PERMITTIVITY AND MEASUREMENTS

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1. INTRODUCTION

Propagation of electromagnetic (EM) waves in radio frequency (RF) and microwave systems is described mathematically by Maxwell's equations with corresponding boundary conditions. Dielectric properties of lossless and lossy materials influence EM field distribution. For a better understanding of the physical processes associated with various RF and microwave devices, it is necessary to know the dielectric properties of media that interact with EM waves. For telecommunication and radar devices, variations of complex dielectric permittivity (referring to the dielectric property) over a wide frequency range are important. For RF and microwave applicators intended for thermal treatments of different materials at ISM (industrial, scientific, medical) frequencies, one needs to study temperature and moisture content dependencies of the permittivity of the treated materials.

Many techniques have been developed for the measurement of material permittivity. Some general descriptions of those methods are provided in the literature [1–4]. The measurement results for diverse dielectric media are compiled in the literature [5–7].

The objective of this article is to provide a brief description of basic physical theory for the measurement of permittivity associated with three popular experimental methods and to review the permittivities for different materials. Most of these data are taken from the literature, but some of permittivity data were measured in Biological Systems Engineering Department of Washington State University. The measurements were conducted by means of open-ended coaxial probe method with commercial instrumentation.

2. THEORY OF PERMITTIVITY

Permittivity is a quantity used to describe dielectric properties that influence reflection of electromagnetic waves at interfaces and the attenuation of wave energy within materials. In frequency domain, the complex relative permittivity ε^* of a material to that of free space can be expressed in the following form:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

The real part ε' is referred to as the *dielectric constant* and represents stored energy when the material is exposed to an electric field, while the dielectric loss factor ε'', which is the imaginary part, influences energy absorption and attenuation, and $j = \sqrt{-1}$. One more important parameter used in EM theory is a tangent of loss angle: $\tan\delta_e = \varepsilon''/\varepsilon'$. Mechanisms that contribute to the dielectric loss in heterogeneous mixtures include polar, electronic, atomic, and Maxwell–Wagner responses [7]. At RF and microwave frequencies of practical importance and currently used for applications in material processing (RF 1–50 MHz and microwave frequencies of 915 and 2450 MHz), ionic conduction and dipole rotation are dominant loss mechanisms [8]:

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{\varepsilon_0 \omega} \tag{2}$$

where subscripts "d" and "σ" stand for contributions due to dipole rotation and ionic conduction, respectively; σ is the ionic conductivity in S/m of a material, ω is the angular frequency in rad/s, and ε_0 is the permittivity of free space or vacuum (8.854×10^{-12} F/m). Dielectric lossy materials convert electric energy at RF and microwave frequencies into heat. The increase in temperature (ΔT) of a material can be calculated from [9]

$$\rho C_p \frac{\Delta T}{\Delta t} = 5.563 \times 10^{-11} f E^2 \varepsilon'' \tag{3}$$

where C_p is the specific heat of the material in $\mathrm{J\,kg^{-1}\,{}^\circ C^{-1}}$, ρ is the density of the material in kg/m^3, E is the electric field intensity in V/m, f is the frequency in Hz, Δt is the time duration in seconds, and ΔT is the temperature rise in the material in °C. It is clear from Eq. (3) that the rise in temperature is proportional to the material's dielectric loss factor, in addition to electric field intensity squared, frequency, and treatment time.

In dielectric materials, the electric field strength decreases with distance z from the surface and is written as

$$E = E_0 e^{-\alpha z} \tag{4}$$

The attenuation factor α depends on the dielectric properties of the material [5] and is given by

$$\alpha = \frac{2\pi}{\lambda_0}\left[\frac{1}{2}\varepsilon'\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right)\right]^{1/2} \tag{5}$$

where λ_0 is the free-space wavelength. Substituting Eq. (4) into power equation Eq. (3), one obtains

$$P = P_0 e^{-2\alpha z} \tag{6}$$

Penetration depth of microwave and RF power is defined as the depth where the power is reduced to $1/e$ ($e = 2.718$) of the power entering the surface (Fig. 1). The penetration depth d_p in meters of RF and microwave energy in a lossy material can be calculated by [5]

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon'\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right]}} \tag{7}$$

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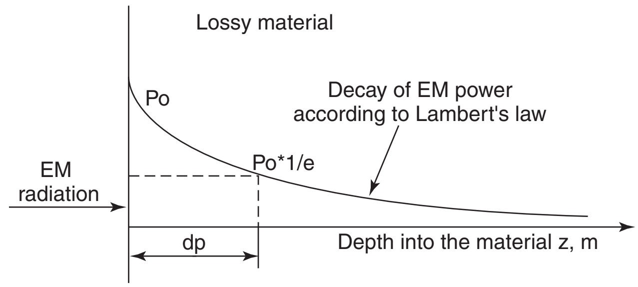

Figure 1. Typical penetration depth inside a large-sized material (larger than the wavelength).

where c is the speed of light in free space (3×10^8 m/s). After obtaining the dielectric properties, the penetration depths of electromagnetic energy into selected materials can be calculated at the required frequency. Given fixed dielectric properties, the penetration depth of a material is inversely proportional to frequency. It is, therefore, expected that in general deeper penetration corresponds to lower frequencies, and that higher frequencies result in greater surface heating. It should be noted that the dielectric properties of lossy materials vary with frequency but penetration depth does not vary exactly as $1/f$. Nevertheless, EM waves with short wavelength do not penetrate deeply into most moist media [7], where the dielectric constants and loss factors are relatively high.

2.1. Frequency Effect

Dielectric properties of materials are affected by many factors, including frequency, temperature, and moisture content. Dielectric properties can vary significantly with frequency, which will be discussed in detail in this section. The frequency-dependent trend of dielectric properties can provide important information of the material characteristics. In theory, electric conduction and various polarization mechanisms (including dipole, electronic, ionic, and Maxwell–Wagner) contribute to the dielectric loss factor (Fig. 2). For moist dielectric materials ionic conductivity plays a major role at lower frequencies (e.g., <200 MHz), whereas both ionic conductivity and dipole rotation of free water play a combined role at microwave frequencies. Maxwell–Wagner polarization arises from buildup of charges in the interface between components in heterogeneous systems. The Maxwell–Wagner polarization effect peaks at about 0.1 MHz [7], but in general, its contribution is small compared to that of ionic conductivity. For low-moisture media, bound water plays a major role in dielectric heating in the frequency range between 20 and 30 GHz [10,11] at room temperature (20°C) [12].

For a pure liquid, the Debye model [13] describes the frequency-dependent dielectric properties in the rectangular form

$$\varepsilon^* = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2\tau^2} - j\frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2} \quad (8)$$

where ε_∞ is the infinite or high frequency relative permittivity, ε_s is the static or zero-frequency relative permittivity, and τ is the relaxation time in seconds of the material. In general, the larger the molecules, the longer the relaxation time. For a pure liquid, such as water, the dielectric loss factor reaches the maximum at a critical frequency related to the relaxation time ($f_c = 1/2\pi\tau$). Water molecules are polar, and the most important constituent that contributes to the dielectric properties of moist dielectrics. Water molecules bound to the surface of polar materials in monolayers or multilayers have much longer relaxation times than do free water molecules. For example, the relaxation time of bound water in different food materials at 20°C is determined to be between 0.98 and 2.00 ns, corresponding to a peak in ε'' at ~100 MHz, whereas the relaxation time τ of free water in those foods at 20°C is between 0.0071 and 0.00148 ns, corresponding to a peak in ε'' at around 16000 MHz [14]. Harvey and Hoekstra [10] found that ε'' of monolayer bound water in lysozyme at 25°C peaked at 300 MHz and ε'' for the second layer bound water peaked at about 10000 MHz. The two

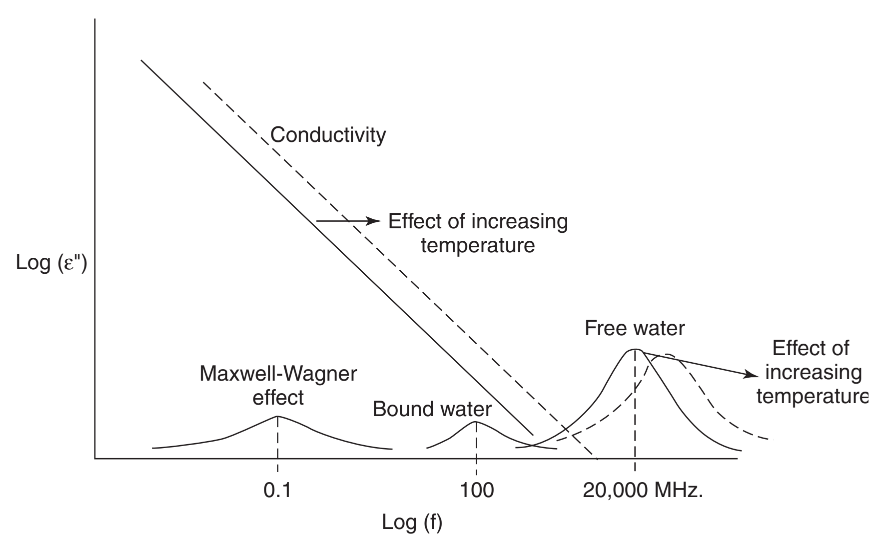

Figure 2. Contributions of various mechanisms of the loss factor (ε'') of moisture materials as a function of frequency (f) [12].

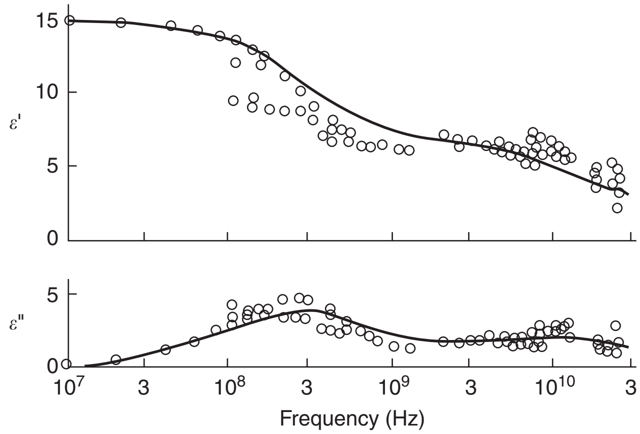

Figure 3. Dielectric constant (ε') and loss factor (ε'') as a function of frequency for packed lysozyme samples containing nearly two layers of bound water at 25°C [10].

dispersions observed in Fig. 3 correspond to the first and second layers of bound water, respectively.

Figure 4 shows a good example of Debye dielectric relaxation for butyl alcohol at 20°C with single relaxation time measured with an open-ended coaxial probe connected to an impedance analyzer [19]. At low frequencies, in a static region, where the dipoles have time to follow the variations of the applied field, the dielectric constant of butyl alcohol has a value of ~17. The loss factor is small for both high and low frequencies and reaches a peak at the relaxation frequency of ~250 MHz.

Similar frequency-dependent permittivity can be found in water, methanol, and ethanol and can be expressed in the following relationships, respectively [15]:

$$\varepsilon^* = 5.62 + \frac{74.59}{1 + jf/17.0 \times 10^9} \text{ (water)}$$
$$\varepsilon^* = 5.76 + \frac{27.89}{1 + jf/2.709 \times 10^9} \text{ (methanol)} \quad (9)$$
$$\varepsilon^* = 4.44 + \frac{20.84}{1 + jf/0.826 \times 10^9} \text{ (ethanol)}$$

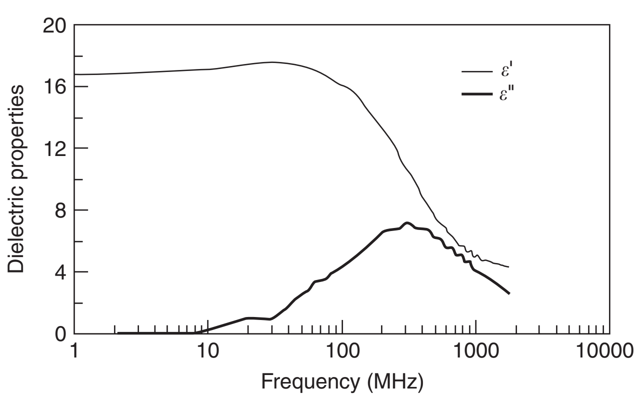

Figure 4. Dielectric constant (ε') and loss factor (ε'') of butyl alcohol at 20°C [19].

Frequency-dependent characteristics of complex biological materials, including moist foods, cannot be described with simple mathematical expressions.

2.2. Temperature Effect

Temperature of a material has a significant effect on the dielectric properties. Generally, the loss factor increases with increasing temperature at low frequencies due to ionic conductance and decreases with increasing temperature at high frequencies due to free-water dispersion (Fig. 2). In multidispersion materials, for example, the transition is gradual because of the combined effects of relaxation and the ionic conduction and there is a U-shape frequency response in ε'' (Fig. 6). Debye related the relaxation time for the spherical molecule to viscosity and temperature as the result of randomizing agitation of the Brownian movement [5]

$$\tau = V\frac{3v}{kT} \quad (10)$$

where v is the viscosity, T is the absolute temperature, V is the volume, and k is a constant. For nonspherical water molecules, we may have the following relation

$$\tau \propto \frac{v}{T} \quad (11)$$

while the viscosity of all fluid decreases with increasing temperature [16]

$$v = v_0 e^{E_a/R_g T} \quad (12)$$

where E_a is activation energy and R_g is the universal gas constant. Therefore, as temperature rises, relaxation time for water decreases. The shifting of the relaxation time toward a lower value (thus the frequency at the maximum ε'' shifts toward a higher value as temperature increases) reduces the value of ε'' for water at a fixed microwave frequency (Fig. 5). For example, as the relaxation time τ decreases with increasing temperature, the dispersion peak moves to higher frequencies and the loss factor of pure water at 2450 MHz decreases with increasing temperature. The dielectric constant ε' of free water also decreases with increasing temperature as the result of increased Brownian movement.

The dielectric loss factor ε''_σ due to conduction decreases with increasing frequency as shown in Eq. (2). The contribution of ε''_σ to the overall loss factors is smaller at 2450 MHz than at 915 Hz (Fig. 6). The electric conductivity σ in ionic solutions increases with temperature due to decreased viscosity and hence increased ion mobility [17]. Therefore, based on Eq. (2), ε''_σ also increases with temperature (Fig. 6). At 915 MHz the dielectric constant of ionic solutions generally increases with temperature.

The dielectric properties of high-moisture-content substances change with temperature [19]. An example of the dielectric loss factor (ε'') of fifth-instar codling moths measured at five temperatures is shown in Fig. 7. The loss factor decreases with increasing frequency, reaching

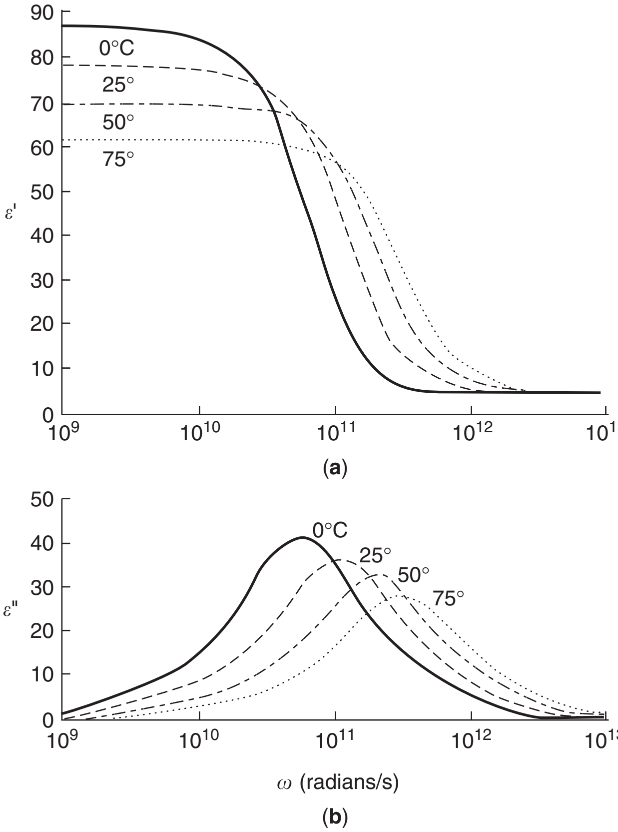

Figure 5. Effect of temperature on dielectric constant (ε') and loss factor (ε'') of free water ($\omega = 2\pi f$, where f is frequency in Hz) [22].

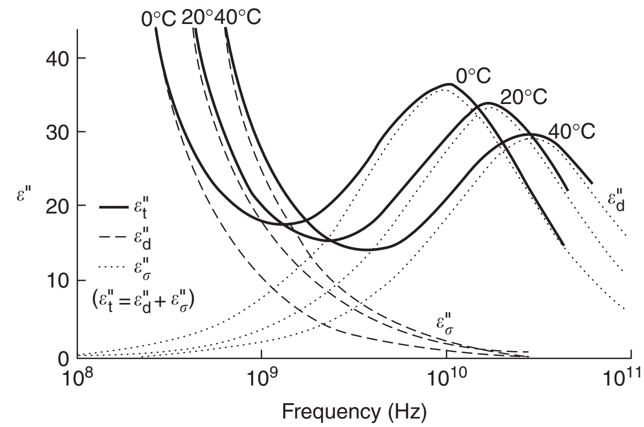

Figure 6. Effect of temperature on dielectric loss factor (ε'') of 0.5 N aqueous sodium chloride at three temperatures [18].

about 12 at 1800 MHz. The loss factor of codling moth larvae increases with temperature, especially at low frequencies. This is due mainly to the increase in ionic conduction at high temperatures [12]. Increasing dielectric loss factor with temperature often results in a well-known phenomenon, commonly referred to as "thermal runaway" [7], in which a preferentially heated subject in an EM field accelerates heating as its temperature rises.

Figure 8 shows the loss factor of a typical dry nut (walnut kernels) over the frequency range from 1 to 1800 MHz at five temperatures. The ε'' values are less than 1 at frequencies below 50 MHz. The ε'' values peak in the range between 500 and 1000 MHz. The peak value of ε'' for walnut kernels decreases with increasing temperature, while the frequency corresponding to the peak ε'' shifts to a higher value. This temperature-dependent trend is typical of polar molecules [20]. At any selected frequency in the tested range, the loss factor of the walnut kernel generally decreases with increasing temperature; that is, for a given EM field intensity, higher temperature walnuts will absorb less energy than cooler ones, resulting in improved heating uniformity.

Ice is almost transparent to microwaves (Table 1). When a lossy material is frozen, both dielectric constant and loss factor are significantly reduced; the degree of reduction depends, to a large extent, on the amount of water

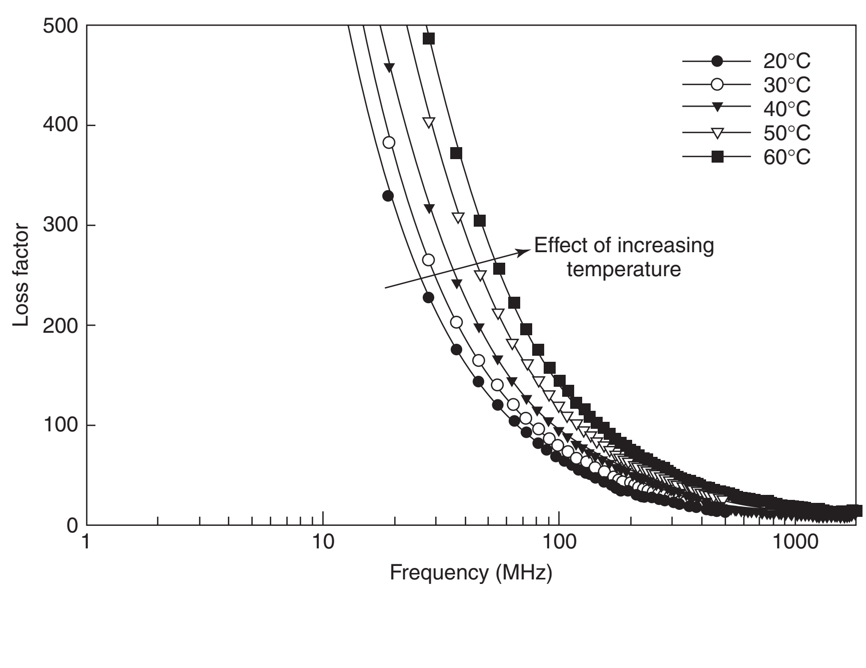

Figure 7. Dielectric loss factor of codling moth larvae (slurry) at five temperatures [19].

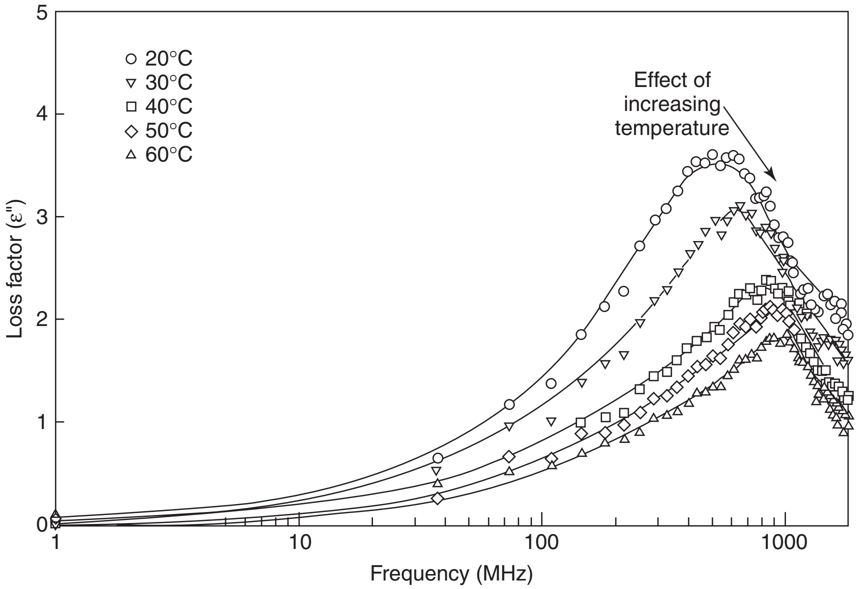

Figure 8. Dielectric loss factor of walnut kernels as a function of frequency at five temperatures [19].

in the unfrozen state and the ionic conductivity of the free water.

2.3. Moisture Effect

Moisture content is one of the major components of most biological materials. In general, the higher the moisture content, the larger the dielectric constant and loss factor of the materials [20, 22, 23]. Water in moist dielectric materials can be divided, in descending mobility, into (1) water held in intercellular space or capillaries, (2) multilayer water, and (3) monolayer water that is tightly bound to the polar sites. The free-water molecules have dielectric properties similar to those of liquid water, while the bound water exhibits icelike dielectric properties. Dielectric properties of biomaterials, in general, decrease rapidly with decreasing moisture content to a critical moisture level. Below this moisture level, the reduction in loss factor is less significant because of the bound water (Fig. 9). During microwave drying, the wetter parts of biomaterials absorb more microwave energy and tend to level off the uneven moisture distribution.

3. MEASUREMENT PRINCIPLES AND METHODS

3.1. Open-Ended Coaxial Probe Method

Open-ended coaxial probe (OCP) method is currently one of the most popular techniques for measuring of complex dielectric permittivity of many materials. Nondestructive, broadband (RF and microwave ranges), and high-temperature ($\leq$1200°C) measurements can be preformed with this method using commercially available instrumentation. Its well-developed theory makes it possible to obtain sufficiently accurate results for both medium-loss and high-loss media [24–26].

Figure 10 illustrates an OCP system used at Washington State University. It consists of an automatic network analyzer (ANA) with a calibration kit, custom-built test

Table 1. Dielectric Properties of Water and Ice at 2450 MHz

State of Water	Relative Dielectric Constant (ε')	Loss Factor (ε'')	Loss Tangent ($\tan\delta$)
Water (25°C)	78	12.5	0.16
Ice	3.2	0.0029	0.0009

Source: Ref. 21.

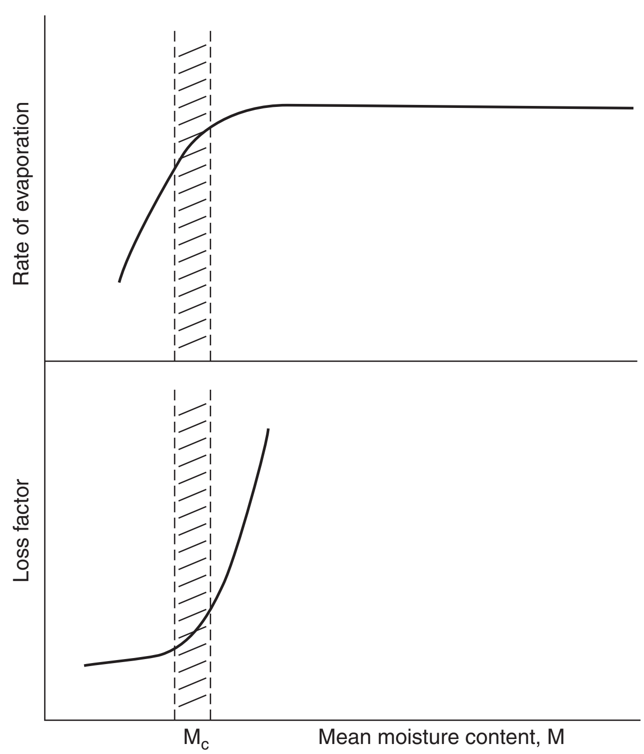

Figure 9. Rate of evaporation and dielectric loss factor as affected by food moisture content [7].

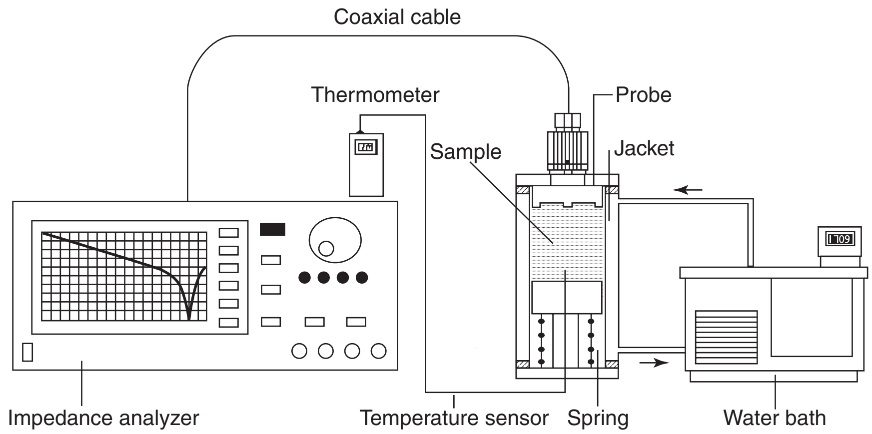

Figure 10. Schematic diagram of experimental setup realizing open-ended coaxial probe method [19].

cell, a programmable circulator, a coaxial cable, and a personal computer connected to the ANA through a special bus. The material under study is placed in a stainless steel pressureproof test cell. The probe is kept in close contact with the sample during the measurements via a stainless steel spring and piston. A thin rigid stainless steel thermocouple probe passes onto the center of the sample to measure sample temperature. The programmable circulator pumps a temperature-controlled liquid (90% ethylene glycol and 10% water by volume) through the water jacket of the test cell, allowing the sample inside to be heated and cooled.

The sensing element of an OCP system is an open-ended cylindrical coaxial line that is excited by transverse electromagnetic (TEM) wave. Parameters (amplitude and phase) of incident and reflected signals are detected by the ANA. The complex dielectric permittivity is determined according to the reflected coefficient ($\Gamma = \Gamma' - j\Gamma''$) as follows [27]

$$\varepsilon' = (A_e f)^{-1}\left\{\frac{-2\Gamma''}{(1+\Gamma')^2 + \Gamma''^2}\right\};$$
$$\varepsilon'' = (A_e f)^{-1}\left\{\frac{1-\Gamma'^2-\Gamma''^2}{(1+\Gamma')^2 + \Gamma''^2}\right\} \quad (13)$$

where A_e is the empirical coefficient dependent on characteristic impedance of the probe and sample size. In order to eliminate the influence of reflections caused by transmission-line discontinuities, a calibration procedure is utilized. The EM characteristics of the measurement system are analyzed using three standard terminations (open, short, and 50 Ω). Then any material with well-known dielectric properties such as deionized water, for example, is tested. The actual reflection coefficient differs from reflection coefficient measured using ANA (Γ_m) [25]

$$\Gamma = \frac{\Gamma_m - a_{11}}{a_{22}(\Gamma_m - a_{11}) + a_{12}} \quad (14)$$

where a_{11} is the directivity error, a_{12} is the frequency response error, a_{22} is the source match error. Taking into account propagation constant (γ) and distance from the connector to the probe head (z) we can calculate a_{ij} in terms of S parameters of the connector:

$$a_{11} = S_{11};\, a_{12} = S_{12}S_{21}e^{-2\gamma z};\, a_{22} = S_{22}e^{-2\gamma z} \quad (15)$$

In the inverse coaxial probe model, it is assumed that a sample has a semiinfinite size. A few additional conditions must be satisfied to avoid measurement error in the OCP method:

- Minimize thermal expansion of both conductors of coaxial line at high temperatures.
- Intimate contact between the probe and the sample; liquid sample may flush the probe and the surface roughness of solid sample should be less than 0.5 μm [28].
- Minimize disturbance caused by temperature, vibration, or any other external factors after calibration and during measurement.

The OCP method is very well suited for liquids or soft solid samples. It is accurate, fast, and broadband (from 0.2 to up to 20 GHz). The measurement requires little sample preparation. A major disadvantage of this method is that it is not suitable for measuring materials with low dielectric property (plastics, oils, etc.).

3.2. Transmission-Line Method

The transmission-line method (TLM) belongs to a large group of nonresonant methods of measuring complex dielectric permittivity of different materials in a microwave range [7,51]. Several modifications to this method exist, including the free-space technique [29], the open-circuit network method (see previous section), and the short-circuited network method. Usually three main types of transmission lines are used as the measurement cell in TLM: rectangular waveguide, coaxial line, and microstrip line.

Consider the distribution of the TEM wave in a short-circuited coaxial line partially filled with a lossy material under study (Fig. 11). Analyzed sample is placed near the short-circuited end of the transmission line. The dielectric properties of the sample are determined using the follow-

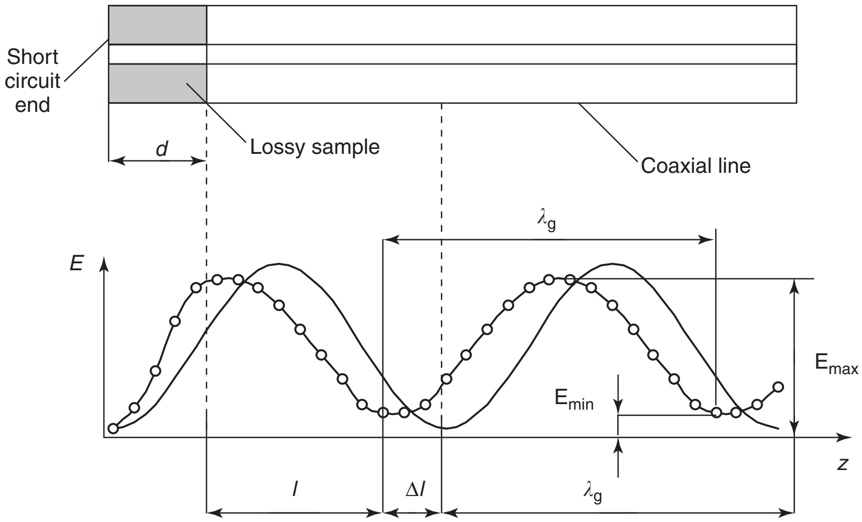

Figure 11. Electric field pattern of TEM wave in empty (solid lines) and partially loaded (lines with circles) short coaxial waveguide. Equations (16)–(19) explain all parameters used in this figure.

ing expressions

$$\varepsilon' = \left(\frac{\lambda}{2\pi d}\right)^2 (x^2 - y^2) + \left(\frac{\lambda}{\lambda_{\mathrm{qc}}}\right)^2; \qquad \varepsilon'' = \left(\frac{\lambda}{2\pi d}\right)^2 2xy \tag{16}$$

where λ is the free-space wavelength, λ_{qc} is the quasicutoff wavelength, d is the sample thickness (Fig. 11), $x = \mathrm{Re}(Z_{\mathrm{in}})$ and $y = \mathrm{Im}(Z_{\mathrm{in}})$, and Z_{in} is the input impedance of the short-circuited line

$$Z_{\mathrm{in}} = \frac{K_{\mathrm{t}}^2 + tg^2(2\pi/\lambda_{\mathrm{a}} l)}{K_{\mathrm{t}}[1 + tg^2(2\pi/\lambda_{\mathrm{a}} l) + j(1 - K_{\mathrm{t}}^2) tg(2\pi/\lambda_{\mathrm{a}} l)]} \tag{17}$$

where l is the distance between the dielectric surface and the first minimum of the standing wave, λ_{a} is the wavelength in unloaded part of transmission line, and K_{t} is the traveling-wave coefficient that is calculated when $K_{\mathrm{t}} \geq 0.4$ as

$$K_{\mathrm{t}} = \sqrt{\frac{E_{\min}}{E_{\max}}} \tag{18}$$

and when $K_{\mathrm{t}} < 0.4$ as

$$K_{\mathrm{t}} = \frac{\sin(2\pi\Delta x/\lambda_{\mathrm{a}})}{\sqrt{((E/E_{\min}) - 1)\sin(2\pi\Delta x/\lambda_{\mathrm{a}})}} \tag{19}$$

where $E_{\min}$ and $E_{\max}$ are the minimum and maximum values of electric field amplitude (see Fig. 11) and $2\Delta x$ is the distance between two points along transmission line on both sides of minimum where measured data are equal and determined from $E = m^2 E_{\min}$ ($2 < m < 10$ is the empirical coefficient found from the calibration procedure).

Dielectric permittivity of lossy media may be also successfully measured employing a two ports coaxial cell with a sample placed in the middle of transmission line, so that the TEM wave could propagate from the input port to the output port. Impedance changes and propagation characteristics (S parameters) of the TEM wave measured by means of ANA in empty and partially loaded transmission line lead to determination of the dielectric properties of lossy material. Basic principles of this technique are given in Ref. 30.

In general, a TLM measurement system is more expensive for the same range of frequency than the open-ended coaxial probe system, and the measurements are more difficult and time-consuming. The method described above gives a good accuracy for high-loss materials. But it has rigid requirements on sample shape and sizes. In particular, the sample shape needs to precisely fit the cross section of the transmission line. In some cases, in order to increase accuracy, it is necessary to measure several samples of various thicknesses. Despite these drawbacks, TLM is still widely used in microwave measuring engineering because of its simplicity. Using coaxial line as a basic unit of measurement cell makes this method sufficiently broadband. The accuracy of this method is generally between that of the OCP method and that of the resonance cavity method.

3.3. Resonant Cavity Method

Resonant cavity methods are also widely utilized in measuring complex dielectric permittivity of lossy materials. The most popular resonant cavity method is the perturbation method (PM), which is based on a comparative analysis of certain EM characteristics between empty and a partially loaded rectangular or cylindrical resonance cavity [31]. A schematic diagram of an experimental setup of PM is shown in Fig. 12.

According to PM theory [32,33], dielectric permittivity and losses of a sample under study are determined as follows:

$$\varepsilon' = 1 + A^{-1}\frac{V_{\mathrm{c}}}{V_{\mathrm{s}}}\frac{\Delta f}{f_0}\ ; \ \varepsilon'' = B^{-1}\frac{V_{\mathrm{c}}}{V_{\mathrm{s}}}\left(\frac{1}{Q_1} - \frac{1}{Q_0}\right) \tag{20}$$

where f_0 and Q_0 are the resonance frequency and Q factor of the empty cavity, f_1 and Q_1 are the resonance frequency

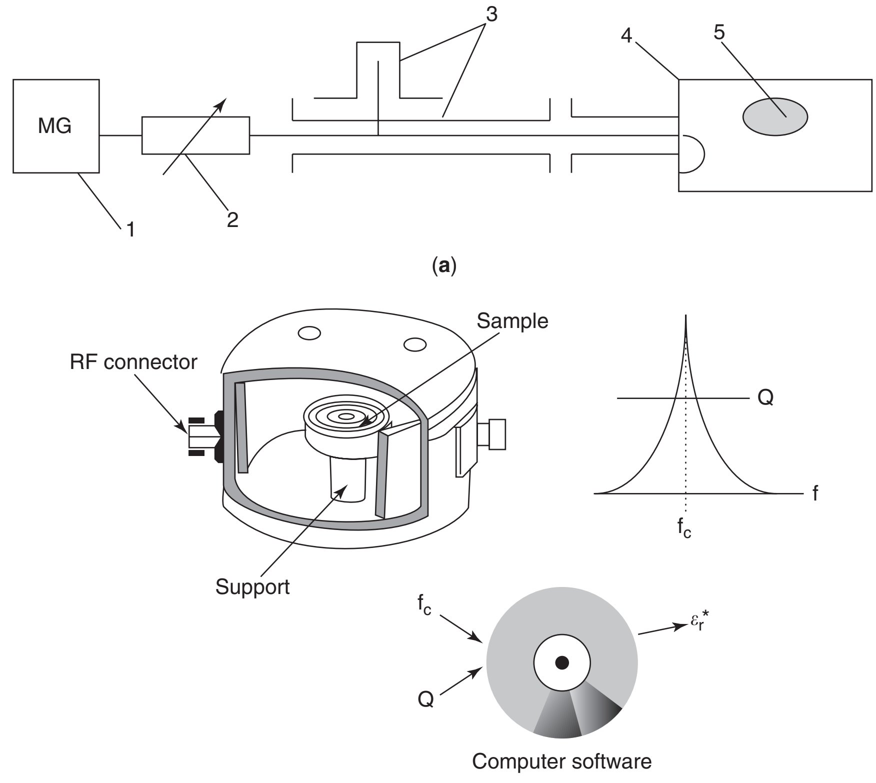

Figure 12. (a) Microwave system for measuring dielectric properties of lossy materials: microwave generator (1), attenuator (2), wavemeter (3), cavity resonator (4), and sample (5); (b) closeup view of a sample, cavity, and related principles for the measurement.

and Q factor of the cavity with a sample, V_c is the cavity volume, V_s is the sample volume; and $\Delta f = f_0 - f_1$ A and B are the coefficients that depend on several parameters: shape, sizes, and location of the sample in the cavity, and configuration and excited operating mode of the cavity. In some cases, A and B may be found analytically for a lossy sheet material placed in a rectangular cavity with operating mode TE_{103} [31], or they may be determined empirically with calibration of the experimental setup. Equation (20) is valid when three main assumptions are satisfied [32]:(1) the dielectric sample does not disturb the general distribution of the EM field in the cavity, (2) metallic wall losses do not influence the resulting losses in the cavity, and (3) Q_0 and Q_1 are measured at the same frequency. Appropriate location of the sample is also a very important factor that affects the accuracy of the measurement. Preliminary numerical modeling of the microwave setup with lossy dielectric material inside the cavity may be a useful approach for determining an optimum sample position in this case [31]. Sometimes, measurement errors are possible when there are airgaps between the specimen and the conducting parts of the metallic resonator.

There are also some restrictions in using conventional resonance PM for measuring the dielectric loss tangent of low-loss media. If conduction losses in cavity walls are higher than (or comparable to) the dielectric losses of the specimen, the resonator Q factor may change and one will not obtain the correct values of ε''. In this case, application of hybrid high-order modes called whispering-gallery modes [34] or a special calibration procedure of Q factor characterization as a function of frequency [32] can help to eliminate the drawbacks of this method.

PM is more accurate than the waveguiding methods. It is particularly suited for medium-loss and low-loss materials and substances. Precisely shaped small-sized samples are usually used with this technique. But PM provides dielectric properties measurements only at a fixed frequency. Commercial systems from Hewlett-Packard are more expensive than the open-end coaxial probe system.

4. PERMITTIVITY OF ORGANIC AND INORGANIC MATERIALS

4.1. Foodstuff and Agricultural Products

Numerous data are reported in the literature on the dielectric properties of biomaterials, especially food materials. This section only summarizes the dielectric properties for some typical materials commonly used in food processing. Table 2 lists electrical property data for different salt solutions, fruits, and codling moth larvae at 27 MHz RF and 915 MHz microwave. Air and deionized water do not absorb much electromagnetic energy at these two frequencies due to near-zero dielectric loss factors. Dielectric and conductivity properties increase with increasing salt content. However, dielectric constant decreases both with frequency and salt content at 915 MHz.

Dielectric properties of dry food solids, fats, and oils are very low and are relatively independent of frequency and temperature. The dielectric properties of selected oils and low-moisture-content food solids are listed in Table 3.

Table 2. Electrical Conductivity (σ) and Dielectric Properties at 27 and 915 MHz of Lossy Materials at Room-Temperature Conditions

Materials	$\sigma \times 100$ (S/m)	At 27 MHz RF		At 915 MHz	
		ε'	ε''	ε'	ε''
Air	~0	1.0	~0	1.0	~0
Water					
Distilled/deionised	$0.5–1.1 \times 10^{-2}$	80.1	0.03	78.4	3.6
Fresh (tapwater, Pullman, WA, USA)	3.25	79.6	18.9	78.8	4.5
+ 0.05% salt (common salt, Nail)	13.3	80.3	75.1	78.9	6.4
+ 0.10%	23.1	80.6	126.6	79.0	8.2
+ 0.15%	32.0	81.5	178.5	78.7	9.9
+ 0.20%	40.5	82.1	226.3	78.6	11.5
+ 0.25%	49.8	83.6	276.0	78.6	13.3
+ 0.50%	92.5	88.0	524.3	78.1	21.8
+ 1.0%	173	99.2	985.8	77.3	37.2
+ 2.0%	333	126.1	1866	75.7	67.1
Sea	400	—	—	—	—
Apples:					
McIntosh/Winesap	1.05–1.33	—	—	—	—
Fuji	0.86–1.3	—	—	—	—
Red Delicious (juice)	18.5	79.5	138.9	74.7	9.9
Apples (flesh)	—	64.3	80.8	56.9	8.9
Immature apple (juice)	43.0	87.5	248.9	77.2	13.5
Cherries:					
Bing, Rainier (flesh)	—	87.6	185.4	69.7	14.3
Sweetheart (juice)	42.0	—	—	—	—
Vegetables pieces	6–10	—	—	—	—
Fruit pieces	5–15	—	—	—	—
Insect: codling moth (5th instars)	31.0	125.2	458.3	59.9	22.4

Source: Ref. 35.

Figure 13 shows the effect of temperature on the dielectric loss factor of selected foods at 3000 MHz [37]. The high salt content in the ham makes the dielectric properties of this product quite different from those of the remaining materials in the graph. Due to ionic polarization, the dielectric loss factors increase with temperature above the freezing point, which is contrary to the trend of dielectric properties of other foods in which loss mechanisms are determined mostly by the dipole polarization of free water. One advantage of the decreased loss factor with increasing temperature is the so-called temperature leveling effect. When a certain portion of a food is overheated, the loss factor of that part is reduced, which results in less conversion of microwave energy to heat at that part of the food and helps reduce nonuniform spatial temperature distribution.

When thawing frozen foods at relatively high microwave power levels, one often experiences the thermal runaway phenomenon, in which certain areas of the food are overheated while the other areas are still frozen. This is because faster thawing of a portion of food due to uneven heating dramatically increases the loss factor of that part of the food due to the high loss factor of free water (Fig. 13), which in turn increases microwave absorption, causing more uneven heating. In practice, a low microwave power level is often used in microwave thawing so that heat conduction can reduce nonuniform temperature distribution. In industrial tempering (a process that brings deep-frozen products from -30° or -10°C to a few degrees below freezing point for further processing) of large blocks of meat or fish, convective surface cooling at below freezing temperature is often used to reduce thermal runaway.

Figure 14 shows the dielectric properties of Red Delicious apples as a function of frequency at three selected moisture contents and two measured temperatures. At a high moisture content (70% wet basis), ε' decreases with increasing frequency, while ε'' decreases to a minimum value and then increases with frequency (Figs. 14a and 14d). The gradual reduction in ε' of high-moisture-content samples with increasing frequency is likely caused by the dispersion of water molecules. In a single dispersion system (e.g., pure water), this transition takes place in a narrow frequency range and follows the Debye equation [Eq. (8)]. In multidispersion food systems, the transition is gradual because of the combined effects of relaxation and ionic conduction. A minimum ε'' is observed at 1000 MHz (Fig. 14a) at 22°C. The frequency corresponding to the minimum ε" shifts to about 2000 MHz at 60°C (Fig. 14d). This shift can be related to the temperature response of both the free-water dispersion and the ionic conduction.

Figure 15 shows the dielectric constant ε' and loss factor $\varepsilon''$of apples at 915 and 2450 MHz as a function of moisture content (MC). In general, ε' and ε'' decreases with decreasing moisture content. In a drying process, as the drying progresses, water dipole becomes less mobile, resulting in reduced loss factor. Reduced moisture content during drying also reduces ionic conductivity, as a small

Table 3. Dielectric Constant (ε′) and Loss Factor (ε″) of Oil and Selected Food Solids

Products	T (°C)		Frequency (Hz) 10^6	10^7	10^8	10^9
Soybean salad oil	25	ε′			2.85	2.62
		ε″			0.159	0.168
	49	ε′			2.88	2.71
		ε″			0.138	0.174
	82	ε′			2.86	2.72
		ε″			0.092	0.140
Cotton oil	25	ε′			2.83	2.64
		ε″			0.174	0.175
	49	ε′			2.87	2.70
		ε″			0.134	0.174
Flour (Mc = 3.2%)	0	ε′	2.8	2.8		
		ε″	0.184	0.184		
	40	ε′	3.5	2.7		
		ε″	0.196	0.235		
	70	ε′	4.0	3.2		
		ε″	0.160	0.275		
Skimmed milk powder	0	ε′	2.1	1.9		
		ε″	0.038	0.040		
	40	ε′	2.1	1.8		
		ε″	0.044	0.054		
	70	ε′	2.4	2.0		
		ε″	0.067	0.072		

Source: Ref. 36.

amount of free water is available as the solvent. In addition, air voids in apple samples as a result of dehydration contribute to the low values of both ε′ and ε″.

Salty products (e.g., macaroni and cheese) have, on the other hand, much larger loss factors than do fresh fruits (Table 4). In addition, the loss factor of fresh fruits and macaroni and cheese increases sharply with increasing temperature, especially at low frequency (e.g., 27 MHz).

There has been increasing interest in using RF and microwave energy as a new thermal treatment method for postharvest insect control in agricultural commodities [36–40]. Knowledge of dielectric properties of insects and commodities is necessary in guiding development, improvement, and scaleup of RF and microwave treatment protocols. Table 5 summarizes the mean values of the dielectric constant and the loss factor of apples, almond, cherry, grapefruit, orange, and walnut as a function of temperature at 27 and 915 MHz. The dielectric constant and the loss factor of fresh fruits at 27 MHz are significantly higher than those at 915 MHz. The loss factor of fresh fruits increases with increasing temperature at 27 MHz and remains nearly constant at 915 MHz, similar to the pattern shown in Fig. 7. However, the temperature effect on dielectric properties of almond and walnut is different from that on fresh fruits as shown in Fig. 8. The peak value of the loss factor decreases and corresponding frequency shifts to larger values with increasing temperature.

Mean values of the dielectric constant and the loss factor of selected insect larvae as a function of temperatures at 27, 40, 915, and 1800 MHz are listed in Table 6. Both the dielectric constant and the loss factor for insects increased with increasing temperature at 27 MHz, but remained almost constant at 915 MHz. This is due mainly to the increase in ionic conduction at high temperatures [12]. The loss factor of insects at 27 MHz decreased in order at all temperatures: Mexican fruitfly, navel orangeworm, codling moth, and Indian meal moth.

Compared to codling moth larvae, the loss factor values of walnuts are much smaller because of high oil content and less moisture in walnut kernels. It is clear from Figs. 7 and 8 that the difference in the value of the ε″ between codling moth larvae and walnut kernels is much larger at lower frequencies than at microwave frequencies, suggesting a better potential for preferential heating of insects in walnuts when using lower-frequency treatments. A theoretical model and experimental evidence have been provided [18] to support the hypothesis that insect larvae can be preferentially heated in dry nuts by 27 MHz RF heating for pest control. This differential heating makes possible in the development of practical RF pest control treatments that the walnut industry can use to replace chemical fumigation.

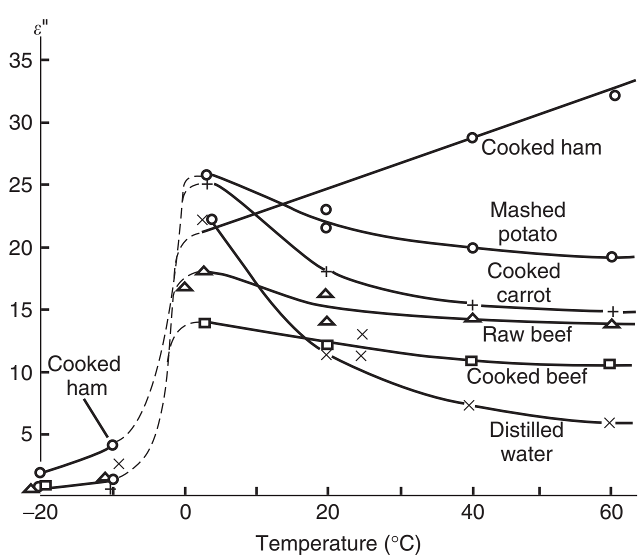

Figure 13. Dielectric loss factor (ε″) of selected foods at 3000 MHz as affected by temperature [37].

4.2. Biological Tissues

High-frequency EM energy is widely used in medical treatments, including physiotherapeutic, diagnostics, rapid rewarming of cryopreserved tissues, pharmacology, reflex therapeutic, blood sterilization, and hyperthermal treatment of cancer [42–45].

The main mechanism for the interaction between EM waves and biological tissues is the same as in foodstuffs: oscillation of polar water molecules (H_2O) and ions. Part of water in biological tissues is linked with albumen (0.3–0.4 g of water on 1 g of albumen), and at relaxation frequencies specific electrical conductivity (σ) of "linked" water sometimes is higher than σ of pure water.

Biological tissues (biotissues) are divided into two main groups: materials with high and low water contents; muscles (73–78%), liver (75–77%), kidneys (76–78%), brain

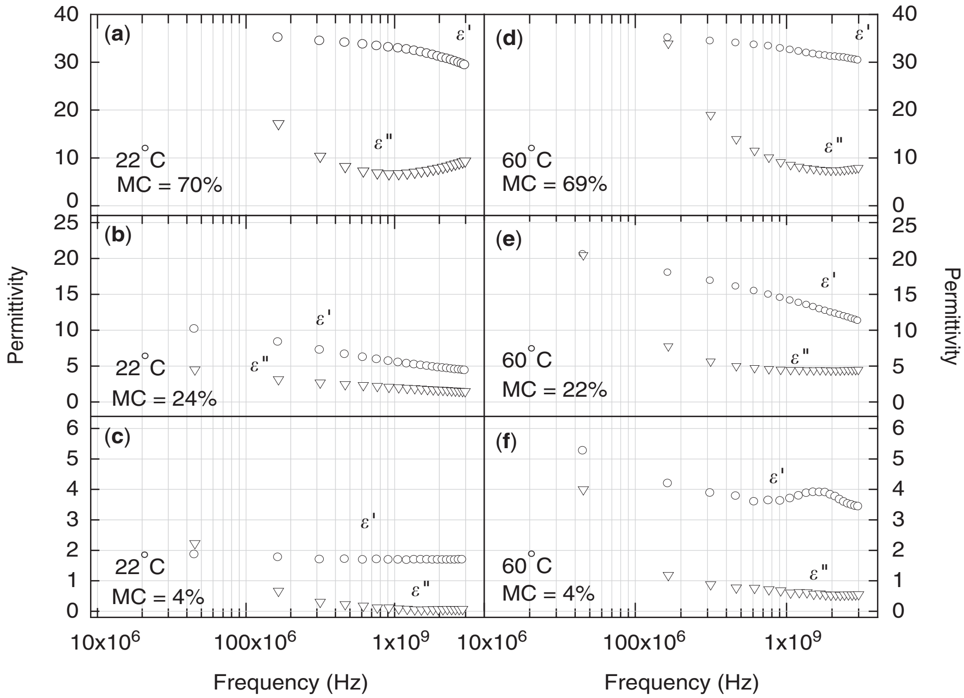

Figure 14. Dielectric properties of Red Delicious apples at three moisture contents and two temperatures [20].

(68–73%), skin (60–76%), lung (80–83%), eye (≤89%) compile the first group. Fat (5–10%) and bone (8–16%) tissues may be included in the second group. Moisture content in blood is higher than in other tissues (≤83%).

Complex dielectric permittivity of some biological materials at room temperature and 2450 MHz taken from Refs. 46 and 47 is represented in Table 7. Bloodflow seldom influences their dielectric properties, excluding tis-

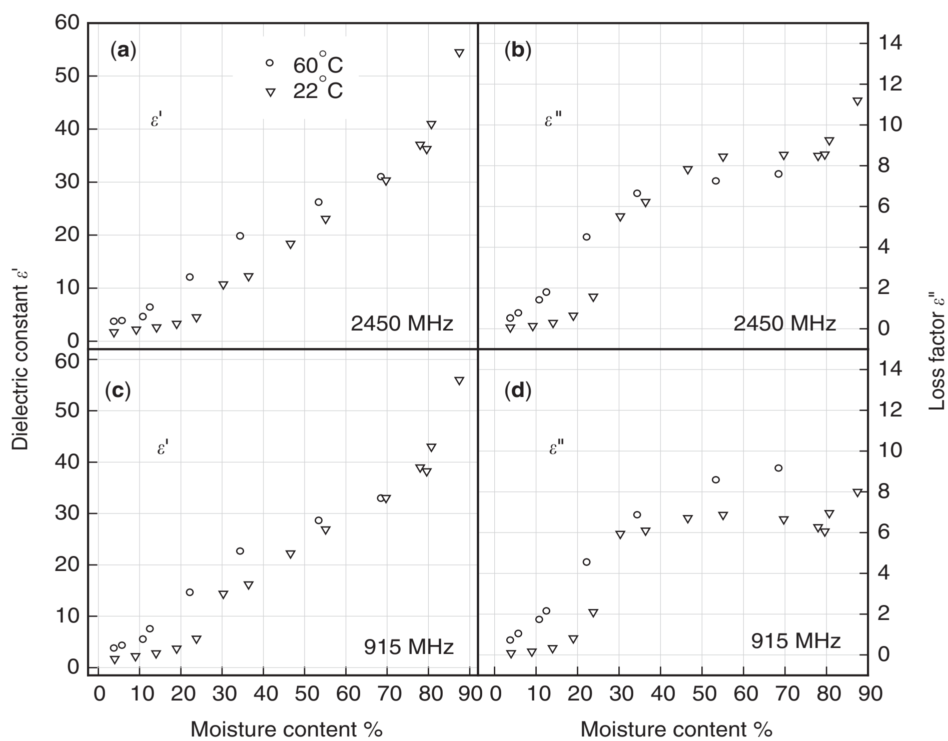

Figure 15. Dielectric properties of Red Delicious apples at 915 and 2450 MHz as influenced by moisture content on a wet basis [20].

Table 4. Dielectric Properties of Macaroni and Cheese

T (°C)		27 MHz	40 MHz	915 MHz	1800 MHz
20	ε'	70.90 ± 8.96	65.27 ± 8.29	40.23 ± 3.71	38.77 ± 5.41
	ε''	400.03 ± 55.18	273.47 ± 37.76	21.33 ± 3.81	17.40 ± 3.39
30	ε'	72.40 ± 9.09	66.53 ± 8.52	40.87 ± 3.18	39.07 ± 5.35
	ε''	486.57 ± 66.47	331.40 ± 45.06	23.47 ± 4.26	17.90 ± 3.46
40	ε'	72.87 ± 8.22	66.63 ± 7.65	40.90 ± 2.88	39.30 ± 5.10
	ε''	593.50 ± 63.65	403.13 ± 43.11	27.30 ± 5.51	19.03 ± 3.21
50	ε'	72.67 ± 8.87	66.27 ± 8.20	40.53 ± 3.07	38.90 ± 5.16
	ε''	688.70 ± 67.08	466.53 ± 45.38	29.77 ± 5.55	19.70 ± 3.03
60	ε'	73.07 ± 8.55	66.13 ± 7.91	40.03 ± 3.00	38.53 ± 5.08
	ε''	800.30 ± 57.46	541.43 ± 38.88	32.87 ± 5.21	20.93 ± 2.71
70	ε'	74.03 ± 8.03	66.67 ± 7.51	40.07 ± 2.70	38.17 ± 4.89
	ε''	921.37 ± 62.49	622.73 ± 42.61	36.23 ± 4.76	22.23 ± 2.49
80	ε''	73.83 ± 8.13	65.67 ± 7.43	39.53 ± 2.39	37.57 ± 4.92
	ε'	1060.27 ± 55.75	716.17 ± 37.55	39.70 ± 4.75	23.67 ± 2.44
90	ε'	76.67 ± 8.37	67.17 ± 7.34	40.67 ± 4.88	37.17 ± 4.60
	ε''	1208.60 ± 67.57	815.70 ± 45.29	43.23 ± 3.30	25.23 ± 1.40
100	ε'	80.93 ± 5.59	69.90 ± 4.75	40.67 ± 4.38	37.13 ± 4.52
	ε''	1382.23 ± 117.32	932.73 ± 78.84	48.17 ± 2.55	27.57 ± 0.84
110	ε'	83.23 ± 4.91	71.13 ± 3.60	40.37 ± 4.48	36.77 ± 4.67
	ε''	1536.13 ± 164.25	1035.87 ± 110.15	52.37 ± 3.04	29.57 ± 1.36
121.1	ε'	84.33 ± 5.26	71.07 ± 4.17	38.93 ± 4.82	35.57 ± 4.84
	ε''	1712.80 ± 172.76	1154.57 ± 115.96	57.40 ± 3.64	31.87 ± 1.75

Source: Ref. 11.

sues with high blood volume (kidneys) or low moisture content (fat). Experimental results [48] have shown that measured data of ε' and ε'' of biotissues in vivo (directly in organism) and in vitro (in the test tube) almost coincide at frequencies higher 100 MHz.

A new technology of microwave diagnostics based on measurement of $\varepsilon' - j\varepsilon''$ of normal and invalid tissues has been proposed [49]. Permittivity of infected gall ($\varepsilon' = 63$–65; $\varepsilon'' = 17$–19) is higher than that of normal gall ($\varepsilon' = 60$; $\varepsilon'' = 15$).

4.3. Wood and Fibrous Materials

Most fibrous materials are organic cellulose–based substances; such as wood, paper, cartoon, fabric, and fibers. Wood is highly hygroscopic and anisotropic. The dielectric properties of wood depend on type of wood, density, moisture content, and temperature [50,51]. Normal moisture content of wood is between 8 and 12%.

According to generalized electrophysical model of wood samples proposed [51], one can consider a second-order tensor for evaluation of its complex dielectric permittivity

$$||\varepsilon' - j\varepsilon''|| = \begin{vmatrix} \varepsilon'_{LL} - j\varepsilon''_{LL} & \varepsilon'_{LR} - j\varepsilon''_{LR} & \varepsilon'_{LU} - j\varepsilon''_{LU} \\ \varepsilon'_{RL} - j\varepsilon''_{RL} & \varepsilon'_{RR} - j\varepsilon''_{RR} & \varepsilon'_{RU} - j\varepsilon''_{RU} \\ \varepsilon'_{UL} - j\varepsilon''_{UL} & \varepsilon'_{UR} - j\varepsilon''_{UR} & \varepsilon'_{UU} - j\varepsilon''_{UU} \end{vmatrix} \quad (21)$$

where L, R, and U are the longitudinal, radial and tangential axes of anisotropy, respectively. Rotation of electric field vector ($\bar{E}$) on a 180° angle does not change the dielectric properties of wood materials; that is L, R, and U are the principal axes of anisotropy, and the tensor in Eq. (21) may be simplified as follows:

$$||\varepsilon' - j\varepsilon''|| = \begin{vmatrix} \varepsilon'_L - j\varepsilon''_L & 0 & 0 \\ 0 & \varepsilon'_R - j\varepsilon''_R & 0 \\ 0 & 0 & \varepsilon'_U - j\varepsilon''_U \end{vmatrix} \quad (22)$$

When $\bar{E}$ is arbitrarily oriented in space and forms an angle ϑ_1 with L, angle ϑ_2 with R and angle ϑ_3 with U closed-form expressions for calculation of ε' and $\tan\delta_e$ are derived as follows [51]:

$$\varepsilon' = \varepsilon'_L \cos^2\vartheta_1 + \varepsilon'_R \cos^2\vartheta_2 + \varepsilon'_U \cos^2\vartheta_3 \quad (23)$$

$$\tan\delta_e = tg\delta_{eL}\cos^2\vartheta_1 + tg\delta_{eR} N \cos^2\vartheta_2 + tg\delta_{eU}\cos^2\vartheta_3 \quad (24)$$

The measured dielectric constant of Douglas fir at 2450 MHz as a function of moisture content [MC (%)] and temperature (°C) is shown in Fig. 16 [50]. Here $\bar{E}$ is oriented parallel to wood fibers. Dependencies ε' (MC) and ε'' (MC) at 9210 MHz for the same type of wood and softwood hembal when $T = 23$°C and $0 \le \text{MC}\% \le 28$ are presented in Ref. 52.

Density of wood [ρ (g/cm^3)] may also influence $\varepsilon' - j\varepsilon''$. Experimentally obtained functions ε' (ρ, MC, T) and ε'' (ρ, MC, T) for $0.3 \le \rho \le 0.8$, $0 \le \text{MC} \le 60$, $20 \le T \le 90$ for various RF and microwave frequencies are given in Ref. 51. These functions are valid for the cases when $\bar{E}$ is perpendicular to wood fibers.

Table 5. Dielectric Properties (Mean ± STD) of Fruits and Nuts at Five Temperatures and Four Frequencies

		Dielectric Constant				Loss Factor			
		Frequency (MHz)				Frequency (MHz)			
Material	Temperature (°C)	27	40	915	1800	27	40	915	1800
Apple (GD[a])	20	72.5±0.6	72.6±0.7	74.3±0.8	67.4±0.9	120.4±2.1	80.5±1.5	8.5±0.8	9.9±0.1
	30	71.3±0.8	71.3±0.8	72.3±0.7	66.0±0.9	143.9±2.0	96.4±1.4	8.5±1.1	8.7±0.0
	40	69.7±0.8	69.6±0.8	70.0±0.8	64.1±0.9	171.8±2.6	115.3±1.7	8.2±0.9	7.6±0.0
	50	68.1±0.8	67.9±0.8	67.8±1.0	62.1±1.0	202.2±3.3	135.8±2.2	8.3±0.6	6.9±0.1
	60	66.5±0.8	66.4±0.9	65.6±1.0	60.1±1.0	234.1±4.3	157.4±2.7	8.7±0.3	6.7±0.1
Apple (RD[a])	20	74.6±0.6	74.7±0.5	77.0±0.0	70.4±0.5	92.0±0.9	61.1±0.8	10.0±1.4	10.8±0.2
	30	72.7±0.8	72.8±0.7	74.5±0.2	68.3±0.4	109.1±0.6	72.8±0.6	9.4±1.8	9.4±0.7
	40	70.6±0.8	70.8±0.8	71.5±0.1	66.1±0.5	130.7±1.1	87.5±0.8	10.0±2.5	8.3+0.7
	50	68.7±0.9	68.7±0.8	68.9±0.2	64.0±0.5	153.8±1.6	103.1±1.3	9.8±2.8	7.4±0.8
	60	66.8±1.0	66.8±0.8	67.1±0.5	62.0±0.8	178.6±2.3	119.9±1.6	8.9±1.9	6.7±0.7
Almond	20	5.9±0.1	5.9±0.1	1.7±0.9	5.8±0.2	1.2± 0.2	1.5±0.2	5.7±0.5	2.9±0.8
	30	5.7±1.7	5.9±1.8	3.2±2.3	3.4±2.3	0.6±0.2	1.1±0.6	6.4±1.8	3.4±0.9
	40	5.8±1.6	6.1± 1.9	3.3±2.0	3.6±2.1	0.6±0.1	1.0±0.5	6.0±1.3	3.5±0.7
	50	5.8±1.6	6.2±1.8	3.4±0.5	4.2±1.6	0.6±0.3	1.1±0.6	5.7±0.1	3.4±0.2
	60	6.0±1.5	6.3±1.8	3.1±1.4	3.9±2.3	0.7±0.1	1.1±0.4	6.4±1.3	3.0±1.2
Cherry	20	91.2±0.1	85.0±0.4	73.7±0.1	70.9±0.1	293.0±4.3	198.5±2.9	16.4±0.0	16.0±0.2
	30	91.4±0.9	84.0±0.8	72.0±0.3	69.7±0.3	363.1±11.2	245.7±7.6	17.2±0.5	15.1±0.6
	40	91.0±2.0	82.4±1.6	69.6±0.7	67.8±0.6	44.01±26.6	297.5±18.0	18.3±1.0	14.6±0.9
	50	89.6±3.6	79.9±2.7	66.7±1.6	65.2±1.5	501.9±37.2	338.9±25.1	19.3±1.4	14.2±1.1
	60	89.8±5.5	78.5±3.8	64.1±1.8	62.8±1.6	565.4±54.0	381.8±36.6	20.4±1.9	14.1±1.4
Grape Fruit	20	89.0±5.1	82.7±1.8	72.7±2.5	72.1±1.2	202.4±9.3	137.8±7.0	12.1±0.0	12.6±0.1
	30	90.3±6.8	81.9±2.7	70.8±2.3	70.2±1.1	242.6±8.9	165.2±6.9	12.5±0.2	11.5±0.2
	40	91.9±9.2	81.4±4.0	68.5±2.1	68.2±1.1	291.4±9.0	198.4±7.3	13.3±0.4	10.9±0.2
	50	93.8±11.3	80.9±5.2	66.1±2.1	66.0±0.9	345.3±7.8	235.2±6.9	14.2±0.3	10.7±0.2
	60	96.5±14.0	80.8±6.6	63.7±2.0	63.7±0.8	401.1±5.8	273.3±5.8	15.5±0.3	10.7±0.2
Orange	20	84.0±0.1	81.0±0.1	72.9±1.9	72.5±0.1	223.3±0.6	151.6±0.3	16.5±2.8	14.8±0.5
	30	82.2±0.3	78.5±0.3	70.6±1.8	70.7±0.3	267.9±1.8	181.6±1.1	17.8±2.7	13.9±0.5
	40	80.2±0.7	75.7±0.6	68.0±2.1	68.6±0.4	318.0±5.3	215.3±3.4	18.7±3.0	13.1±0.5
	50	78.0±0.5	72.7±0.4	66.1+0.6	65.6±0.2	367.7±5.0	248.6±3.4	17.5±1.2	12.3±0.2
	60	75.8±0.9	69.9±0.6	63.2±0.7	62.7±0.3	418.4±6.5	282.8±4.3	18.4±1.2	12.2±0.2
Walnut	20	4.9±0.0	4.8±0.0	2.2±1.6	2.1±0.7	0.6±0.0	0.7±0.1	2.9±0.1	1.8±0.2
	30	5.0±0.1	4.9±0.1	2.1±0.3	2.7±0.2	0.5±0.1	0.6±0.1	2.6±0.1	1.6±0.2
	40	5.1±0.1	5.1±0.1	3.0±0.1	3.2±0.0	0.4±0.0	0.6±0.1	2.3±0.1	1.3±0.2
	50	5.2±0.1	5.1±0.0	3.4±0.0	3.5±0.0	0.3±0.1	0.5±0.1	2.0±0.0	1.1±0.1
	60	5.3±0.0	5.2±0.0	3.8±0.0	3.7±0.0	0.4±0.1	0.5±0.0	1.8±0.0	1.0±0.1

[a]GD, Golden Delicious; RD, Red Delicious
Source: Ref. 41.

4.4. Resins and Plastics

According to the classification proposed in Ref. 53, resins and plastics are divided into three main groups: (1) no polar high-frequency (HF) dielectrics, including polyethylene, polypropylene, and polyester (2) weak polar and polar HF and low-frequency (LF) dielectrics, including polyformaldegid, rubbers, and polybutadiene; and (3) polar LF dielectrics such as polyamide, epoxide, and polyvinylchloride.

Rubber-based resins are multimolecular substances described by the formula $(C_5H_8)m$, where m is the number of molecular chains. Vulcanization (heating of rubber after mixing with sulfur containing matters) of crude rubber allows improving its heatproof properties. The dielectric constant of rubbers in a microwave range has been studied in several works [5,53,54]. For example, temperature dependencies of $\varepsilon'(T)$ and $\varepsilon''(T)$ of stearine butadiene rubber (SBR) at 2800 MHz are represented in Ref. 7. These dependencies may be approximated with polynomial expressions:

$$\varepsilon' = 0.1172 \times 10^{-9} T^5 - 0.6167 \times 10^{-7} T^4 + 0.121 \times 10^{-4} \times T^3 - 0.001088 T^2 + 0.03727 T + 8.821$$

$$\varepsilon'' = -0.27561 \times 10^{-11} T^6 + 0.163672 \times 10^{-8} T^5 - 0.38772 \times 10^{-6} T^4 + 0.46581 \times 10^{-4} T^3 - - 0.0029782 \times T^2 + 0.096531 \times T - 0.971 \quad (25)$$

Similar functions for cured and vulcanized nitrile butadiene rubber (NBR) at 2450 MHz have been measured [54] (see Fig. 17). Experimental data of the complex dielectric permittivity of some rubbers at various frequencies have also been given [5].

Table 6. Dielectric Properties (Mean ± STD) of Four Insect Larvae at Five Temperatures and Four Frequencies

Material	Temperature (°C)	Dielectric Constant				Loss Factor			
		Frequency (MHz)				Frequency (MHz)			
		27	40	915	1800	27	40	915	1800
Codling moth	20	71.5 ± 0.9	64.9 ± 0.9	47.9 ± 0.2	44.5 ± 0.1	238.1 ± 0.1	163.3 ± 0.4	11.7 ± 0.1	12.0 ± 0.2
	30	71.5 ± 0.1	63.9 ± 0.2	45.9 ± 0.9	42.9 ± 0.9	277.8 ± 8.5	190.2 ± 5.4	12.5 ± 0.4	11.7 ± 0.3
	40	73.8 ± 0.1	64.5 ± 0.1	44.6 ± 0.6	41.6 ± 0.4	332.4 ± 16.3	227.5 ± 10.5	13.9 ± 0.5	11.9 ± 0.3
	50	79.3 ± 1.1	68.5 ± 1.6	45.6 ± 1.5	42.7 ± 1.5	422.5 ± 5.9	288.6 ± 4.4	16.5 ± 0.3	13.2 ± 0.3
	60	84.5 ± 2.5	71.5 ± 2.9	45.0 ± 2.4	41.9 ± 2.2	511.3 ± 26.6	349.1 ± 18.3	19.1 ± 1.0	14.2 ± 0.7
Indian-meal moth	20	81.3 ± 1.9	69.1 ± 0.9	39.9 ± 0.4	37.5 ± 0.5	210.9 ± 4.8	149.0 ± 3.7	13.4 ± 1.4	10.6 ± 0.6
	30	85.8 ± 2.7	72.0 ± 1.4	39.2 ± 0.0	36.9 ± 0.1	244.1 ± 3.7	172.4 ± 3.0	14.3 ± 1.4	10.6 ± 0.8
	40	94.4 ± 1.5	77.3 ± 0.9	37.6 ± 0.8	35.5 ± 0.9	268.7 ± 25.1	190.9 ± 16.9	15.2 ± 2.1	10.6 ± 1.2
	50	103.7 ± 0.8	83.7 ± 0.5	37.2 ± 1.3	35.3 ± 1.4	314.0 ± 42.8	223.1 ± 28.1	16.9 ± 2.4	11.4 ± 1.5
	60	113.0 ± 3.3	90.4 ± 2.2	37.8 ± 1.6	35.6 ± 1.7	397.4 ± 57.8	280.7 ± 37.9	19.9 ± 2.8	12.8 ± 1.7
Mexican fruitfly	20	90.3 ± 13.6	71.2 ± 0.3	48.5 ± 3.4	47.0 ± 0.7	343.9 ± 15.1	230.9 ± 5.9	17.5 ± 2.0	13.3 ± 1.7
	30	105.1 ± 21.5	87.2 ± 12.1	47.3 ± 3.5	45.5 ± 0.4	384.7 ± 15.2	272.2 ± 18.2	21.3 ± 3.9	13.9 ± 1.9
	40	117.4 ± 28.2	95.4 ± 16.6	46.4 ± 2.9	44.7 ± 0.8	446.1 ± 19.0	316.5 ± 22.4	24.2 ± 5.1	14.5 ± 2.2
	50	128.7 ± 33.6	102.9 ± 20.0	45.7 ± 2.3	44.1 ± 1.4	521.8 ± 32.1	370.7 ± 33.0	26.8 ± 5.7	15.4 ± 2.5
	60	141.2 ± 37.5	111.5 ± 22.8	44.5 ± 2.0	43.0 ± 1.6	582.2 ± 28.1	414.5 ± 31.7	29.4 ± 5.9	16.5 ± 2.7
Navel orange worm	20	80.2 ± 0.3	68.6 ± 0.4	44.5 ± 1.3	42.2 ± 1.4	307.8 ± 4.9	212.6 ± 3.1	16.1 ± 0.1	12.7 ± 0.0
	30	83.6 ± 1.5	70.4 ± 1.0	43.6 ± 0.4	41.5 ± 0.7	359.7 ± 10.5	248.0 ± 7.5	17.5 ± 0.6	12.9 ± 0.4
	40	87.7 ± 2.1	72.7 ± 1.6	42.8 ± 0.1	40.7 ± 0.1	419.4 ± 17.3	288.8 ± 12.0	19.2 ± 0.9	13.4 ± 0.6
	50	92.8 ± 1.6	75.9 ± 1.2	42.3 ± 0.4	40.2 ± 0.1	480.3 ± 24.5	330.8 ± 16.5	21.2 ± 1.0	14.1 ± 0.6
	60	99.4 ± 0.0	80.1 ± 0.0	42.2 ± 0.1	40.0 ± 0.0	562.7 ± 3.3	386.7 ± 2.2	24.0 ± 0.1	15.5 ± 0.0

Source: Ref. 41.

Resins such as polyamide and polyimide have wide practical applications in modern microelctronics electrical, and airspace engineering. The dielectric properties of some of these materials at microwave frequencies have been studied closely. In particular, $\varepsilon'(T)$ and $\varepsilon''(T)$ of Nylon-6 at 2450 MHz have been obtained [55]. These results are represented in Fig. 18.

Plastic dielectrics have weak interaction with EM fields because of their nonpolar molecular structure. Plastics are often used as package material for foods treated by microwaves. Most of plastics have a very weak linear dependence on temperature at RF and microwave frequencies. For example, the dielectric permittivity and loss factor of plastic materials have been analyzed in by Von Hippel [5] at 10,000 MHz: $2.5 \le \varepsilon' \le 6$; $\tan\delta_e \le 0.05$. Table 8 lists the dielectric permittivities of selected plastic materials at 2450 MHz.

4.5. Ceramics

Ceramics are widely applied in many areas of science and engineering because of their unique features such as high temperature stability of physical properties, low wearability, thermal conductivity, and weight. Dielectric properties of selected ceramics as a function of temperature and frequency have also been studied [5]. The dielectric constant of ceramic may be sufficiently low (Mullite, $\varepsilon' < 10$), average (titanic ceramics N1400-110, N750T, $30 \le \varepsilon' \le 150$) or high ($TiO_2$, $CaTiO_3$ and $LaAlO_3$, $\varepsilon' > 200$) .

The complex dielectric permittivity of ceramics Hilox-882, which consists of Al_2O_3, SiO_2, MgO, CrO_2, and CaO at two microwave frequencies and three temperatures, is shown in Table 9 [56]. An analytical model that describes the behavior of ε' and ε'' of composite ceramics in temperature range $0 < {}^{\circ}\mathrm{C} < 2500$ at 2450 MHz has been derived [57]

$$\varepsilon = \varepsilon_{\mathrm{in}} + 10^{-4}(T - 25) - j \cdot 10^{-3}(T - 25) \qquad (26)$$

Where $\varepsilon_{\mathrm{in}} = 3.9 - j0.46$ is the initial value at $T = 25$°C.

Several types of ceramics—aluminosilicate and zircona fibre board, alumina, Ni–Zn–ferrite, and PZT ceramics—were analyzed at 2422 MHz by Hamlin et al. [58], who treated these materials by microwave in a cylindrical applicator with operating mode TM_{010}.

Measured values of $\varepsilon'(T) - j\varepsilon''(T)$ at 3000 MHz for soda lime glass (Corning 0080), borosilicate glass, Mullite MV20, cupric oxide, aluminum nitride, zeolite Fig. 19, alumina cement AC56, zirconia cement, and felt can be found in Ref. 59. Some of these dependencies (zeolite) may

Table 7. Dielectric Permittivity (ε') and Loss Factor (ε') of Biotissues at 2450 MHz and Room Temperature

Tissue	Eye	Brain	Fat	Muscle	Kidneys	Skin	Blood
$\varepsilon' - j\varepsilon''$	$30 - j8$	$32 - j15.5$	$5 - j0.99$	$46 - j13.5$	$44.5 - j14.9$	$43 - j14$	$65 - j19.5$

Sources: Refs. 46 and 47.

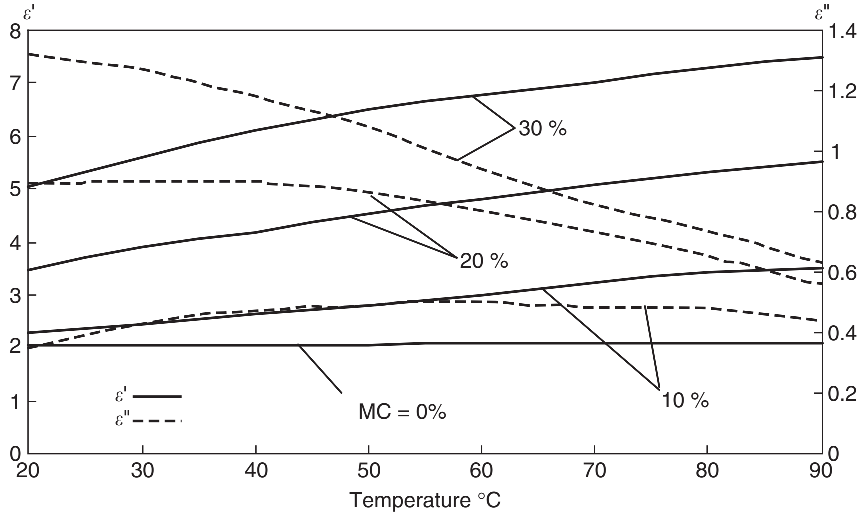

Figure 16. Dielectric permittivity (ε′) and loss factor (ε″) of Douglas fir at different moisture content [50].

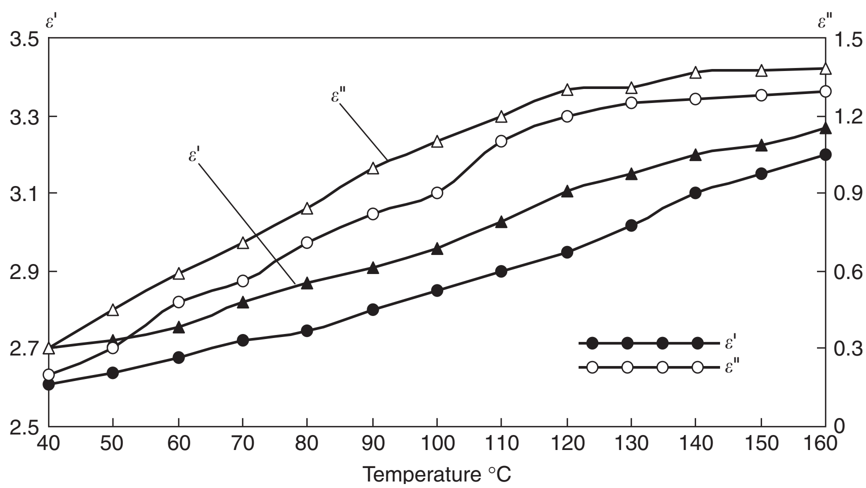

Figure 17. Dielectric permittivity (ε′) and loss factor (ε″) of nitrile butadiene rubber: crude rubber (lines with triangles), vulcanized rubber (lines with circles) [54].

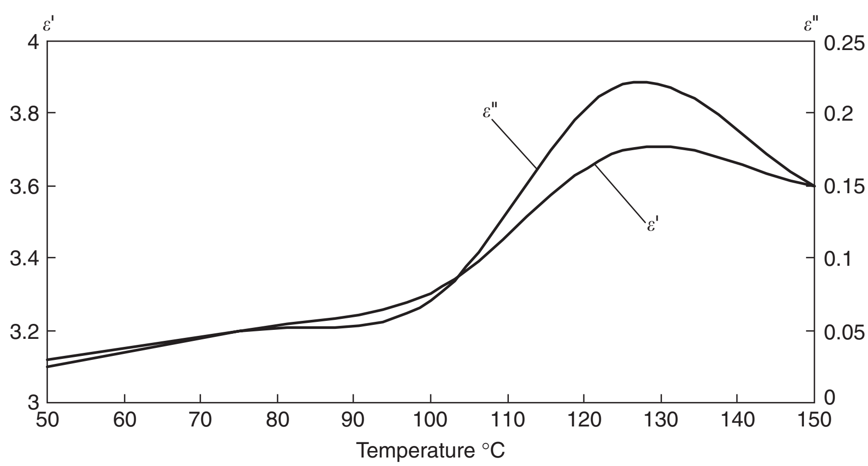

Figure 18. Dielectric permittivity (ε′) and loss factor (ε″) of Nylon-6 [55].

Table 8. Dielectric Permittivity (ε′) and Loss Factor (ε′) of Plastics [5,7] at 2450 MHz

Material	China	Ultem	Polyetilene	Polystirol	Teflon	Glass
$\varepsilon' - j\varepsilon''$	$5.7 - j0.05$	$3.5 - j0.0013$	$2.2 - j0.004$	$2.5 - j0.001$	$2.05 - j0.002$	$7.6 - 0.156$

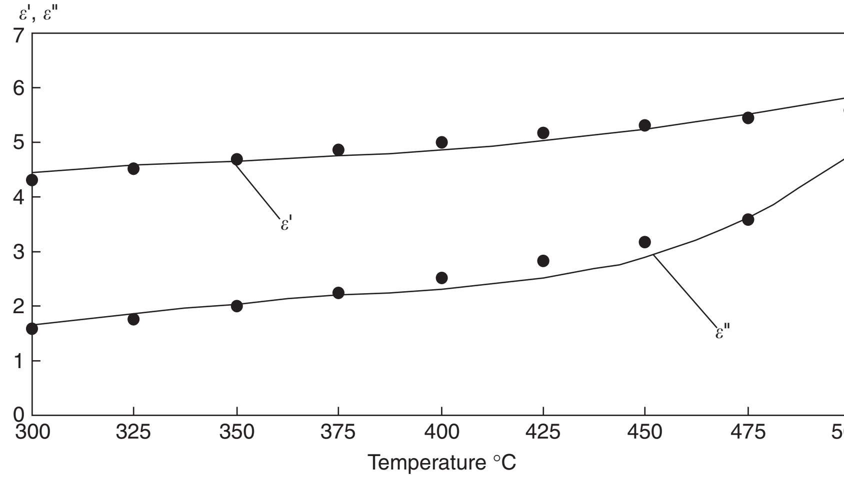

Figure 19. Dielectric permittivity (ε') and loss factor (ε'') of zeolite ceramics: experiment (solid lines) and approximation (black circles) [59].

Table 9. Dielectric Permittivity (ε') and Loss Factor (ε') of Ceramic Materials

	$T = 500°C$		$T = 1000°C$		$T = 1200°C$	
f (MHz)	ε'	ε''	ε'	ε''	ε'	ε''
915	9.13	0.022	10.47	0.66	13.32	3.83
2450	9.13	0.087	10.86	0.53	12.66	2.01

Source: Ref. 56.

Table 10. Dielectric Permittivity (ε') and Loss Factor (ε') of Some Soils

	MC = 4%		MC = 12%		MC = 20%	
Soil	1 GHZ	3 GHZ	1 GHZ	3 GHZ	1 GHZ	3 GHZ
Sand ($\varepsilon' - j\varepsilon''$)	$3.33 - j0.13$	$3.05 - j0.26$	$11.6 - j0.78$	$10.8 - j1.04$	$20.3 - j1.17$	$19.4 - j1.96$
Clay ($\varepsilon' - j\varepsilon''$)	$3.05 - j0.78$	$2.88 - j0.73$	$12.5 - j4.30$	$11.4 - j2.35$	$22.2 - j8.87$	$19.2 - j4.43$

Source: Ref. 64.

Table 11. Dielectric Permittivity (ε') and Loss Factor (ε') of Selected Minerals [66] at 2450 MHz

	$T = 25°C$		$T = 100°C$		$T = 200°C$		$T = 300°C$	
Mineral	ε'	ε''	ε'	ε''	ε'	ε''	ε'	ε''
Chalcocite	16.72	1.64	17.14	1.76	15.46	1.52	11.82	1.12
Chalcopyrite	11.01	8.02	11.41	10.20	11.20	12.5	9.01	1.41

be approximated by expressions:

$$\varepsilon' = 0.2509933T^{0.499713},$$
$$\varepsilon'' = 0.383887e^{0.0047014 \cdot T}\ R^2 = 0.962 \qquad (27)$$

Where R^2 is the coefficient of determination. Both equations are valid when $300 < °C < 500$. The dielectric constant of Mullite MV20 $\varepsilon'(T) = 5.3 \sim 7.8$, $\varepsilon''(T) = 0.05 \sim 1.3$, $400 \leq °C = 1300$ at 915 MHz has been investigated [60].

4.6. Soils and Minerals

Moisture dependent dielectric constants of many soils (sandy, high-clay, loami and etc.) over RF and microwave frequency ranges have been published by several authors [61–64]. Most of these studied have been carried out in the temperature range ($5 \leq °C \leq 25$) for fixed values of soils density. As an example in Table 10, complex dielectric permittivity of two types of soils is listed for different moisture content at two microwave frequencies [64].

At 2450 MHz all dry sandy soils may be classified on three groups according to the value of loss factor: sands with low losses ($\varepsilon'' = 0.0075$), sands with average losses

($0.011 \leq \varepsilon'' \leq 0.031$), and sands with high losses ($0.05 \leq \varepsilon'' \leq 0.1$) [65]. Dry clay soils are characterized by $3.91 \leq \varepsilon' \leq 4.21$ and $0.14 \leq \varepsilon'' \leq 0.32$. Dielectric properties of loami soils with moisture content: $2 \leq \mathrm{MC} \leq 50\%$ and $3.49 \leq \varepsilon' \leq 32.53$ and $0.22 \leq \varepsilon'' \leq 1.3$.

EM fields are used today in mining industry, geology, road building technologies, and so on. Determination of dielectric properties of minerals allows more accurate mathematical modeling of physical processes of EM waves interaction with lossy media. The open-end-coaxial line method has been utilized [63] for measuring $\varepsilon'(f,T) - j\varepsilon''(f,T)$ of over 60 minerals in the temperature range 25–325°C and frequency range $300 \leq f, \mathrm{MHz} \leq 3000$. Some of these experimental data at 2450 GHz are given in Table 11. Most minerals exhibit increasing values of ε' and ε'' versus temperature, except for minerals presented in Table 11 which have complicated dependencies $\varepsilon'(T)$ and $\varepsilon''(T)$ [66].

5. CONCLUSION

Wide applications of dielectric materials require the knowledge of their dielectric properties. We have represented data about dielectric permittivity for some of these materials in RF and microwave ranges. Many of the experimental results given in Section 4 have been implemented in mathematical models of RF and microwave technological applicators developed at Washington State University.

Three main factors—frequency, temperature and moisture content—which significantly influence the value of $\varepsilon' - j\varepsilon''$ are analyzed in details. In many cases, the nonlinear characteristic of temperature dependences of dielectric permittivity dictates that the physical processes in RF and microwave systems are highly coupled EM and heat conduction problem. A major challenge in RF and microwave heating research and development is to design RF applicators and microwave cavities that provide uniform *E*-field patterns in treated materials. With precise measurements of dielectric and thermal properties for different materials, great success of new designs in industrial implementations will be expected in the future.

BIBLIOGRAPHY

1. M. N. Afsar, J. R. Birch, and R. N. Clarke, The measurement of the properties of materials, *Proc. IEEE* **74**:183–199 (1986).
2. J. Krupka and R. G. Geyer, Loss-angle measurement, *Wiley Encyclopedia of Electrical and Electronics Engineering Online*, Wiley, New York, 1999.
3. S. Aditya and A. Arokiaswami, Microwave measurement instrumentation, *Wiley Encyclopedia of Electrical and Electronics Engineering Online*, Wiley, New York, 1999.
4. R. Bartnikas, Dielectric measurement, *Wiley Encyclopedia of Electrical and Electronics Engineering Online*, Wiley, New York, 1999.
5. A. Von Hippel, *Dielectrics and Waves*, Wiley, New York, 1954.
6. P. S. Neelakanta, *Handbook of Electromagnetic Materials: Monolithic and Composite Versions of Their Application*, CRC Press LLC, Boca Raton, FL, 1995.
7. A. C. Metaxas and R. J. Meredith, *Industrial Microwave Heating*, Peter Peregrinus, London, 1983.
8. S. Ryynänen, The electromagnetic properties of food materials: A review of the basic principles, *J. Food Eng.* **29**:409–429 (1995).
9. S. O. Nelson, Review and assessment of radio-frequency and microwave energy for stored-grain insect control, *Trans. ASAE* **39**:1475–1484 (1996).
10. S. C. Harvey and P. Hoekstra, Dielectric relaxation spectra of water adsorbed on lysozyme, *J. Phys. Chem.* **76**:2987–2994 (1972).
11. Y. Wang, T. Wig, J. Tang, and L. M. Hallberg, Dielectric properties of food relevant to RF and microwave pasteurization and sterilization, *J. Food Eng.* **57**:257–268 (2003).
12. J. Tang, H. Feng, and M. Lau, Microwave heating in food processing, in X. Young and J. Tang, eds., *Advances in Bioprocessing Engineering*, World Scientific, 2002.
13. P. Debye, *Polar Molecules*, The Chemical Catalog Co., New York, 1929.
14. S. Mashimo, S. Kuwabara, S. Yagihara, and K. Higasi, Dielectric relaxation time and structure of bound water in biological materials, *J. Phys. Chem.* **91**:6337–6338 (1987).
15. P. Gregory, R. N. Clarke, T. E. Hodgetts, and G. T. Symm, *RF and Microwave Dielectric Measurements upon Layered Materials Using Reflectrometric Coaxial Sensor*, Natl. Phys. Lab. Report DES 125, 1993.
16. C. W. Macosko, *Rheology, Principles, Measurements, and Applications*, VCH Publishers, Cambridge, UK, 1994.
17. J. G. Trump, Dielectric materials and their applications, in A. R. von Hippel, ed., *Dielectric Properties and Waves*, Wiley, New York, 1954.
18. B. D. Roebuck and S. A. Goldblith, Dielectric properties of carbohydrayte-water mixtures at microwave frequencies, *J. Food Sci.* **37**:199–204 (1972).
19. S. Wang, J. Tang, R. P. Cavalieri, and D. Davis, Differential heating of insects in dried nuts and fruits associated with radio frequency and microwave treatments, *Trans. ASAE* **46**:1175–1182 (2003).
20. H. Feng, J. Tang, and R. P. Cavalieri, Dielectric properties of dehydrated apples as affected by moisture and temperature, *Trans. ASAE* **45**:129–135, 2002.
21. R. F. Schiffmann, Food product development for microwave processing, *Food Technol.* **40**:94–98 (1986).
22. R. E. Mudgett, Dielectric properties of foods, in R. V. DeCareau, ed., *Microwaves in the Food Processing Industry*, Academic Press, New York, 1985.
23. S. O. Nelson, J. Forbus, and K. Lawrence, Permittivity of fresh fruits and vegetables at 0.2 to 20 GHz, *J. Microwave Power Electromagn. Energy* **29**:81–93 (1994).
24. M. A. Stuchly and S. S. Stuchly, Coaxial line reflection methods for measuring dielectric properties of biological substances at radio and microwave frequencies—a review, *IEEE Trans. Instrum. Meas.* **29**:176–183 (1980).
25. D. V. Blackham and R. D. Pollard, An improved technique for permittivity measurement using a coaxial probe, *IEEE Trans. Instrum. Meas.* **46**:1093–1099 (1997).
26. G. P. Otto and W. C. Chew, Improved calibration of a large open-ended coaxial probe for dielectric measurements, *IEEE Trans. Instrum. Meas.* **40**:742–746 (1991).

27. J. de los Santos, D. Garsia, and J. A. Eiras, Dielectric characterization of materials at microwave frequency range, *Mater. Res.* **6**:97–101 (2003).

28. M. Arai, J. G. P. Binner, and T. E. Cross, Estimating errors due to sample surface roughness in microwave complex permittivity measurements obtained using a coaxial probe, *Electron. Lett.* **31**:115–117 (1995).

29. D. K. Ghodgaonkar, V. V. Varadan, and V. K. Varadan, A free space method for measurement of dielectric constants and loss tangents at microwave frequencies, *IEEE Trans. Instrum. Meas.* **37**:789–793 (1989).

30. C. C. Courtney, Time-domain measurement of the electromagnetic properties of materials, *IEEE Trans. Microwave Theory Tech.* **46**:517–522 (1998).

31. V. V. Komarov. and V. V. Yakovlev, Modeling control over determination of dielectric properties by perturbation technique, *Microwave Opt. Technol. Lett.* **39**N(6):443–446 (2003).

32. L. Chen, C. K. Ong, and B. T. Tan, Amendment of cavity perturbation method for permittivity measurement of extremely low-loss dielectrics, *IEEE Trans. Instrum. Meas.* **48**:1031–1037 (1999).

33. A. W. Kraszewski and S. O. Nelson, Observation on resonant cavity perturbation by dielectric objects, *IEEE Trans. Microwave Theory Tech.* **40**:151–155 (1992).

34. J. Krupka, D Cros, M. Auburg, and P. Guillon, Study of whispering gallery modes in anisotropic single-crystal dielectric resonators, *IEEE Trans. Microwave Theory Tech.* **42**:56–61 (1994).

35. J. N. Ikediala, J. Hansen, J. Tang, S. R. Drake, and S. Wang, Development of saline-water-immersion technique with RF energy as a postharvest treatment against codling moth in cherries, *Postharvest Bio. Technol.* **24**:25–37 (2002).

36. M. Kent, *Electrical and Dielectric Properties of Food Materials*, COST 90bis Production, Science and Technology Publishers, Hornchurch, Essex, UK, 1987.

37. N. E. Bengtsson and P. O. Risman, Dielectric properties of foods at 3 GHz as determined by a cavity perturbation technique, *J. Microwave Power EM Energy* **6**:107–123 (1971).

38. J. Tang, J. N. Ikediala, S. Wang, J. Hansen, and R. Cavalieri, High-temperature-short-time thermal quarantine methods, *Postharvest Bio. Technol.* **21**:129–145 (2000).

39. S. Wang, J. N. Ikediala, J. Tang, J. Hansen, E. Mitcham, R. Mao, and B. Swanson, Radio frequency treatments to control codling moth in in-shell walnuts, *Postharvest Bio. Technol.* **22**:29–38 (2001).

40. S. Wang, J. Tang, J. A. Johnson, E. Mitcham, J. D. Hansen, R. Cavalieri, J. Bower, and B. Biasi, Process protocols based on radio frequency energy to control field and storage pests in in-shell walnuts, *Postharvest Bio. Technol.* **26**:265–273 (2002).

41. S. Wang, J. Tang, J. A. Johnson, E. Mitcham, J. D. Hansen, G. Hallman, S. R. Drake, and Y. Wang, Dielectric properties of fruits and insect pests as related to radio frequency and microwave treatments, *Biosyst. Eng.* **85**:201–212 (2003).

42. C. C. Lu, H. Z. Li, and D. Gao, Combined electromagnetic and heat conduction analysis of rapid rewarming of cryopreserved tissues, *IEEE Trans. Microwave Theory Tech.* **MTT-48**:2185–2190 (2000).

43. F. A. Gibbs, Clinical evaluation of a microwave/radiofrequency system (BSD Corporation) for induction of local and regional hyperthermia, *Int. J. Microwave Power EM Energy* **16**:185–192, (1981).

44. J. C. Lin, S. Hirai, C. L. Chiang, W. L. Hsu, J. L. Su, and Y. J. Wang, Computer simulation and experimental studies of SAR distributions of interstitial arrays of sleeved-slot microwave antennas for hyperthermia treatment of brain tumors, *IEEE Trans. Microwave Theory Tech.* **MTT-48**:2191–2198 (2000).

45. M. F. Iskander and C. H. Durney, Microwave methods of measuring changes in lund water, *Int. J. Microwave Power EM Energy* **18**:265–275 (1983).

46. M. A. Stuchly and S. S. Stuchly, Dielectric properties of biological substances—tabulated international, *Int. J. Microwave Power EM Energy* **15**:19–26 (1980).

47. R. Pethig, Dielectric properties of biological materials: Biophysical and medical applications, *IEEE Trans. Electric. Insul.* **EI-19**:453–474 (1984).

48. A. Kraszewski, M. A. Stuchly, S. S. Stuchly, and A. M. Smith, In vivo and in vitro dielectric properties of animal tissues at radio frequencies, *Electromagnetics* **3**:421–432 (1982).

49. S. B. Kumar, K. T. Mathew, U. Raveendranath, and P. Augustine, Dielectric properties of certain biological materials at microwave frequencies, *Int. J. Microwave Power EM Energy* **36**:67–75 (2001).

50. W. Tinga, *Multiphase Dielectric Theory Applied to Cellulose Mixtures*, Ph.D. thesis, Univ. Alberta, Canada, 1969.

51. G. I. Torgovnikov, *Dielectric Properties of Wood and Wood Based Materials*, Springer-Verlag, Berlin, 1993.

52. W. A. Voss, Factors affecting the operation of high-power microwave heating systems for lumber processing, *IEEE Trans. Indust. Gener. Appl.* **GE-20**:234–243 (1966).

53. D. M. Kazarnovskiy and S. A. Yamanov, *Radio Engineering Materials*, Vishaya Shkola Issue, Moscow, 1972 (in Russian).

54. J. M. Catala-Civera, S. Giner-Maravilla, D. Sanchez-Hernandez, and E. de las Reyes, Pressure-aided microwave rubber vulcanization in a ridged three-zone cylindrical cavity, *Int. J. Microwave Power EM Energy* **35**:92–104 (2000).

55. F. Liu, I. Turner, E. Siores, and P. Groombridge, A numerical and experimental investigation of the microwave heating of polymer materials inside a ridge waveguide, *Int. J. Microwave Power EM Energy* **31**:71–82 (1996).

56. M. Arai et al., Elevated temperature dielectric property measurements: Results of a parallel measurement program, *Proc. Symp. Microwave Theory Appl. Mater. Process. II* **36**:539–546, 1993.

57. J. Braunstein, K. Connor, S. Salon, and L. Libelo, Investigation of microwave heating with time varying material properties, *IEEE Trans. Magn.* **MAG-35**:1813–1816 (1999).

58. M. G. Hamlin, A. L. Bowden, and N. G. Evans, Measurement and use of high temperature dielectric properties in ceramic processing, *Proc. Int. Conf. Microwave and High-Frequency Heating'95*, Cambridge, UK, 1995, pp. 11–14.

59. W. Xi and W. Tinga, Error analysis and permittivity measurements with re-entrant high-temperature dielectrometer, *Int. J. Microwave Power EM Energy* **28**:104–112 (1993).

60. W. Xi and W. Tinga, A high temperature microwave dielectrometer, *Proc. Symp. Microwave Theory Appl. Mater. Process.* **34**:215–224 (1991).

61. P. Hoekstra and A. Delaney, Dielectric properties of soils at UHF and microwave frequencies, *J. Geophys. Res.* **79**:1699–1708 (1974).

62. J. E. Hipp, Soil electromagnetic parameters as a function of frequency, soil density and soil moisture, *Proc. IEEE* **62**:98–103 (1974).

63. J. R. Wang and T. J. Schmugge, An empirical model for the complex dielectric permittivity of soils as a function of water content, *IEEE Trans. Geosci. Remote Sens.* **GE-18**:288–295 (1980).

64. A. M. Shutko, *Microwave Radio Sensing of Water Surfaces and Soils*, Nauka, Moscow, 1986 (in Russian).

65. L. V. Gonchariva, V. I. Barinova, U. M. Egorov and V. M. Fedorov, Dielectric properties of disperse soils in microwave range, *Proc. Int. Conf. Application of Microwave Energy in Technology and Science*, Saratov, Russia, 1991, pp. 104–105 (in Russian).

66. J. B. Salsman, Measurement of dielectric properties in the frequency range of 300 MHz to 3 GHz as a function of temperature and density, *Proc. Symp. Microwave Theory Appl. Mater. Process.* **34**:203–214 (1991).