

TECH NOTES

DECEMBER 2011



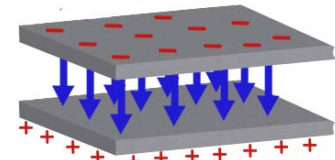
DIELECTRICS

Maxwell's equations define two terms which determine the response of a material to electromagnetic fields. These are the electric permittivity ϵ and the magnetic permeability μ . If these quantities are known for a material, then the reaction of a wave to the material is completely determined.

The permeability is a measure of a material's response to the magnetic portion of an EM wave. This paper assumes the material has no magnetic properties therefore the permeability is equal to that of free space.

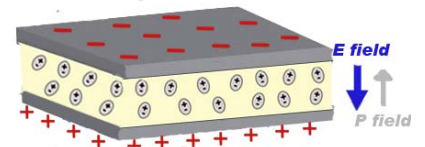
What are dielectrics?

In the broad sense, dielectrics are materials that can influence and be influenced by the electric portion of an electromagnetic field. While all objects exhibit dielectric properties to differing degrees, this paper will concern itself with simple dielectric materials with low conductivity and no 'semi-conducting' properties. Also, certain dielectrics have high loss and are used to attenuate a propagating wave. These dielectric absorbers will not be treated in this paper.



In a capacitor, charge accumulates on each plate, creating an electric field between the plates. The displacement field is given by

$$D = \epsilon_0 E$$



When a dielectric is inserted between the plates, dielectric polarization causes dipoles to form which oppose the applied electric field

$$D = \epsilon_0 E + P \quad \text{or} \quad D = \epsilon E$$

The energy storage occurs in the polarized dipoles.

When inserted between capacitor plates, a dielectric material will increase the capacitance

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DIELECTRIC THEORY

A capacitor when connected to a voltage source will store charge proportional to the area A of the capacitor plates. When subjected to a voltage, the capacitor will draw a charging current which leads the voltage by 90° . The voltage creates an electric field E between the plates. The charge is stored on the capacitor plates.

If a dielectric material is inserted between the capacitor plates the capacitance of the capacitor will increase. The relation between the electric field E and the dielectric flux density D is given by

$$D = P + \epsilon_0 E$$

Where P is the polarization in the dielectric induced by the electric field and ϵ_0 is the permittivity of free space and is equal to is 8.854×10^{-12} farads/m

DIELECTRIC THEORY

Rearranging, we get

$$P = D - \epsilon_0 E = (\epsilon^* - \epsilon_0) E$$

Where ϵ^* = the permittivity of the dielectric material. In general the permittivity is a complex quantity $\epsilon^* = \epsilon' - j\epsilon''$. Commonly the permittivity of materials is compared to the permittivity of free space. The real part ϵ' is generally called the dielectric constant and the imaginary portion ϵ'' is called the loss factor. No passive material can exhibit a permittivity less than that of free space hence dielectric constants are always greater than 1. The ratio ϵ''/ϵ' is called the loss tangent.

As can be seen, the dielectric serves to increase the electric flux density through the dielectric. Note that the electric field in a capacitor remains constant. The additional flux density is due to the polarization of the material.

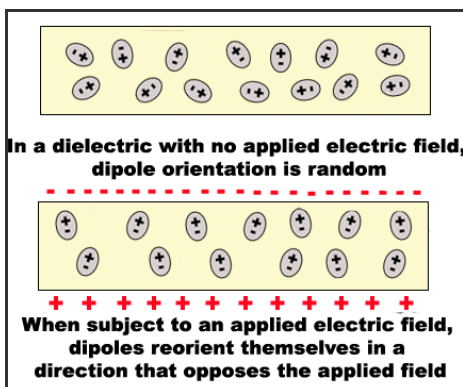
Molecular basis of dielectrics. A dielectric material becomes polarized in response to an electric field because it contains charge carriers that can be displaced. This polarization can take four forms. The first is due to bound charge in the electron cloud surrounding the nucleus becoming displaced slightly upon the application of an electric field. This displacement results in a virtual electric dipole formed by the positive nucleus and the negative electron cloud. A second source of polarization arises in molecules formed by atoms from different elements. In the absence of an electric field the electrons will be displaced towards the stronger binding atoms.

The presence of an external electric field will shift the equilibrium position of the atoms, thus creating a dipole moment. In addition, the asymmetric charge distribution in molecules will result in permanent dipole moments which will reorient themselves in response to an external field. A fourth source is due to free charge carriers which are restricted in their motion through the material which will result in an increase in capacitance. Note that the first three polarization mechanisms consist of charge carriers bound to atoms while the fourth consists of

The permittivity of a material is a complex quantity given by

$$\epsilon^* = \epsilon' - j\epsilon''$$

ϵ' is commonly called the dielectric constant or the K value. The ratio ϵ''/ϵ' is called the loss tangent ($\tan \delta$)



An applied electric field will cause bound charge carriers to create electric dipoles resulting in polarization of the material. This polarization decreases the effective electric field between the plates and hence increases the capacitance

DIELECTRIC THEORY

free electrons with restricted motion. Also note that the presence of these free electrons will contribute to material loss since their motion requires work which will attenuate the energy of the electric field. Desirable low loss dielectrics minimize free electrons. In the macroscopic world we are less concerned with the polarization mechanisms and lump them together in the material polarization to determine the permittivity.

$$\epsilon^* = \epsilon' - j\epsilon''$$

Dielectric Operation

All materials on earth can be considered dielectrics. They all have a permittivity greater than that of free space and will become polarized to varying extents due to an external electric field. In this paper we are concerned primarily with a class of dielectrics with very small loss factors. An electromagnetic wave will propagate (or resonate) in the material with a minimum amount of attenuation.

Most naturally occurring materials can have a dielectric constant as low as two or as high as several thousand. Artificial dielectrics consist of combinations of materials with various dielectric constants which macroscopically will have the desired effective dielectric constant.

A dielectric will reduce the wavelength of an electromagnetic wave by a factor proportional to the square root of the dielectric constant. This factor is used in applications to reduce the physical size of components. In circuit board or patch antenna applications, a high dielectric substrate enables the designer to reduce the overall size of the component. This doesn't come without cost however. The bandwidth or efficiency could be reduced due to the higher dielectric storing energy. A high dielectric material can also substantially reduce the size of a resonator.

A dielectric will also cause a wave in free space to reflect and refract when it impinges on its surface. Dielectrics are often used as lenses to shape antenna beams or to focus energy as with Luneberg lenses. A lens can be used to transform a spherical wave into a plane wave which will increase the directivity of the antenna

In the RF/microwave realm, dielectrics are primarily used to modify, compress or redirect electromagnetic energy. They can be used to reduce the size of antennas or other components or to change the path of electromagnetic energy through controlled reflections or lenses.

DIELECTRIC THEORY

Reflection and transmission of waves at a dielectric boundary

Dielectrics can be used to modify a wave by exploiting its reflection/transmission characteristics. At a dielectric interface, the incident, reflected and refracted waves must obey the boundary condition that the sum of E and H fields of the waves must be continuous. Requiring continuity of the amplitudes leads to Fresnel's equations. Continuity of phase leads to Snell's Law. Reflection from a dielectric interface depends on the polarization. There are two polarization states defined. Parallel polarization occurs when the E field vector is parallel to the plane of incidence. The plane of incidence is defined by the vector normal to the material and the propagation direction of the incident wave. Perpendicular polarization occurs when the E field vector is perpendicular to the plane of incidence.

$$r_{par} = \frac{\sqrt{\mu^* \epsilon^* - \sin^2 \theta} - \mu^* \epsilon^* \cos \theta}{\sqrt{\mu^* \epsilon^* - \sin^2 \theta} + \mu^* \epsilon^* \cos \theta} \quad \text{and} \quad r_{perp} = \frac{\cos \theta - \sqrt{\mu^* \epsilon^* - \sin^2 \theta}}{\cos \theta + \sqrt{\mu^* \epsilon^* - \sin^2 \theta}}$$

The phase delay experienced by the wave in propagating a distance d is given by

$$\phi = \frac{2\pi d}{\lambda} \sqrt{\mu^* \epsilon^* - \sin^2 \theta}$$

Note that for a non-magnetic material these equations are simplified by $\mu^*=1$

The interface reflection coefficients are only half the story though. Eventually the wave will reach the other side of the dielectric and reflect. The total reflection is then derived from the sum of the reflected waves.

The voltage reflection coefficient for a thickness d of a material is

$$R = \frac{-r^* (1 - e^{-j2\phi})}{1 - r^2 e^{-j2\phi}}$$

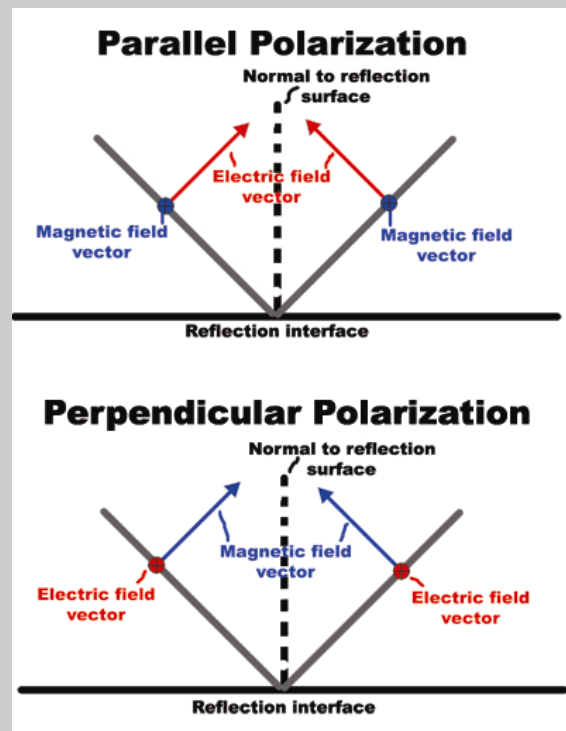
where r is the appropriate interface reflection coefficient

The voltage transmission coefficient is given by

$$T = \frac{(1 - r^2) e^{-j\phi}}{1 - r^2 e^{-j2\phi}}$$

If the sample is metal backed, the total reflection coefficient becomes

$$R_{MB} = \frac{r - e^{-j2\phi}}{1 - r e^{-j2\phi}}$$



DIELECTRIC THEORY

Wave propagation in dielectrics

For waves in a dielectric medium two of Maxwell's equations can be written as

$$\nabla \times H = \varepsilon^* \frac{\partial E}{\partial t} \quad (\text{Ampere's Law}) \quad \nabla \times E = -\mu^* \frac{\partial H}{\partial t} \quad (\text{Faraday's Law})$$

Differentiating each equation by t and substituting yields

$$\frac{\partial^2 E}{\partial x^2} = \varepsilon^* \mu^* \frac{\partial^2 E}{\partial t^2} \quad \text{and} \quad \frac{\partial^2 H}{\partial x^2} = \varepsilon^* \mu^* \frac{\partial^2 H}{\partial t^2}$$

If it is assumed that E and H are functions of x and t only the solution is a plane wave

$$E = E_0 e^{j\omega t - \gamma x} \quad \text{and} \quad H = H_0 e^{j\omega t - \gamma x}$$

where $\gamma = j\omega \sqrt{\varepsilon^* \mu^*} = \alpha + j\beta$
 and $\omega = 2\pi * \nu = 2\pi * \text{frequency}$

Expanding gives

$$E = E_0 e^{-\alpha x} e^{j2\pi(\nu t - \frac{\beta x}{2\pi})}$$

A nonzero α leads directly to an exponential attenuation of the wave. The complex exponential leads to a time period of

$$T = \frac{1}{\nu}$$

and a space period (wavelength)

$$\lambda = \frac{2\pi}{\beta}$$

For all materials with $\beta > 1$ (all dielectric materials) the wavelength will be compressed inside the dielectric compared to free space by a factor of β . For a low loss material, a very good approximation to β is

$$\beta = \omega \sqrt{\varepsilon^* \mu^*}$$

Hence for nonmagnetic material, wavelength compression inside a dielectric is proportional to the square root of the dielectric constant.

DIELECTRIC THEORY

Dielectric Polarization-The microscopic and the macroscopic form of Maxwell's equation for Gauss's Law are

$$\nabla \cdot E = \frac{\rho}{\epsilon_0}$$

E=electric field
 ρ =total charge density
 ϵ_0 =permittivity of vacuum

Where the electric field in a volume is dependent on the total charge density. In the presence of matter Maxwell introduced a displacement field D which is dependent only on the free charge density

$$\nabla \cdot D = \rho_f \quad \rho = \rho_f + \rho_b$$

ρ_b =bound charge density
 ρ_f =free charge density

These equations are equivalent if we define

$$\rho_b = -\nabla \cdot P \quad D = \epsilon_0 E + P$$

Artificial Dielectrics

Permittivity of a material generally arises from the effect on electrons within individual atoms or molecules in the material. An artificial dielectric is created when two or more dissimilar materials are mixed together. The combination will exhibit an effective permittivity somewhere intermediate between the permittivity of the materials. In order for the material to exhibit this macroscopic permittivity the spacing between the filler components must be less than a wavelength which is not an issue in the RF/microwave realm. Generally artificial dielectrics are created by combining particles or fibers (inclusions) with a matrix material. The dielectric constant of the composite will increase or decrease relative to the matrix depending on the dielectric of the inclusions. Inclusions of hollow particles can serve to substantially lower the dielectric constant (and weight) of the composite; these materials are called syntactic foams.

Dielectric Metamaterials- No naturally occurring material can have a dielectric constant less than 1. Metamaterials can exploit the macroscopic behavior of materials to create an effective dielectric constant less than 1 or even less than zero. These materials are made with high dielectric inclusions with specific shapes and sizes (rods, donuts, etc) in a lower dielectric matrix. Under certain conditions, these materials can exhibit a dielectric constant less than zero. What exactly does this mean? Recall the equation $D=\epsilon E$. A positive ϵ implies that the displacement field is in phase with the electric field. A negative ϵ means it is 180° out of phase with the electric field. A metamaterial can introduce a phase delay into the material response which will result in the displacement field being out of phase with the applied electric field.

Resonator concepts

It is well known that a dielectric material can act as a waveguide, supporting TE (transverse electric) and TM (transverse magnetic) modes like a more conventional hollow metallic waveguide. Like the metallic waveguide, if the dielectric waveguide is truncated, standing waves will exist and it will behave as a resonant cavity.

Analysis of hollow metallic cavities is straightforward as matching the boundary conditions of zero tangential E field on the metallic boundaries leads to exact solutions for simple shapes. For a dielectric resonator, it is a little more complex. The air dielectric boundary confines most of the field to the dielectric material but the boundary conditions are less straightforward. Often the dielectric is used inside a metallic enclosure and hence serves to reduce the size of the enclosure. The quality factor Q can be very high for a dielectric resonator and is proportional to the inverse of the material loss tangent.

A dielectric resonator when not enclosed by metal can be an efficient antenna with wider bandwidth than comparably sized patch antennas at the cost of the antenna no longer having a low profile. Dielectric Resonator Antennas (DRA) also have qualities useful in creating antenna arrays. A single dielectric resonator will resonate at many different frequencies with different field configurations. This can be exploited with different feed locations and mechanisms in a DRA enabling dual band performance.

DIELECTRIC FORMS

Low K materials ($1 < K < 2$)

Materials with a dielectric constant very close to 1 are available in two forms. Foams are available with very low dielectric constants. The matrix material provides structural support while the foam cavities have a dielectric of 1. Alternatively, the inclusions would consist of tiny glass spheres (microspheres). The inside of these spheres is a vacuum which gives them a very low effective dielectric constant. When used as an inclusion, microspheres can substantially lower the dielectric constant of a composite.



Medium K materials ($2 < K < 30$)

Wide ranges of material types are available over this range of dielectric constants. Circuit board laminates which are made with layers of materials interspersed with higher dielectric inclusions are available in K values up to 10. These materials are limited in their thickness to less than 0.125". Thicker dielectrics made of different plastics are available for higher thicknesses.



High K materials ($K > 30$)

To achieve the very high dielectric constants needed for dielectric resonators, ceramic materials must be used. These are sintered materials with dielectrics as high as 80. For a precision resonator, the dimensions of the material are crucial which can be a problem due to the difficulty in machining most ceramic materials.

Flexible dielectrics

Traditionally dielectric materials used in electronics have been rigid. Some applications (conformal antennas) require a dielectric material that can be applied around a radius. Flexible dielectrics composed of an elastomer are available with k values from 2-30



Injection moldable dielectrics

Many dielectric applications require a custom shape. Machining cost of traditional dielectric materials can be prohibitive. Dielectrics from 2-15 are available in pelletized form suitable for injection molding.



DIELECTRIC APPLICATIONS

Dielectrics have many applications in the RF/microwave world. The primary uses are as circuit board materials, radomes, and antennas. Desired properties differ in each case.

Circuit board laminates

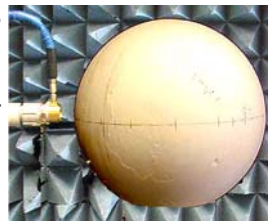
Dielectrics are used as circuit board laminates. The laminate is plated with a conductive material on two sides. One side serves as the ground plane while circuit pathways are etched into the other side. The dielectric constant of the laminate material is key to determining the etch pattern. Higher dielectric constants will shrink the needed circuit size, enabling lower overall size and weight.

Radomes

Antennas which are outdoors must be protected from the weather with a radome. However, since all dielectric materials will reflect some incident energy, the radome must be carefully designed to minimize reflections. Well designed radomes exploit the fact that a low loss material that is a quarter wavelength thick will exhibit almost perfect transmission.

Antennas

All antennas use dielectrics. The value of the dielectric constant is critical for correct design of an antenna. If the dielectric constant is different, the antenna resonant frequency will change. For many antennas it is critical to have known, consistent dielectric materials.



A Luneberg lens with feed

Patch antennas

Patch antennas are a class of antenna which uses a microstrip circuit board substrate with a rectangular patch etched into the surface. Patch antennas are used where some gain is desired and wide bandwidth is not critical. The patch resonates at the center frequency

Virtually every component of a microwave system uses dielectrics. Proper choice of dielectric properties is a cost effective way to enhance design

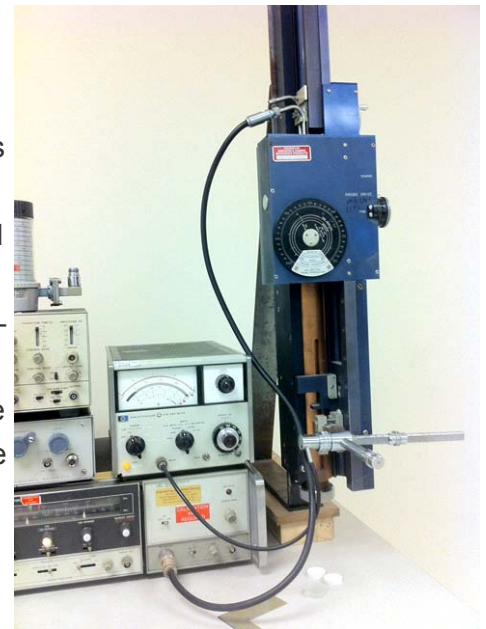
DIELECTRIC TEST METHODS

Free space-Insertion loss/phase

A quick nondestructive method for measuring dielectric constant of a flat sheet material is by using insertion loss and phase. In this test two antennas are set up and are boresighted. A calibration measurement (magnitude and phase) is taken with a network analyzer to establish the baseline. The material under test is placed between the antennas and the signal magnitude and phase are measured. Computer software is then used to determine the dielectric constant. Note that it is not possible to directly calculate the permittivity from the measured magnitude and phase so iterative techniques must be employed. Also a given value for magnitude and phase does not have a unique solution for permittivity. A phase measurement of, for example -60° may represent -60° or -420° or -780° , etc. This is because it is unknown how many complete wavelengths have passed through the material. This becomes particularly relevant for thick samples or material with very high dielectric constant. This can be resolved by measuring two or more thicknesses of material. The interferometer does not result in accurate values for the loss factor of the material.



Slotted line-An empty slotted line waveguide terminated in a short, when excited by a CW signal, will exhibit a standing wave caused by the superposition of the incident and reflected wave. This standing wave behavior will recur every half wavelength. Also, if the line is lossless, the nulls of the standing waves will be very deep and narrow. A precision probe can be used to measure the location and width of the nulls to a high degree of accuracy. If a sample of dielectric material is placed next to the short the location of the nulls will shift. If the material has loss the width of the nulls will increase. The new location and widths of the nulls are measured and very accurate values for the dielectric constant and loss tangent can be calculated. Note that this procedure has the same issues with multiple wavelengths inside the material as does the interferometer method but again, measuring multiple thicknesses can resolve this issue. The slotted line method can give very accurate results for both dielectric constant and loss tangent.

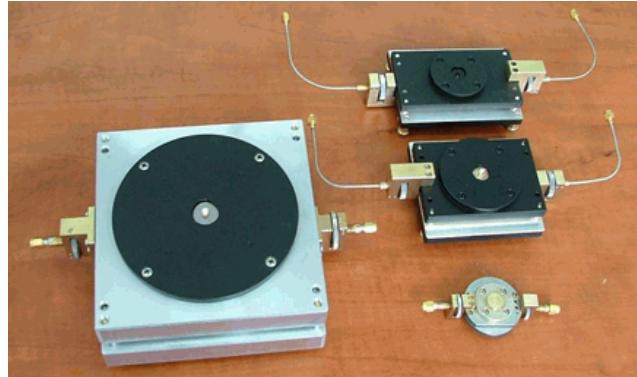


Resonator methods

Various resonator methods exist which share the common characteristic of measuring the resonant frequency and resonant width of a high Q resonator both with and without the dielectric sample.

Split Post Dielectric Resonator

The SPDR utilizes closely spaced dielectric resonators which couple to create a very high Q resonator. The resonant frequency and Q (3dB bandwidth) are measured and recorded. The sample is inserted between the resonators and the frequency and Q are measured. This results in very accurate values for dielectric constant and loss tangent without stringent requirements in machining samples.



A series of Split Post Dielectric Resonators
for different resonant frequencies

Resonant cavity

Like the SPDR, resonant cavity methods measure the resonant frequency and Q of a cavity. The cavity is then filled with the material to be tested and the dielectric constant and loss tangent are determined by the shift. This procedure can be very accurate but suffers from the drawback of error introduced if the material does not completely fill the cavity, often requiring expensive, precision machining.

Cavity perturbation

The cavity perturbation method relies on partially filling a cavity with the material to be tested. If the exact volume of the inserted material is known relative to the full volume of the cavity, the dielectric constant can be accurately derived. The value attained for loss tangent is less accurate, particularly for very low loss materials as there is insufficient loss in the partially filled cavity. This technique also does not require precision machined samples and is very cost effective.

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Arthur von Hippel, Editor

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Paul Dixon

Director of Technology

Emerson & Cuming Microwave Products, Inc

28 York Avenue

Randolph, MA 02368

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