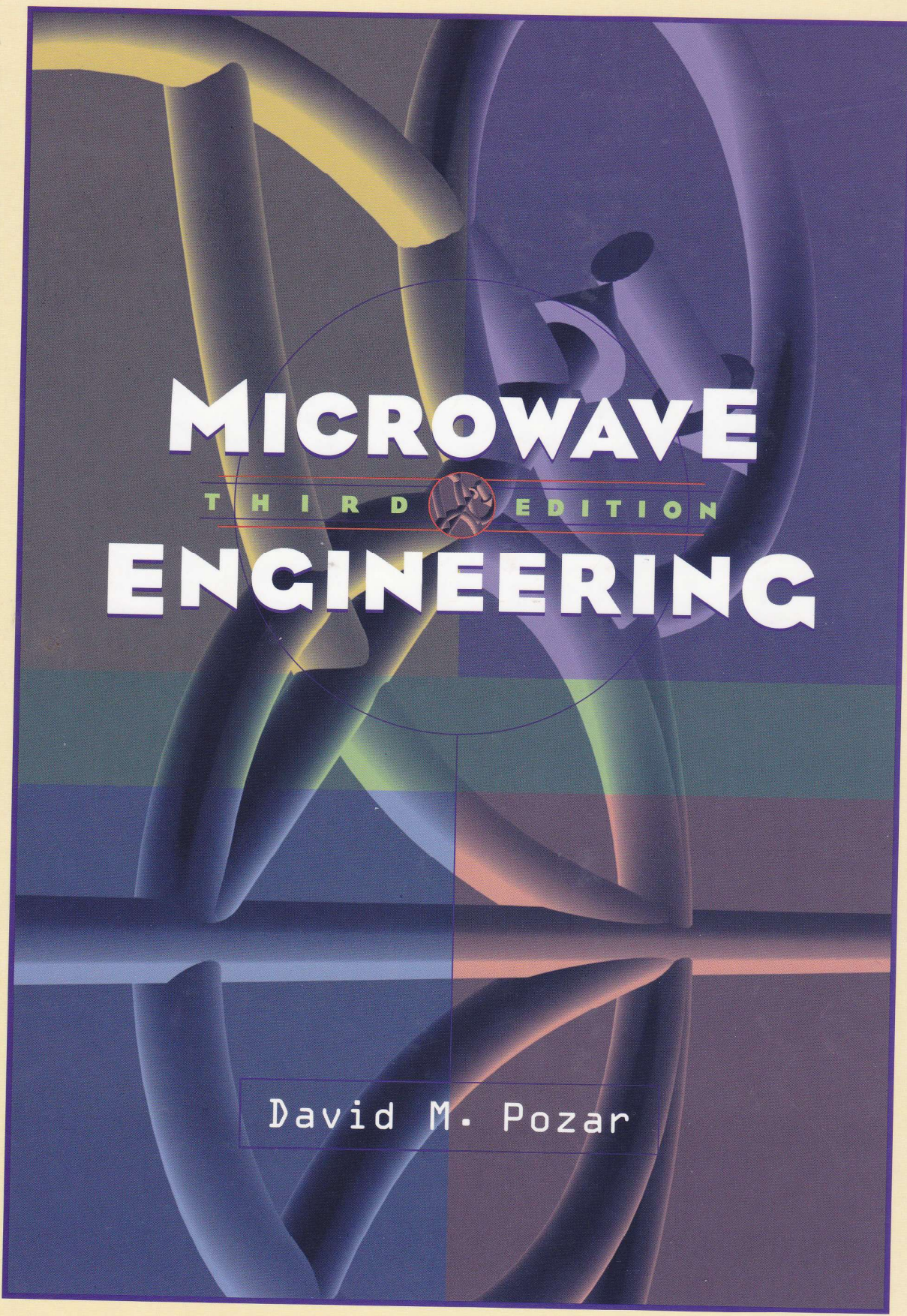




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David M. Pozar

Microwave Engineering

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which is an equation for $\bar{E}$. This result can be simplified through the use of vector identity (B.14), $\nabla \times \nabla \times \bar{A} = \nabla(\nabla \cdot \bar{A}) - \nabla^2 \bar{A}$, which is valid for the rectangular components of an arbitrary vector $\bar{A}$. Then,

$$\nabla^2 \bar{E} + \omega^2 \mu \epsilon \bar{E} = 0, \quad (1.42)$$

since $\nabla \cdot \bar{E} = 0$ in a source-free region. Equation (1.42) is the wave equation, or Helmholtz equation, for $\bar{E}$. An identical equation for $\bar{H}$ can be derived in the same manner:

$$\nabla^2 \bar{H} + \omega^2 \mu \epsilon \bar{H} = 0. \quad (1.43)$$

A constant $k = \omega \sqrt{\mu \epsilon}$ is defined and called the wavenumber, or propagation constant, of the medium; its units are 1/m.

As a way of introducing wave behavior, we will next study the solutions to the above wave equations in their simplest forms, first for a lossless medium and then for a lossy (conducting) medium.

Plane Waves in a Lossless Medium

In a lossless medium, ϵ and μ are real numbers, so k is real. A basic plane wave solution to the above wave equations can be found by considering an electric field with only an $\hat{x}$ component and uniform (no variation) in the x and y directions. Then, $\partial/\partial x = \partial/\partial y = 0$, and the Helmholtz equation of (1.42) reduces to

$$\frac{\partial^2 E_x}{\partial z^2} + k^2 E_x = 0. \quad (1.44)$$

The two independent solutions to this equation are easily seen, by substitution, to be of the form

$$E_x(z) = E^+ e^{-jkz} + E^- e^{jkz}, \quad (1.45)$$

where E^+ and E^- are arbitrary amplitude constants.

The above solution is for the time harmonic case at frequency ω . In the time domain, this result is written as

$$\mathcal{E}_x(z, t) = E^+ \cos(\omega t - kz) + E^- \cos(\omega t + kz), \quad (1.46)$$

where we have assumed that E^+ and E^- are real constants. Consider the first term in (1.46). This term represents a wave traveling in the $+z$ direction, since, to maintain a fixed point on the wave ($\omega t - kz = \text{constant}$), one must move in the $+z$ direction as time increases. Similarly, the second term in (1.46) represents a wave traveling in the negative z direction; hence the notation E^+ and E^- for these wave amplitudes. The velocity of the wave in this sense is called the *phase velocity*, because it is the velocity at which a fixed phase point on the wave travels, and it is given by

$$v_p = \frac{dz}{dt} = \frac{d}{dt} \left(\frac{\omega t - \text{constant}}{k} \right) = \frac{\omega}{k} = \frac{1}{\sqrt{\mu \epsilon}} \quad (1.47)$$

In free-space, we have $v_p = 1/\sqrt{\mu_0 \epsilon_0} = c = 2.998 \times 10^8$ m/sec, which is the speed of light.

The wavelength, λ , is defined as the distance between two successive maxima (or minima, or any other reference points) on the wave, at a fixed instant of time.

Thus,

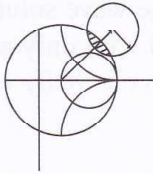
$$[\omega t - kz] - [\omega t - k(z + \lambda)] = 2\pi,$$

$$\text{so,} \quad \lambda = \frac{2\pi}{k} = \frac{2\pi v_p}{\omega} = \frac{v_p}{f}. \quad (1.48)$$

A complete specification of the plane wave electromagnetic field must include the magnetic field. In general, whenever $\vec{E}$ or $\vec{H}$ is known, the other field vector can be readily found by using one of Maxwell's curl equations. Thus, applying (1.41a) to the electric field of (1.45) gives $H_x = H_z = 0$, and

$$H_y = \frac{1}{\eta} [E^+ e^{-jkz} - E^- e^{jkz}], \quad (1.49)$$

where $\eta = \omega\mu/k = \sqrt{\mu/\epsilon}$ is the wave impedance for the plane wave, defined as the ratio of the $\vec{E}$ and $\vec{H}$ fields. For plane waves, this impedance is also the intrinsic impedance of the medium. In free-space we have $\eta_0 = \sqrt{\mu_0/\epsilon_0} = 377 \Omega$. Note that the $\vec{E}$ and $\vec{H}$ vectors are orthogonal to each other and orthogonal to the direction of propagation ($\pm\hat{z}$); this is a characteristic of transverse electromagnetic (TEM) waves.



EXAMPLE 1.1 BASIC PLANE WAVE PARAMETERS

A plane wave propagating in a lossless dielectric medium has an electric field given as $\mathcal{E}_x = E_0 \cos(1.51 \times 10^{10}t - 61.6z)$. Determine the wavelength, phase velocity, and wave impedance for this wave, and the dielectric constant of the medium.

Solution

By comparison with (1.46) we identify $\omega = 1.51 \times 10^{10}$ rad/sec and $k = 61.6 \text{ m}^{-1}$. Using (1.48) then gives the wavelength as

$$\lambda = \frac{2\pi}{k} = \frac{2\pi}{61.6} = 0.102 \text{ m}.$$

The phase velocity can be found from (1.47):

$$v_p = \frac{\omega}{k} = \frac{1.51 \times 10^{10}}{61.6} = 2.45 \times 10^8 \text{ m/sec}.$$

This is slower than the speed of light by a factor of 1.225. The dielectric constant of the medium can be found as

$$\epsilon_r = \left(\frac{c}{v_p} \right)^2 = \left(\frac{3.0 \times 10^8}{2.45 \times 10^8} \right)^2 = 1.50.$$

The wave impedance is

$$\eta = \eta_0 / \sqrt{\epsilon_r} = \frac{377}{\sqrt{1.5}} = 307.8 \Omega. \quad \blacksquare$$

Plane Waves in a General Lossy Medium

Now consider the effect of a lossy medium. If the medium is conductive, with a conductivity σ , Maxwell's curl equations can be written, from (1.41a) and (1.20) as

$$\nabla \times \vec{E} = -j\omega\mu\vec{H}, \quad (1.50a)$$

$$\nabla \times \vec{H} = j\omega\epsilon\vec{E} + \sigma\vec{E}. \quad (1.50b)$$