

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

ISBN 0-13-582099-5

Prentice-Hall International (UK) Limited, *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S.A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Simon & Schuster Southeast Asia Pte. Ltd., *Singapore*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*

Preface

This combined textbook and laboratory manual is intended for a two-semester, introductory course at the community college or lower-division level; however, it should also be of interest to individual experimenters and radio amateurs. The reader interested in fiber optic and other optic applications may find here a helpful background in wave theory.

Since the student is expected to be familiar with elementary circuit theory, we use circuit concepts to develop topics in wave theory. Rather than attempt a comprehensive overview of current technology, we have developed a select number of topics that are either useful for technicians working in industry or that are fundamental concepts not subject to technological obsolescence.

The text and applications are closely integrated. Occasionally, theory or systems applications are developed in the applications and problems that appear at the end of each chapter. Numerical examples are worked out in both the text and the applications sections. In the first few chapters the numerical examples include instructions for solving the problems with a scientific calculator.

Since small schools often have little microwave or optic equipment, we have tried to present laboratory applications that require a minimum of resources. If a large, well-equipped laboratory is available, the applications can be varied accordingly; for example, if a microwave generator and slotted line are available for each pair of students, there is little incentive for using rope lines to demonstrate standing waves.

Because the mathematical prerequisites are geometry, algebra, and trigonometry, these subjects are reviewed briefly in the text. There is often a gap between mathematics and its application in technology, which can be closed by an instructor familiar with both.

Where some of the material presented is unique or difficult to find in technical literature, we have developed a topic somewhat more extensively than is expected in an introductory course. Such developments can be omitted without loss of continuity. In microwave and optic technology several disciplines overlap, and notation is a problem. We have tried to use symbols that are commonly accepted, redefining them as they take on new meanings in different aspects of the subject.

We thank Tom Hommel and Mike Pieson of Paragon Cable for their enthusiastic consultations.

Contents

1

Waves

1–1 INTRODUCTION

The higher the frequency of an electromagnetic wave, the shorter its wavelength. At microwave and optic frequencies we shall be working with wavelengths as short as a few centimeters or a few millimeters; thus the length of a connection between components may be a substantial fraction of a wavelength or several wavelengths. This means that phase change and the impedance of the connection must be considered in attempting to transfer energy from one component to another. We cannot simply connect components with a length of wire as we do in dc or low-frequency circuits.

We shall see that when a conductor is about a wavelength in size, it may radiate, that is, act like a broadcasting antenna. This is another reason why we cannot connect components together with wires. Instead of just conducting electromagnetic energy from one component to another, the wires will also radiate energy in the form of electromagnetic waves into surrounding space. We shall have to connect electronic components together with short, carefully designed transmission lines.

Wave effects become so important at high frequencies that we had best start our program of microwave and optical electronics with a study of waves.

1–2 DEFINITION OF A WAVE

A wave is a disturbance moving through a medium; for example, a water wave is a change in height of the water moving across the surface of the water. The surface of the water is the medium. We note that the medium is not transported with the wave: A cork on the surface bobs up and down with the water but does not move across the surface with the wave. Rather than thinking of the disturbance as moving through the medium, it is more accurate to think of the disturbance as reproducing itself at ever-greater distances from its source. For this reason we say that *a wave is a change of state propagating through a medium.*

1–3 WAVELENGTH, FREQUENCY, AND VELOCITY

We speak and hear using sound waves, see with light waves, but can most easily visualize the familiar water wave. The *amplitude* of a water wave is the height of a crest above the mean water surface. *Wavelength* is the horizontal distance between two corresponding points: for example, the distance from crest to crest or trough to trough. These definitions are illustrated in Fig. 1–1.

The *velocity* of a wave is given by the distance s that it travels in an interval of time t,

$$v = \frac{s}{t} \tag{1–1}$$

We can determine velocity by watching a particular wave and measuring the time it takes for it to travel from one point to another; however, an easier way is to count the number of waves that pass a given point in an interval of time t. If n is the number, the total distance traveled by the first wave is $n\lambda$, and its velocity must be $v = n\lambda/t$. Since the number of waves that pass by in an interval of time is defined as the *frequency*, $f = n/t$, we have

$$v = f\lambda \tag{1–2}$$

This derivation is illustrated in Fig. 1–2 for the case in which five waves pass a point P in 1 s.

EXAMPLE 1–1

From Fig. 1–2 and Eq. (1–2) we have

$$\begin{aligned} v &= f\lambda \\ &= 5\text{ Hz} \times 1\text{ cm} \\ &= 5\text{ cm/s} \end{aligned}$$

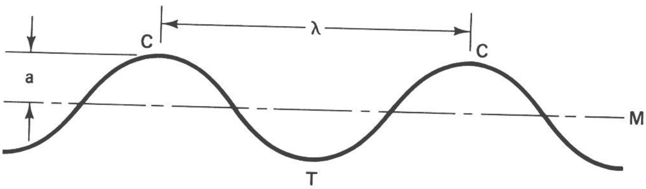

Figure 1–1 Wave parameters: λ, wavelength; a, amplitude; C, crests; T, trough; M, mean water level or reference height.

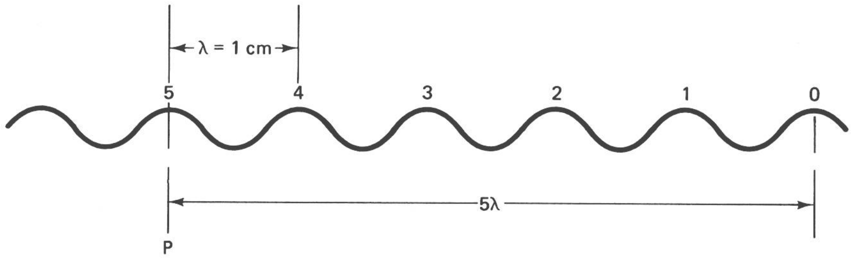

Figure 1–2 Determination of wave velocity from a count of the number of waves that pass a point *P* in 1 second.

Equation (1–2) is of wide application. It is valid for sound waves, seismic, electromagnetic, and magnetohydromagnetic waves, as well as for water waves. For electromagnetic or light waves in free space it is customary to use the letter c for the speed: $c = \lambda f$. If we know wavelength and frequency, we can immediately determine the wave velocity.

EXAMPLE 1–2

A radio transmitter broadcasts a wavelength of 30 m at a frequency of 10 MHz. What is the wave velocity?

Solution From Eq. (1–2)

$$\begin{aligned} c &= \lambda f \\ &= 30 \times (10 \times 10^6) \\ &= 3 \times 10^8 \text{ m/s} \end{aligned}$$

which is the speed of light in free space.

Another way to derive Eq. (1–2) is to notice that a wavelength passes a fixed point in a time equal to its period. Its speed must be $v = \lambda/T$, where T is the period. Since frequency is the inverse of period, $f = 1/T$, we again obtain Eq. (1–2).

Since the speed of light in free space is a physical constant, we see, from Eq. (1–2), that wavelength must decrease as frequency increases. For each frequency there is only one corresponding wavelength. Electromagnetic waves are given different names depending on their frequency or wavelength bands, as shown in the electromagnetic spectrum in Fig. 1–3. A sound-wave spectrum is shown in Fig. 1–4.

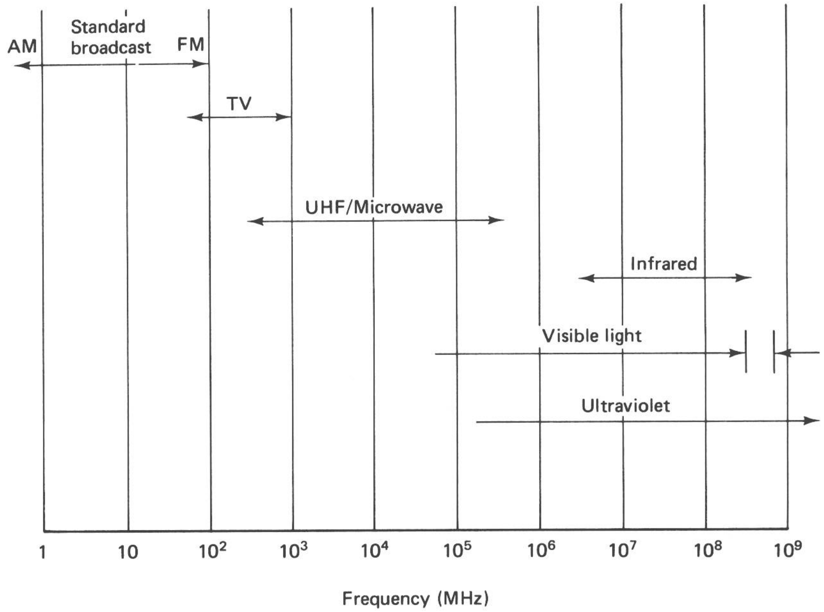

Figure 1–3 Portion of the electromagnetic spectrum.

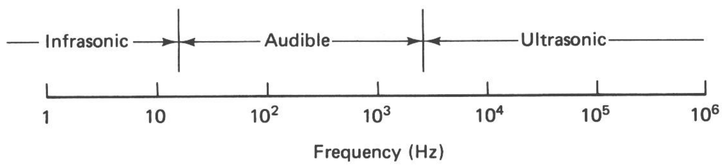

Figure 1–4 Spectrum of sound waves.

1–4 WAVE TYPES

We have been discussing traveling waves; obviously, these are waves that travel or propagate. Another type of wave is the standing wave, a wave that appears to stand still. It is familiar to anyone who has tied a rope to a fixed object and moved the free end of the rope rapidly up and down. The waves reflected from the fixed end combine with the incident waves to form standing waves, as shown in Fig. 1–5. A standing wave actually is formed from two traveling waves moving in opposite directions.

Those points on a standing wave that are not displaced by the motion are called *nodes*, and points at which maximum displacement occurs are *antinodes*. If only one antinode occurs on a line, the line is said to be in its *fundamental mode* of oscillation. If the frequency is doubled, two antinodes appear on the line; if

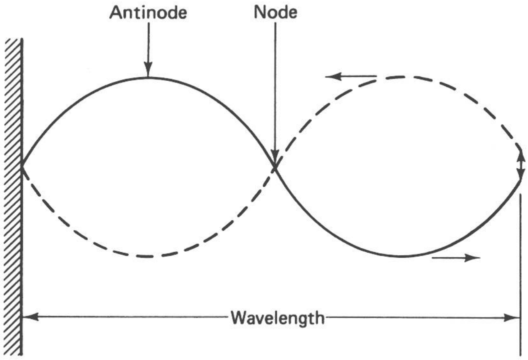

Figure 1–5 Standing wave on a rope line.

tripled, three antinodes; and so on. Frequencies that are integral multiples of the fundamental are called *harmonics*.

If there are two antinodes on a line and the frequency is sufficiently increased, three antinodes will appear, but during the time the frequency is being increased the line appears to be in wild disarray. This is suggestive of the mysterious quantum jump in modern physics. The ultimate nature of matter is dualistic: matter is wavelike as well as corpuscular. If a particle wave is confined, as, for example, an orbital electron is confined in an atom, its wave pattern must contain an integral number of antinodes. The electron can jump to quantum states having fewer or more antinodes, just as can the rope line. Stable or steady states correspond only to integral numbers of antinodes in the standing-wave pattern.

A more complicated wave pattern can be achieved by joining two ropes of different weights, that is, of different linear weight densities. The linear density of a rope is its weight divided by its length. For example, a 100-m line of weight 6 kg has a linear density of 60 g/m. In general, more antinodes will occur on the heavier section of line than on the lighter, as shown in Fig. 1–6.

For the two-rope line there is an increased number of possible modes, each mode defined by the different numbers of antinodes occurring on the heavy and light sections of the line. We are not aware that any system of classification has ever been devised for modes on rope lines, but when we study electromagnetic waves in transmission lines we shall see that an elaborate classification system has

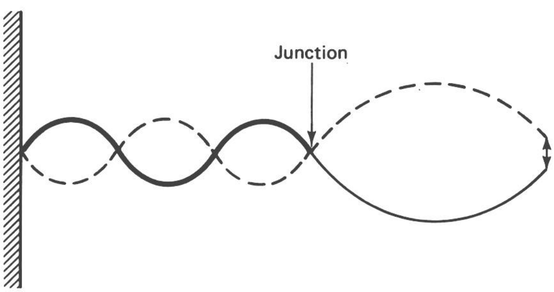

Figure 1–6 Standing waves on rope lines of unequal densities.

been devised in terms of the numbers of antinodes in the electric and magnetic field components of the waves. In summary, a *mode* is a particular configuration of nodes and antinodes of waves in a confined system.

Waves can also be classified in terms of type of motion or displacement. The wave on a rope line is a *transverse* wave, because the displacement of the rope is transverse, or at right angles, to the direction of wave propagation. Electromagnetic waves in free space are transverse; sound waves, however, are *longitudinal*. A longitudinal displacement is a displacement in the direction of propagation. For a sound wave the longitudinal displacements are compressions or dilations of the gas which correspond to variations in pressure and density.

1–5 WAVE MEDIA

Some of the characteristics of a wave, such as frequency and amplitude, are determined by its source, but others, speed for example, are determined by the medium in which the wave propagates. In general, the more rigid the medium, the greater the wave velocity. We see, in Table 1–1, that the speed of sound is 1117 ft/s in air but 16,000 ft/s in steel.

TABLE 1–1 SPEED OF SOUND IN VARIOUS MEDIA

	Speed	
Medium	English Units	Metric Units
Air[a]	1,117 ft/s	340.5 m/s
Water	4,800 ft/s	1.463 km/s
Steel	16,000 ft/s	4.88 km/s

[a] For standard atmospheric pressure and a temperature of 59°F.

The formula for the speed of sound in air is, in terms of the physical characteristics of the atmosphere,

$$v = \left(\frac{\gamma k T}{m}\right)^{1/2} \tag{1–3}$$

where, for the earth's atmosphere, the ratio of specific heats is $\gamma = 1.4$; Boltzmann's constant is $k = 1.38 \times 10^{-23}$ joules per kelvin, T is the absolute temperature in kelvin, $T = 273 + °\text{C}$, and m is the average molecular mass in a standard atmosphere, 4.78×10^{-26} kg.