Dielectric Theory and Its Properties

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Abstract – Dielectric materials are insulators used for their exceptional dielectric properties. An important property of a dielectric is its ability to support an electrostatic field while dissipating minimal energy in the form of heat. The lower the dielectric loss (the proportion of energy lost as heat), the more effective is a dielectric material. Another consideration is the dielectric constant, the extent to which a substance concentrates the electrostatic lines of flux. Substances with a low dielectric constant include a perfect vacuum, dry air, and most pure, dry gases such as helium and nitrogen. Materials with moderate dielectric constants include ceramics, distilled water, paper, mica, polyethylene, and glass. Metal oxides, in general, have high dielectric constants. This paper discusses the various dielectric properties such as capacitance, permittivity, dielectric constant, loss tangent, and resistivity. Various losses such as insertion loss, return loss and power absorption are also discussed.

Index Terms – Dielectrics, capacitance, permittivity, loss tangent, microwave absorption.

1. INTRODUCTION

A dielectric material is a substance that is a poor conductor of electricity, but an efficient supporter of electrostatic fields. If the flow of current between opposite electric charge poles is kept to a minimum while the electrostatic lines of flux are not impeded or interrupted, an electrostatic field can store energy. This property is useful in capacitors, especially at radio frequencies [5]. Dielectric materials are also used in the construction of radio-frequency transmission lines.

In practice, most dielectric materials are solid. Examples include porcelain (ceramic), mica, glass, plastics, and the oxides of various metals. Some liquids and gases can serve as good dielectric materials. Dry air is an excellent dielectric, and is used in variable capacitors and some types of transmission lines. Distilled water is a fair dielectric. A vacuum is an exceptionally efficient dielectric.

Every material has a unique set of electrical characteristics that are dependent on its dielectric properties. Accurate measurements of these properties can provide scientists and engineers with valuable information to properly incorporate the material into its intended application for more solid designs or to monitor a manufacturing process for improved quality control.

2. DIELECTRIC PROPERTIES

The various dielectric properties are capacitance, permittivity, dielectric constant, loss tangent, and resistivity. It is important to note that permittivity is not constant and can vary with frequency, temperature, orientation, mixture, pressure, and molecular structure of the material. Various losses such as insertion loss, return loss and power absorption are also discussed.

1.1 Capacitance

Capacitance is the ability of a material to hold an electrical charge. It is also a measure of the amount of electric charge stored (or separated) for a given electric potential. A common form of charge storage device is a parallel-plate capacitor.

If the charges on the plates are +Q and −Q, and V give the voltage between the plates, then the capacitance is given by

$$C = \frac{Q}{V} \qquad (1)$$

The capacitance can be calculated if the geometry of the conductors and the dielectric properties of the insulator between the conductors are known [1]. For example, the capacitance of a parallel-plate capacitor constructed of two parallel plates both of area A separated by a distance d is approximately equal to the following:

$$C = \varepsilon_r \varepsilon_0 \frac{\mathrm{A}}{\mathrm{d}} \qquad (2)$$

where

C is the capacitance in farads, F

A is the cross-sectional area of the plates measured in square meters.

ε_r is the relative static permittivity (sometimes called the dielectric constant) of the material between the plates, (for vacuum ε_r=1)

ε_0 is the permittivity of free space where ε_0 = 8.854x10^{-12} F/m

d is the separation between the plates, measured in meters.

1.2. Permittivity

Permittivity is a measure of how an electric field affects, and is affected by, a dielectric medium, and is determined by the ability of a material to polarize in response to the field, and thereby reduce the total electric field inside the material. Thus, permittivity relates to a material's ability to transmit (or permit) an electric field [2]. It is directly related to electric susceptibility, which is a measure of how easily a dielectric polarizes in response to an electric field.

In SI units, permittivity ε′ is measured in farads per meter (F/m); electric susceptibility (χ) is dimensionless. They are related to each other through

$$\varepsilon = \varepsilon_r \varepsilon_0 = (1+\chi)\,\varepsilon_0 \quad (3)$$

where ε_r is the relative permittivity of the material, and

$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the vacuum permittivity.

In electromagnetism, the electric displacement field D represents how an electric field E influences the organization of electrical charges in a given medium, including charge migration and electric dipole reorientation. Its relation to permittivity in the very simple case of linear, homogeneous, isotropic materials with instantaneous response to changes in electric field is

$$D=\varepsilon E \quad (4)$$

where the permittivity ε is a scalar. If the medium is anisotropic, the permittivity is a second rank tensor.

In general, permittivity is not a constant, as it can vary with the position in the medium, the frequency of the field applied, humidity, temperature, and other parameters. In a nonlinear medium, the permittivity can depend on the strength of the electric field. Permittivity as a function of frequency can take on real or complex values.

2.3 Dielectric constant

A material is classified as dielectric if it has the ability to store energy when an external electric field is applied. If a DC voltage source is placed across a parallel plate capacitor, more charge is stored when a dielectric material is between the plates than if no material (a vacuum) is between the plates. The dielectric material increases the storage capacity of the capacitor by neutralizing charges at the electrodes, which ordinarily would contribute to the external field [7]. The capacitance with the dielectric material is related to dielectric constant. If a DC voltage source V is placed across a parallel plate capacitor, more charge is stored when a dielectric material is between the plates than if no material (a vacuum) is between the plates.

The dielectric constant (relative static permittivity) is represented as ε_r or sometimes K or κ. It is defined as

$$\varepsilon_r=\varepsilon/\varepsilon_0 \quad (5)$$

where ε is the static permittivity of the material, and

ε_0 is the electric permittivity of free space (=8.854x10^{-12} F/m).

2.4 Loss tangent

The loss tangent is a parameter of a dielectric material that quantifies its inherent dissipation of electromagnetic energy. The term refers to the angle in a complex plane between the resistive (lossy) component of an electromagnetic field and its reactive (lossless) component.

For time varying electromagnetic fields, the electromagnetic energy is typically viewed as waves propagating either through free space, in a transmission line, in a microstrip line, or through a waveguide. Dielectrics are often used in all of these environments to mechanically support electrical conductors and keep them at a fixed separation, or to provide a barrier between different gas pressures yet still transmit electromagnetic power.

When complex permittivity is drawn as a simple vector diagram (Figure 1), the real and imaginary components are 90° out of phase. The vector sum forms an angle δ with the real axis (ε_r'). The relative lossiness of a material is the ratio of the energy lost to the energy stored.

$$\tan\delta=\varepsilon_r''/\varepsilon_r' \quad (6)$$

= energy lost per cycle / energy stored per cycle

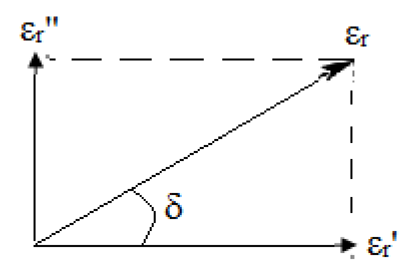

Figure 1 Loss tangent vector diagram

The loss tangent or tanδ is defined as the ratio of the imaginary part of the dielectric constant to the real part [6]. D denotes dissipation factor and Q is quality factor. The loss tangent tanδ is called tan delta, tangent loss or dissipation factor. Sometimes the term quality factor (or Q-factor) is used with respect to an electronic microwave material, which is the reciprocal of the loss tangent. For very low loss materials, since tanδ ≈ δ, the loss tangent can be expressed in angle units, milliradians or microradians.

2.5 Resistivity

Electrical resistivity (also known as specific electrical resistance or volume resistivity) is a measure of how strongly a material opposes the flow of electric current. A low resistivity indicates a material that readily allows the movement of electrical charge [11]. The SI unit of electrical resistivity is the ohm metre (Ω m).

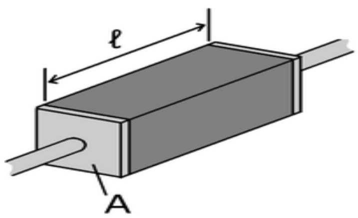

Figure 2 A piece of resistive material with electrical contacts on both ends [2].

Electrical resistivity ρ (Greek: rho) is defined by

$$\rho = \frac{E}{J} \qquad (7)$$

where

ρ is the static resistivity (measured in volt-metres per ampere, V m/A);

E is the magnitude of the electric field (measured in volts per metre, V/m);

J is the magnitude of the current density (measured in amperes per square metre, A/m²).

The electrical resistivity ρ can also be given by,

$$\rho = R\frac{A}{\ell} \qquad (8)$$

where

ρ is the static resistivity (measured in ohm-metres, Ω m);

R is the electrical resistance of a uniform specimen of the material (measured in ohms, Ω);

ℓ is the length of the piece of material (measured in metres, m);

A is the cross-sectional area of the specimen (measured in square metres, m²).

Finally, electrical resistivity is also defined as the inverse of the conductivity *σ* (*sigma*), of the material, or

$$\rho = \frac{1}{\sigma} \qquad (9)$$

The reason resistivity has the units of ohm-metres rather than the more intuitive ohm per metre (Ω/m) can perhaps best be seen by transposing the definition to make resistance the subject;

$$R = \rho\frac{\ell}{A} \qquad (10)$$

The resistance of a given sample will increase with the length, but decrease with the cross sectional area. Resistance is measured in ohms. Length over Area has units of 1/distance. To end up with ohms, resistivity must be in the units of ohms × distance (SI ohm-metre, US ohm-inch).

3 DIELECTRIC MECHANISMS

A material may have several dielectric mechanisms or polarization effects that contribute to its overall permittivity (Figure 3). A dielectric material has an arrangement of electric charge carriers that can be displaced by an electric field. The charges become polarized to compensate for the electric field such that the positive and negative charges move in opposite directions [1]. At the microscopic level, several dielectric mechanisms can contribute to dielectric behaviour. Dipole orientation and ionic conduction interact strongly at microwave frequencies. Water molecules, for example, are permanent dipoles, which rotate to follow an alternating electric field. These mechanisms are quite lossy – which explains why food heats in a microwave oven. Atomic and electronic mechanisms are relatively weak and usually constant over the microwave region. Each dielectric mechanism has a characteristic cut-off frequency. As frequency increases, the slow mechanisms drop out in turn, leaving the faster ones to contribute to ε'. The loss factor (ε_r") will correspondingly peak at each critical frequency. The magnitude and cut-off frequency of each mechanism is unique for different materials.

A resonant effect is usually associated with electronic or atomic polarization. A relaxation effect is usually associated with orientation polarization.

Orientation (dipolar) polarization

A molecule is formed when atoms combine to share one or more of their electrons. This rearrangement of electrons may cause an imbalance in charge distribution creating a permanent dipole moment. These moments are oriented in a random manner in the absence of an electric field so that no polarization exists. The electric field E will exercise torque T on the electric dipole, and the dipole will rotate to align with the electric field causing orientation polarization to occur. If the field changes the direction, the torque will also change.

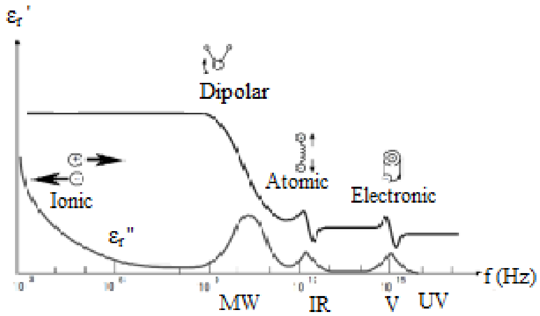

Figure 3 Frequency response of dielectric mechanisms [10]

The friction accompanying the orientation of the dipole will contribute to the dielectric losses [8]. The dipole rotation causes a variation in both ε_r' and ε_r" at the relaxation frequency which usually occurs in the microwave region. Water is an example of a substance that exhibits a strong orientation polarization.

3.2 Electronic and atomic polarization

Electronic polarization occurs in neutral atoms when an electric field displaces the nucleus with respect to the electrons that surround it. Atomic polarization occurs when adjacent positive and negative ions stretch under an applied electric field. For many dry solids, these are the dominant polarization mechanisms at microwave frequencies, although the actual resonance occurs at a much higher frequency. In the infrared and visible light regions the inertia of the orbiting electrons must be taken into account. Atoms can be modelled as oscillators with a damping effect similar to a mechanical spring and mass system [8]. The amplitude of the oscillations will be small for any frequency other than the resonant frequency. Far below resonance, the electronic and atomic mechanisms contribute only a small constant amount to ε_r' and are almost lossless. The resonant frequency is identified by a resonant response in ε_r' and a peak of maximum absorption in ε_r". Above the resonance, the contribution from these mechanisms disappears.

3.3 Relaxation time

Relaxation time τ is a measure of the mobility of the molecules (dipoles) that exist in a material. It is the time required for a displaced system aligned in an electric field to return to 1/e of its random equilibrium value (or the time required for dipoles to become oriented in an electric field). Liquid and solid materials have molecules that are in a condensed state with limited freedom to move when an electric field is applied. Constant collisions cause internal friction so that the molecules turn slowly and exponentially approach the final state of orientation polarization with relaxation time constant τ. When the field is switched off, the sequence is reversed and random distribution is restored with the same time constant.

The relaxation frequency f_c is inversely related to relaxation time:

$$\tau = \frac{1}{\omega_c} = \frac{1}{2\pi f_c} \quad (11)$$

At frequencies below relaxation the alternating electric field is slow enough that the dipoles are able to keep pace with the field variations. Because the polarization is able to develop fully, the loss (ε_r") is directly proportional to the frequency [9]. As the frequency increases, ε_r" continues to increase but the storage (ε_r') begins to decrease due to the phase lag between the dipole alignment and the electric field. Above the relaxation frequency both ε_r' and ε_r" drop off as the electric field is too fast to influence the dipole rotation and the orientation polarization disappears.

3.4 Ionic conductivity

The measured loss of material can actually be expressed as a function of both dielectric loss (ε_{rd}") and conductivity (σ).

$$\varepsilon_r = \varepsilon_{rd}" + \frac{\sigma}{\omega\varepsilon_0} \quad (12)$$

At low frequencies, the overall conductivity can be made up of many different conduction mechanisms, but ionic conductivity is the most prevalent in moist materials. ε_r" is dominated by the influence of electrolytic conduction caused by free ions which exist in the presence of a solvent (usually water). Ionic conductivity only introduces losses into a material [10]. At low frequencies the effect of ionic conductivity is inversely proportional to frequency and appears as a 1/f slope of the ε_r" curve.

4. INSERTION LOSS

In telecommunications, insertion loss is the loss of signal power resulting from the insertion of a device in a transmission line and is usually expressed in dBs. Insertion loss is a measure of attenuation but is a more precisely defined term. For instance, attenuation can include loss due to the source and load impedances not matching, but is not included in insertion loss since this is a loss that was already present before the insertion was made.

If the power incident to the load before insertion is P_i and the power transmitted by the load after insertion is P_T, then the insertion loss in dB is given by,

$$IL(dB) = 10\log(\frac{P_i}{P_T}) \quad (13)$$

Clearly this ratio is always less than one, so it would be more correct to call the property Insertion Gain. It is often called Attenuation.

In metallic conductor systems, radiation losses, resistive losses in the conductor as well as losses in the surrounding dielectric all reduce the power [4]. Line terminations play an important part in insertion loss because they reflect some of the power.

All of these effects can be conceptually modeled as various elements which make up the equivalent circuit of the line.

The effect of line terminations on the reflection of power reveals that not all of the power which is sent into the line at one end appears at the other. This is because of losses in the line due to the various elements which make up its equivalent circuit [5]. The loss which results from inserting a transmission line between a source and a load is called the Insertion Loss of the line.

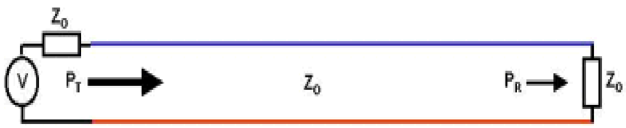

Figure 4 Insertion loss

For maximum power transfer the Insertion Loss should be as small as possible. In other words the ratio P_i /P_T should be as close to 1 as possible, which in decibels means as close to 0dB as possible.

5. RETURN LOSS

In telecommunications, return loss or reflection loss is the loss of signal power resulting from the reflection caused at a discontinuity in a transmission line or optical fiber. This discontinuity can be a mismatch with the terminating load or with a device inserted in the line. It is usually expressed as a ratio in decibels (dB);

$$RL(dB) = 10\log(\frac{P_i}{P_R}) \qquad (14)$$

Where RL is the return loss in dB,

P_i is the incident power and

P_R is the reflected power.

Two lines or devices are well matched if the return loss is high. A high return loss is therefore desirable as it results in a lower insertion loss. Properly, loss quantities, when expressed in decibels, should be positive numbers [7]. However, return loss has historically been expressed as a negative number, and this convention is still widely found in the literature. Taking the ratio of reflected to incident power results in a negative sign for return loss;

$$RL'(dB) = 10\log(\frac{P_R}{P_i}) \qquad (15)$$

where RL ’(dB) is the negative of RL(dB).

Caution is required when discussing increasing or decreasing return loss since these terms strictly have the opposite meaning when return loss is defined as a negative quantity.

The amount of power which is reflected back to the source from an incorrectly terminated line is an important property called Return Loss, and measurement of return loss can reveal line faults due to mismatching.

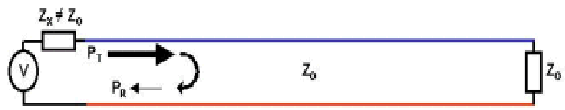

Figure 5 Return loss

Power can be reflected from mismatching at either end, but for lines of a reasonable length, the matching of the transmitter has more effect on the return loss than the matching of the receiver. This is because reflections from the far end are attenuated by the line before they arrive back at the transmitter. Often, high return loss is caused by changes in characteristic impedance at cable joints near to the transmitter.

For maximum power transfer the return loss should be as small as possible. This means that the ratio P_i/P_r should be as small as possible, or expressed in dB, the return loss should be as large a negative number as possible. For example a return loss of -40dB is better than one of -20dB.

6. MICROWAVE ABSORPTION

Absorption of electromagnetic radiation is the way by which the energy of an electron is taken up by matter. Thus, the electromagnetic energy is transformed to other forms of energy for example, to heat. The absorption of energy during wave propagation is often called attenuation. Usually, the absorption of waves does not depend on their intensity (linear absorption), although in certain conditions such as in optical ceramics, the medium changes its transparency dependently on the intensity of waves going through, and the saturable absorption (or nonlinear absorption) occurs.

Absorbed power = incident power – (transmitted power + reflected power)

$$= P_i - (P_T + P_R) \qquad (16)$$

The electromagnetic radiation interference is one of the unfortunate by-products of the rapid proliferation of electronic devices [11]. These are undesired conducted or radiated electrical disturbances including transients which can interfere with the operation of electrical or electronic components. The nano-structured materials have attraction for microwave radiation absorbing and shielding materials in the GHz frequency range due to their unique chemical and physical properties. The volume to weight ratio of shielding material is very important in microwave absorbing materials for lightweight and strong absorption properties.

7. CONCLUSION

The paper discussed the theory of dielectrics which is a poor conductor of electricity, but supports electrostatic fields. The properties of dielectric materials have been studied along with the insertion and return losses. Absorption of electromagnetic radiations also known as attenuation has also been discussed. Orientation, electronic and atomic polarizations contribute the overall dielectric mechanism.

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