# CHAPTER 2
# Basic Electromagnetic Theory

## 2.1  MAXWELL'S EQUATIONS

To analyze wave propagation in an isotropic medium we begin with a statement of Maxwell's equations:

$$\nabla \times E(r, t) = -\frac{\partial}{\partial t} B(r, t) \tag{2.1}$$

$$\nabla \times H(r, t) = \frac{\partial}{\partial t} D(r, t) + J(r, t) \tag{2.2}$$

$$\nabla \cdot D(r, t) = \rho(r, t) \tag{2.3}$$

$$\nabla \cdot B(r, t) = 0 \tag{2.4}$$

In the above relations, the field quantities $E$ and $H$ represent, respectively, the electric and magnetic fields, and $D$ and $B$ the electric and magnetic displacements. $J$ and $\rho$ represent the current and charge sources. Further, the position vector $r$ defines a particular location in space $(x, y, z)$ at which the field is being measured. That is,

$$E(x, y, z, t) \equiv E(r, t)$$

An auxiliary relation, called the continuity equation, relates the current and charge sources $J$ and $\rho$.

$$\nabla \cdot J(r, t) + \frac{\partial}{\partial t} \rho(r, t) = 0 \tag{2.5}$$

It is important to note that Eqs. 2.1–2.5 are not all independent. In fact, only Eqs. 2.1, 2.2, and 2.5 are needed to derive Eqs. 2.3 and 2.4. This is readily seen by taking the divergence of Eqs. 2.1 and 2.2. Taking $\nabla \cdot$ (Eq. 2.1) yields

$$\nabla \cdot (\nabla \times E) = -\frac{\partial}{\partial t} (\nabla \cdot B)$$

where we have freely interchanged the spatial and temporal operators, $\nabla \cdot$ and $\partial/\partial t$. Note, however, that the divergence of the curl of any vector is identically zero. This implies from above that the divergence of $B$ is at most equal to a constant which is independent of time. If such a "background" field exists, it has been with us since creation and is of little interest to any kind of time-varying problem. Therefore, we arbitrarily set the constant equal to zero, thus yielding Eq. 2.4. If we take the divergence of Eq. 2.2 we obtain

$$\nabla \cdot (\nabla \times H) = \frac{\partial}{\partial t} (\nabla \cdot D) + \nabla \cdot J$$

However, the continuity equation 2.5 shows that the divergence of $J$ is equal to minus the time derivative of the charge density $\rho$. Thus, to within an arbitrary constant, we obtain Eq. 2.3.

## 2.2  CONSTITUTIVE RELATIONS FOR AN ISOTROPIC MEDIUM

An examination of Maxwell's curl equations, 2.1 and 2.2, indicates that there are a total of 6 equations (one for each vector component) and 12 unknowns (one for each component of $E$, $H$, $B$, and $D$). Note that $J$ represents a source term which is considered to be given. It is the constitutive relations that provide the additional constraints needed to solve Eqs. 2.1 and 2.2. These relations characterize a given material on a macroscopic level and are described in terms of the two scalar quantities, the permeability $\mu$ and the permittivity $\epsilon$:

$$B = \mu H \tag{2.6}$$

$$D = \epsilon E \tag{2.7}$$

In free space, $\mu = \mu_0 = 4\pi \times 10^{-7}$ henrys/meter (H/m), $\epsilon = \epsilon_0 = 8.85 \times 10^{-12}$ farads/meter (F/m). Note that Eqs. 2.6 and 2.7 represent a set of six equations, one for each field component.

component can be represented as

$$A_x(r, t) = A_x(r) \cos(\omega t + \phi_x(r))$$

$$= \operatorname{Re}[A_x(r) e^{j(\omega t + \phi_x)}]$$

$$= \operatorname{Re}[\tilde{A}_x(r) e^{j\omega t}]$$

where the complex phasor quantity $\tilde{A}_x(r)$ is defined by

$$\tilde{A}_x(r) = A_x(r) e^{j\phi_x}$$

The $y$ and $z$ components of the field are similarly described and the total field may, therefore, be written as

$$A(r, t) = \operatorname{Re}[\tilde{A}(r) e^{j\omega t}] \tag{2.8}$$

where

$$\tilde{A}(r) = \hat{x} \tilde{A}_x(r) + \hat{y} \tilde{A}_y(r) + \hat{z} \tilde{A}_z(r)$$

To obtain Maxwell's equations for time-harmonic fields, we assume all field quantities to be of the form given by Eq. 2.8. That is,

$$\begin{Bmatrix} E(r, t) \\ H(r, t) \\ D(r, t) \\ B(r, t) \end{Bmatrix} = \operatorname{Re}\left[ \begin{Bmatrix} \tilde{E}(r) \\ \tilde{H}(r) \\ \tilde{D}(r) \\ \tilde{B}(r) \end{Bmatrix} e^{j\omega t} \right]$$

The appropriate field quantities are then substituted into Maxwell's equations 2.1–2.4. Thus, for example, Eq. 2.1 becomes

$$\nabla \times \operatorname{Re}[\tilde{E}(r) e^{j\omega t}] = -\partial/\partial t \operatorname{Re}[\tilde{B}(r) e^{j\omega t}] \tag{2.9}$$

To simplify this expression, we need to show that it is possible to move the operators $\nabla \times$ and $\partial/\partial t$ inside the indicated square brackets. That is, we wish to show that Eq. 2.9 is equivalent to

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