ELECTROMAGNETIC MATERIAL PARAMETERS & RELATIONS

Pioneering 21st Century Electromagnetics and Photonics

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FUNDAMENTAL PARAMETERS

These parameters are fundamental to Maxwell's equations, but it is difficult to conclude their effect on fields and waves.

Electrical Permittivity, ε

$\varepsilon \equiv$ permittivity

$\varepsilon_0 \equiv$ free space permittivity

$\varepsilon_r \equiv$ relative permittivity (dielectric constant)

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

$$\varepsilon_r \geq 1$$

$$\varepsilon_0 = 8.8541878176 \times 10^{-12} \text{ F/m}$$

Magnetic Permeability, μ

$\mu \equiv$ permeability

$\mu_0 \equiv$ free space permeability

$\mu_r \equiv$ relative permeability

$$\mu = \mu_0 \mu_r$$

$$\mu_r \geq 1$$

$$\mu_0 = 1.2566370614 \times 10^{-6} \text{ H/m}$$

Electrical Conductivity, σ

$\sigma \equiv$ conductivity ($1/\Omega\cdot\text{m}$)

Two Sets of Electrical Properties

Real permittivity ε and real conductivity σ

or

Complex permittivity $\tilde{\varepsilon}$

$$\tilde{\varepsilon} = \varepsilon' - j\varepsilon'' = \varepsilon + \sigma / j\omega$$

$$\varepsilon' = \varepsilon \qquad \varepsilon'' = \sigma/\omega$$

Frequency, Velocity, and Wavelength

$f \equiv$ ordinary frequency (Hz)

$\omega = 2\pi f \equiv$ angular frequency (s^{-1})

$\lambda_0 \equiv$ free space wavelength

$\lambda = \lambda_0 / n_o \equiv$ wavelength inside medium

$c_0 = f\lambda_0 = 299,792,458$ (m/w) $\equiv$ speed of light in vacuum

Wave velocity

$$c_0 = 1\Big/\sqrt{\mu_0 \varepsilon_0}$$

$$v = c_0 / n_o$$

MEANINGFUL PARAMETERS

These parameters isolate specific information about fields and waves into single quantities. They are more intuitive than the fundamental parameters.

Refractive Index, n

$$n = n_o - j\kappa = \sqrt{\mu_r \varepsilon_r}$$

For non-magnetic materials:

$$\varepsilon_r = n^2 \qquad \eta = \frac{\eta_0}{n}$$

The ordinary refractive index n_o is the factor by which the phase of a wave slows down inside of a medium.

The extinction coefficient κ quantifies growth or decay of a wave due to gain or loss, respectively.

$$E(z) = e^{-jk_0 nz} = \underbrace{e^{-jk_0 n_o z}}_{\text{speed/oscillation}} \underbrace{e^{-k_0 \kappa z}}_{\text{growth/decay}}$$

Impedance, η

$$\eta = \eta' + j\eta'' = |\eta| \measuredangle \theta_\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

Impedance η quantifies the relationship between the electric field E and magnetic field H due to the coupling in Maxwell's equations.

$$\eta = E_0 / H_0$$

$$\eta_0 = \sqrt{\mu_0 / \varepsilon_0} = 376.73031346177\ \Omega \equiv \text{free space impedance}$$

$\eta' \equiv$ resistive component

$\eta'' \equiv$ reactive component

$|\eta| \equiv$ amplitude relation between E_0 and H_0

$\theta_\eta \equiv$ phase relation between E_0 and H_0

Propagation Constant, γ

$$\gamma = \alpha + j\beta = jk_0 n$$

$$E(z) = e^{-\gamma z} = \underbrace{e^{-\alpha z}}_{\text{growth/decay}} \underbrace{e^{-j\beta z}}_{\text{speed/oscillation}}$$

$\alpha \equiv$ attenuation coefficient $\left(\text{m}^{-1}\right)$

$$\beta = \frac{2\pi}{\lambda} = k_0 n \equiv \text{wave number } \left(\text{m}^{-1}\right)$$

Loss Parameters

The absorption coefficient α_P describes decay of power.

$$P(z) = P_0 e^{-\alpha_P z}$$

$$\alpha_P = 2\alpha$$

The loss tangent $\tan\delta$ describes decay of power.

$$P(z) = P_0 e^{-\delta k_0 n_o z}$$

$$\delta = 2\kappa / n_o = \frac{2\alpha}{k_0 n_o}$$