

Dielectric Materials at Microwave Frequencies

The effects of microwave energy on materials are important in industry, biology, medicine and your microwave oven

Kurt Fenske and Devendra Misra
University of Wisconsin-Milwaukee

Radio frequency and microwave signals have numerous scientific and industrial applications in modern technology. Among others, these include wireless communications, telemetry, biomedical engineering, food science, material processing and process controls in the industry. These applications require the electrical characteristics of media with which the signal interacts or through which the signal propagates. This article briefly reviews the characteristic parameters associated with dielectric materials and their characterization techniques.

Microwave energy is frequently employed in industrial processing of materials not only because of its efficiency but also because it yields a superior product. For example, the conventional process to dry the paper-ink using hot air in a printing press reduces the moisture content of the paper as well. This, in turn, reduces the life span of the product. On the other hand, microwaves leave the paper almost unaffected. Since microwave energy can pass through non-conducting (dielectric) materials, it can be used to cure composite structures efficiently. It also allows constructing internal images of the dielectric objects.

In biomedical engineering, microwaves are used to produce controlled heating for hyperthermia. Wireless communication signals interact with the medium they propagate through. Therefore, knowledge of the medium characteristics can assist in designing an efficient communication network.

In brief, there are many engineering systems that involve interaction of electromagnetic energy with the material medium. The design of these systems requires a good understanding of

the phenomenon that is directly related to electrical characteristic parameters of the medium. This paper summarizes the characteristic parameters associated with non-magnetic dielectric materials and their characterization techniques.

Dielectric materials

In dielectric materials, most of the charge carriers are bound and cannot participate in electrical conduction. However, if an external electric field is applied to the material, these bound charges may be displaced. This displacement of charge creates a dipole field that opposes the applied field and the material is polarized.

In a linear and isotropic medium, the volume density of polarization is directly related to the applied electric field intensity. This is given by

$$\vec{P} = \epsilon_0 \chi_e \vec{E} \quad (1)$$

where ϵ_0 is the permittivity of free-space and χ_e is electrical susceptibility of the material.

Electric flux density or displacement, \vec{D} , is related to the polarization density and the electric field intensity as follows:

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P} = \epsilon \vec{E} = \epsilon_0 \epsilon_r \vec{E} \quad (2)$$

where ϵ is called the permittivity of the material. Since it is a very small number, the relative permittivity, ϵ_r , of a material is generally specified for convenience. It is also known as the dielectric constant of that material.

Equation (2) is valid only in the frequency domain unless permittivity is independent of the frequency. Most of materials are dispersive, that is, their permittivity is frequency-dependent. If this is the case, then the right-hand-side

Material	Dielectric constant	Loss-tangent
Alumina	9.0	0.0006
Bacon (smoked)	2.50	0.05
Beef (frozen)	4.4	0.12
Beef (raw)	52.4	0.3302
Blood*	58	0.27
Butter (salted)	4.6	0.1304
Butter (unsalted)	2.9	0.1552
Borosilicate glass	4.3 0	0047
Concrete (dry)	4.5	0.0111
Corn oil	2.6	0.0077
Cottonseed oil	2.64	0.0682
Sandy soil (dry)	2.55	0.0062
Egg white	35.0	0.5
Fused quartz	4.0	0.0001
Fat*	5.5	0.21
Glass ceramic	6.0	0.0050
Lard	2.5	0.0360
Lung*	32	0.3
Muscle*	49	0.33
Nylon	2.4	0.0083
Olive oil	2.46	0.0610
Paper	3-4	0.0125-0.0333
Soda lime glass	6.0	0.02
Teflon	2.1	0.0003
Thermoset polyester	4.0	0.0050
Wood	1.2-5	0.0040-0.4167

*At 37°C

▲ Table 1. Characteristic parameters of selected dielectric materials at room temperature and 2.45 GHz.

of Equation (2) transforms to a convolution integral in the time-domain.

A time-varying electric field induces two different kinds of currents in a material medium. Conduction current is produced by a net flow of free charges, and the bound charges generate a displacement current. The former is related to the electric field intensity by Ohm's law as follows:

$$\vec{J}_C = \sigma \vec{E} \quad (3)$$

where J_C is the conduction current density that is expressed in Ampere per meter, and σ is the conductivity of material in Siemens per meter.

Displacement current density J_D is related to electric flux density by

$$\vec{J}_D = j\omega \vec{D} \quad (4)$$

Total current density J_T is the sum of conduction and displacement current densities. Hence,

$$\vec{J}_T = \sigma \vec{E} + j\omega \epsilon \vec{E} \quad (5)$$

Conduction current represents the loss of power. There is another source of loss in dielectric materials. When a time-harmonic electric field is applied, the polarization dipoles flip constantly back and forth. Since the charge carriers have a finite mass, field must do work to move them and the response may not be instantaneous. Hence, the polarization vector may lag behind the applied electric field, which is noticeable especially at higher frequencies. In order to include this phenomenon, equation (5) is modified as follows:

$$\begin{aligned} \vec{J}_T &= \sigma \vec{E} + \omega \kappa'' \vec{E} + j\omega \epsilon \vec{E} \\ &= j\omega \left(\epsilon - j \frac{\sigma + \omega \kappa''}{\omega} \right) \vec{E} = j\omega \epsilon^* \vec{E} \end{aligned} \quad (6)$$

where ϵ^* is called the complex permittivity of material.

Complex relative permittivity of a material is defined as follows:

$$\begin{aligned} \epsilon_r^* &= \frac{\epsilon^*}{\epsilon_0} = \frac{1}{\epsilon_0} \left(\epsilon - j \frac{\sigma + \omega \kappa''}{\omega} \right) \\ &= \epsilon_r' - j\epsilon_r'' = \epsilon_r (1 - j \tan \delta) \end{aligned} \quad (7)$$

where ϵ_r' and ϵ_r'' represent real and imaginary parts of the complex relative permittivity. The imaginary part is zero for a lossless material. Term $\tan \delta$ is called the loss-tangent because it represents tangent of the angle between displacement phasor and total current. It is close to zero for a low-loss material. Characteristics of selected dielectric materials are given in Table 1.

Dispersion characteristics of materials can be represented by the Cole-Cole equation

$$\epsilon_r^* = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + \left(j \frac{f}{f_r} \right)^{1-\alpha}} \quad (8)$$

where ϵ_∞ and ϵ_s are relative permittivities of the material at infinite and zero frequencies, respectively. Frequencies f and f_r (in Hertz) represent the signal frequency and the characteristic relaxation frequency of the material, respectively. If α is zero, then Equation 8 can be reduced to the Debye equation. Dispersion parameters of selected liquids are given in Table 2.

Experimental methods

At low frequencies, complex permittivity of the material is generally determined using a capacitive fixture. Capacitance and dissipation factor of the lumped capacitor are measured using a bridge or a resonant circuit [1]. Complex permittivity of the material is then calculated from this data. At microwave frequencies, the sample may be placed inside a transmission line or a reso-

Substance	ϵ_∞	ϵ_s	α	f_r (GHz)
Acetone	1.9	21.2	0	47.6
Butanol	2.95	17.1	0.08	0.33
Chlorobenzene	2.35	5.63	0.04	15.5
Distilled Water	5	78	0	19.7
Ethanol	4.2	24	0	1.24
Ethylene glycol	3	37	0.23	2.0
Methanol	5.7	33.1	0	3.0
Propanol	3.2	19	0	0.54

▲ **Table 2. Dispersion parameters for some liquids at room temperature.**

nant cavity. The resulting characteristics are then measured to compute the dielectric parameters. Since propagation characteristics of electromagnetic waves are influenced by complex permittivity of the medium it propagates through, the material can be characterized by monitoring the reflected and transmitted waves as well. Some of these high frequency techniques are summarized below [1–5].

Resonant cavity method—Measurement techniques employing lumped capacitive sample-holders are useful only up to the lower end of VHF band. At microwave frequencies, a number of techniques have been developed on the basis of distributed networks. Reflection and transmission characteristics of waves inside a transmission line or in free-space are used in this case. Resonant cavities are also used to determine the complex permittivity of materials at discrete frequencies.

Since resonance characteristics depend on the material loaded in a cavity, its quality factor and resonance frequency can be monitored to determine the dielectric parameters. If a cavity can be filled completely with the sample, then its dielectric properties can be determined by the following method:

- Measure the resonant frequency f_1 and the quality factor Q_1 of an empty cavity,
- Repeat the experiment after filling the cavity completely with the sample material.

If the cavity's new resonant frequency is f_2 and the quality factor is Q_2 , then the dielectric parameters of the sample are

$$\epsilon_r = \left(\frac{f_1}{f_2} \right)^2 \quad (9)$$

and

$$\tan \delta = \frac{1}{Q_2} - \frac{1}{Q_1} \sqrt{\frac{f_1}{f_2}} \quad (10)$$

For smaller samples, a cavity perturbation technique

may be used. A circular cylindrical sample is placed in the region of maximum electric field inside the rectangular cavity that operates in its TE_{101} mode. Resonant frequency and quality factor of this cavity are measured with and without sample. Complex permittivity of the sample is then calculated as follows:

$$\epsilon_r' = 1 + \frac{1}{2} \left(\frac{f_1 - f_2}{f_2} \right) \frac{V}{v} \quad (11)$$

and

$$\epsilon_r'' = \frac{V}{4v} \left(\frac{Q_2 - Q_1}{Q_1 Q_2} \right) \quad (12)$$

where V and v are cavity and sample volumes, respectively.

Similarly, for a small spherical sample of radius r that is placed in a uniform field at the center of the rectangular cavity, the dielectric parameters are found by:

$$\epsilon_r' = \frac{abl}{8\pi r^3} \left(\frac{f_1 - f_2}{f_2} \right) \quad (13)$$

and

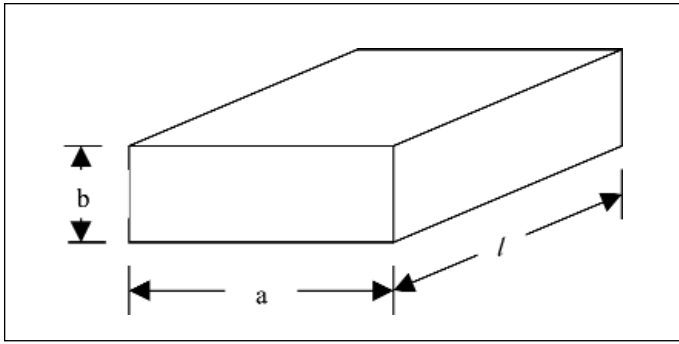
$$\epsilon_r'' = \frac{abl}{16\pi r^3} \left(\frac{Q_2 - Q_1}{Q_1 Q_2} \right) \quad (14)$$

As illustrated in Figure 1, a , b and l are the width, height, and length of the rectangular cavity, respectively. The frequency shift ($f_1 - f_2$) must be very small for better accuracy.

Modified infinite sample method—This technique can be used for the liquid or powder samples. In this method, a waveguide termination is completely filled with the sample as shown in Figure 2. Since a tapered termination is embedded inside, it absorbs the incident wave completely. Therefore, it looks as if the sample is extending to infinity. Impedance at its input port depends on electrical properties of the sample filling. Following the slotted-line method of impedance measurement, its VSWR S and location of first minimum d from the load-plane are measured. Complex permittivity of the sample is then calculated by [4]:

$$\epsilon_r' = 1 - \left(\frac{\beta}{\beta_0} \right)^2 + \frac{\left[\frac{\beta}{\beta_0} \right]^2 \times \left[S^2 \sec^4(\beta d) - (1 - S^2)^2 \tan^2(\beta d) \right]}{\left[1 + S^2 \tan^2(\beta d) \right]^2} \quad (15)$$

and



▲ Figure 1. Geometry of a rectangular cavity.

$$\epsilon_r'' = \frac{\left[\frac{\beta}{\beta_o}\right]^2 \times \left[2S(1-S^2)^2 \sec^4(\beta d) \tan(\beta d)\right]}{\left[1+S^2 \tan^2(\beta d)\right]^2} \quad (16)$$

where β_o is the phase constant of the signal in free-space, and β is the phase constant in the feeding guide. It is assumed that the waveguide supports TE₁₀ mode only.

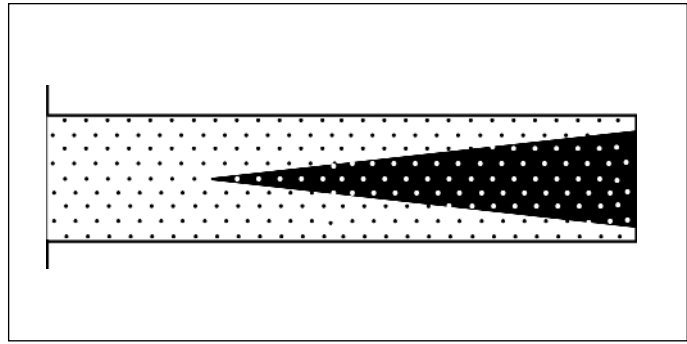
Free-space method for the measurement of complex permittivity— Reflection and transmission of an electromagnetic wave at the interface of two dielectric materials depend on the contrast in their dielectric parameters. Some researchers have used these phenomena to determine the complex permittivity of dielectric materials. The sample is placed in free-space and phase-corrected horn antennas are used to monitor different waves via an automatic network analyzer [5]. The system is calibrated using the TRL (through, reflect, and line) technique. A time domain gating may be used to minimize the error due to multiple reflections. The sample of thickness t is placed in front of a conducting plane and its reflection coefficient Γ_1 is measured. Complex permittivity of the material is then determined by:

$$\Gamma_1 = \frac{j \tan\left(k_o t \sqrt{\epsilon_r^*}\right) - \sqrt{\epsilon_r^*}}{j \tan\left(k_o t \sqrt{\epsilon_r^*}\right) + \sqrt{\epsilon_r^*}} \quad (17)$$

where k_o is the free-space wave-number of electromagnetic signal.

Open-ended coaxial line method— Sometimes it may not be possible to cut out the sample of a material for the measurement. This is especially important in the case of biological specimens to perform in-vivo measurements because the material characteristics may change otherwise, in which case the following technique may be used:

- An open-ended coaxial line is placed in close contact with the sample, as shown in Figure 3;



▲ Figure 2. A waveguide termination filled with the sample.

- Its input reflection coefficient (or admittance) is measured using an automatic network analyzer [2].

If the coaxial cross-section is electrically small, then its aperture admittance, Y_L , can be represented by:

$$Y_L = \frac{j2k^2}{\omega\mu_o \left[1n\left(\frac{b}{a}\right)\right]^2} \int_a^b \int_0^\pi \int_0^{2\pi} \frac{\cos(\phi') \exp(-jkr)}{r} d\rho d\rho' d\phi' \quad (18)$$

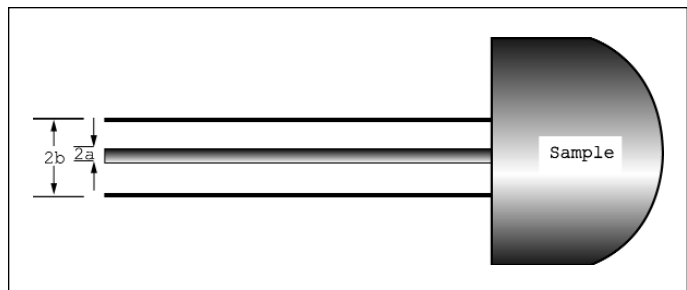
where

$$r = \sqrt{\rho^2 + \rho'^2 - 2\rho\rho' \cos(\phi')} \quad (19)$$

$$k = \omega\sqrt{\mu_o\epsilon_o\epsilon_r^*} \quad (20)$$

Inner and outer radii of the coaxial line are a and b , respectively; ω is the angular frequency; and μ_o and ϵ_o are the permeability and permittivity of the free space, respectively.

Equation 18 is solved numerically for k and the complex permittivity ϵ_r^* is then found via Equation 20. For materials with high permittivity, the coaxial cross-section may not be small enough; therefore, higher order modes of the field over the aperture need to be taken into account. This is accomplished through an electric field integral equation [2]. However, this numerical procedure becomes much more complex.



▲ Figure 3. Coaxial line geometry with terminating sample.

Using the manufacturer's recommended technique, the network analyzer is calibrated initially using three standards: an open-circuit, a short-circuit, and a matched load. The reference plane is then moved to the sample end of the coaxial line using a short circuit. Alternately, three standard materials (materials with known ϵ_r *) can be used in conjunction with (18) to calibrate the system directly at the sample plane.

Conclusions

An electrical characterization of materials is desired in many scientific and industrial applications. This paper has summarized the characteristic parameters associated with dielectrics along with the properties of a variety of materials. Selected measurement techniques have also been briefly described; these can help the practicing engineers in selecting one for their specialized application. Relevant references, though by no means complete, are included that can provide further details. ■

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Author information

Devendra Misra is currently the Chair of Electrical Engineering at the University of Wisconsin-Milwaukee and can be reached via e-mail at misra@uwm.edu.

Kurt Fenske is currently a Senior Lecturer and working towards his M.S. in Electrical Engineering at the University of Wisconsin-Milwaukee. He can be reached via e-mail at kurtf@uwm.edu.