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Analysis of UWB Signal Propagation Through Common Building Materials

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Abstract

Present day wireless communication systems are in the Ultra Wide Band ranging 3.1-10.6 GHz. Two major advantages of this band is low power operation and wide band width that made this band very popular in recent times for short distance communication. It is necessary to investigate the response of the common materials used such as, bricks, walls, glass and so on for the propagation of these signals due to passage of these signals through these materials. This paper presents a method for the estimation of the dielectric constant, path loss and attenuation for the propagation of the UWB signals and presented the measured values from 3 to 4 GHz.

Keywords: Ultra wide band, propagation, Dielectric loss

Introduction

Electromagnetic waves generated from transmitter propagate from indoor to outdoor and vice versa to reach the receiver. These waves many times have to pass through materials such as concrete, bricks, cloth partitions, glass, and plywood so on. It is desired to estimate the behavior of these materials when UWB waves propagate through them. Amendment by Federal Communications Commission (FCC) of part 15 of its first authorization in February 2012 has opened a new era of wireless communication systems and devices, in many areas of the society. This amendment has led to the development of Ultra-Wideband (UWB) technology that operates using narrow, short duration pulses with a very large bandwidth.

The commission has permitted design, development and operation of UWB devices and systems without causing potential interference to existing licensed radio operators [1]. Various techniques that are commonly used for the measurement of parameters of low-loss dielectric materials whose loss tangent is less than 0.005 such as glasses, plastics, single crystals and ceramics are reported. Cavity resonators and dielectric rod resonators have been used to measure parameters of thin (thickness less than 2 mm) dielectric materials at microwave frequencies. For measurements in millimeter range open resonators such as Fabry-Perot cavities have been used. Parameters of various low-loss materials are compared and analyzed [2]. Determination of complex permittivity of an arbitrary-shaped dielectric material using an arbitrary-shaped cavity by finite element method is reported. A rectangular shaped dielectric material is placed in a rectangular cavity and conducted eight different error measurements between the S-parameters of computed and experimental values and the resultant errors are placed in to two groups and checked for their convergence. After reaching the convergence the simulated S-parameter is matched with experimental values and the accuracy of the permittivity of the sample is determined [3]. Measurement of complex permittivity of plastic materials used in the making of electronic devices is reported in this paper. Measurement technique of complex permittivities of commonly used plastic materials at microwave frequencies and at high temperatures is reported. A cylindrical cavity designed with metal walls was used in the measurement. The electromagnetic energy is coupled into the cavity and the material sample using coupling loops. At each temperature the permittivity and the loss tangent behavior are obtained [4]. The perturbation method of evaluation of loss factor and dielectric constant of Teflon material of small size at microwave frequency range is reported. In this technique the rectangular cavity is used to measure the change in resonant frequency and quality factor of the cavity with and without the dielectric sample in the cavity. The complex permittivity is obtained using the shift in quality factor and change in resonant frequency at X-band frequency range. The resonant cavity consists of X-band rectangular wave guide with slot on the broad side wall with a moving sample holder and the measured values possess good accuracy [5]. A technique of measurement of dielectric constant of thin materials is presented. This technique is useful for determining the dielectric constant of leaves and other natural objects at microwave frequency range. The reported method is highly useful in remote sensing applications using microwave sensors. An improved technique is presented in this paper that gives correct value of the complex dielectric constant even if there is offset in the position of the sample from the waveguide flange [6]. A multimode circular cavity is proposed for the measurement of properties of low-loss dielectric materials at microwave frequency range at 1500° C temperature. The circular cavity is carefully designed to maintain the unwanted modes away from the desired mode. The proposed method of dielectric property measurements using circular cavity gives low error margin, easy to fabricate and the electric field is parallel to the surface of the dielectric sample [7]. The coaxial probe method of measurement of permittivity of liquids such as water, ethanol and methanol is reported. Measured results are compared with standard data available in the literature. A standard procedure for measurement of permittivity of liquids at high temperatures at microwave frequency range is reported [8].

The objective of this paper is to determine the dielectric constant of the common materials at UWB frequency range such as 3-4GHz. The proposed method involves solving the transfer function to get the dielectric constant based on the received signal in the frequency domain. Material properties for propagation of waves up to 1 GHz have been reported widely in the literature, but their behavior at UWB range are not deeply investigated.

Wave Propagation in Building Materials

The parameters of lossy dielectric materials for propagation of electromagnetic waves are analyzed. Consider a plane electromagnetic wave propagating in the +Z direction, represented by

$$E(Z,\omega) = E_{\circ} e^{-pZ} \quad (1)$$

Where, $\omega = 2\pi f$ is the angular frequency in radians, and 'p' is the propagation constant.

$$p(\omega) = \alpha(\omega) + j\beta(\omega) = j\omega\sqrt{\mu\varepsilon} \quad (2)$$

Where

α = *attenuation constant in* (Np/m)

β = *phase constant in* (Rad/m)

ε = *permittivity in* (F/m)

μ = *permeability in* (H/m)

Permeability of a non-magnetic material is $\mu = \mu_r \mu_{\circ} = \mu_{\circ}$

The complex permittivity $\varepsilon(\omega) = \varepsilon^{'}(\omega) - j\varepsilon^{''}(\omega)$

Where is the real permittivity and $\varepsilon^{''}$ = *dielectric loss*

Another way of presenting the dielectric loss is by loss tangent

$$\tan\delta = \frac{\varepsilon^{''}(\omega)}{\varepsilon^{'}(\omega)} \quad (3)$$

The attenuation constant and the phase constant are functions of the complex permittivity. Taking in to account of the conductivity loss of the dielectric material, its permittivity is represented as

$$\varepsilon(\omega) = \varepsilon^{'} - j\left(\varepsilon^{''} + \sigma/\omega\right) \quad (4)$$

$\sigma(\omega)$ is the conductivity of the material under consideration which is a function of frequency. The conductivity and dielectric losses are not separable hence the effective loss tangent is represented as

$$q(\omega) = \frac{\varepsilon^{''} + \sigma/\omega}{\varepsilon^{'}} = \frac{\varepsilon^{''}}{\varepsilon^{'}} + \frac{\sigma}{\omega\varepsilon^{'}} \quad (5)$$

The complex effective relative permittivity is defined as

$$\varepsilon_{re}(\omega) = \varepsilon_r(\omega)[1 - jq_e(\omega)] \quad (6)$$

The characteristics of any dielectric material depends mainly on two parameters
The dielectric constant
The effective loss tangent $q_e(\omega)$
The complex propagation constant is represented by

$$p(\omega) = \frac{j\omega}{c}\sqrt{\varepsilon_{re}} = \frac{j\omega}{c}\sqrt{\varepsilon_r(1 - jq_e)} \tag{7}$$

Where c=3x10^8 m/sec. A plane wave in a dielectric material propagating in +Z direction is represented by

$$E(Z,\omega) = E_{\circ}e^{-p(\omega)Z} = E_{\circ}e^{-j\beta(\omega)Z}.e^{-\alpha(\omega)Z} \tag{8}$$

The complex propagation constant $p(\omega)$ can be solved to obtain the real part, attenuation constant and its imaginary part phase constant β.

The attenuation constant is obtained as

$$\alpha(\omega) = \frac{\omega}{c}\left\{\frac{\varepsilon_r}{2}\left[\sqrt{1 + q_e^2} - 1\right]\right\}^{1/2} dB/m \tag{9}$$

And the imaginary part, phase constant is obtained as

$$\beta(\omega) = \frac{\omega}{c}\left\{\frac{\varepsilon_r}{2}\left[\sqrt{1 + q_e^2} + 1\right]\right\}^{1/2} rad/m \tag{10}$$

Many practical sub-surfaces are combination of a variety of materials, resulting in the effective permittivity.

The Transfer Function

The dielectric constant of the material is obtained by radiated transmission method in UWB frequency range. This is a frequency domain method.

The delay in the signal propagation is $\tau = \frac{t}{\upsilon_{\circ}}$ where't' is the thickness of the material under test and $\upsilon_{\circ}$ is the velocity of the light in free space. Let $E_t^{fs}(j\omega)$be the electric field intensity of the transmitted wave in free space. Hence

$$\frac{E_t^{fs}(j\omega)}{E_i(j\omega)} = e^{-j\omega\tau_{\circ}} \tag{11}$$

The insertion transfer function is now defined as the ratio of

$$H(j\omega) = \frac{E_t(j\omega)/E_i(j\omega)}{E_t^{fs}(j\omega)/E_i(j\omega)} = \frac{E_t(j\omega)}{E_t^{fs}(j\omega)} = \frac{\upsilon_t(j\omega)}{\upsilon_t^{fs}(j\omega)} \tag{12}$$

$$S_{21}(j\omega) = H(j\omega)e^{-j\omega\tau_{\circ}} \tag{13}$$

The received signals are measured with the material under test placed between transmitting and receiving antennas. The attenuation constant and dielectric constant of the material are obtained by solving the transfer function S_{21}.

Analysis for Determination of Dielectric Constant

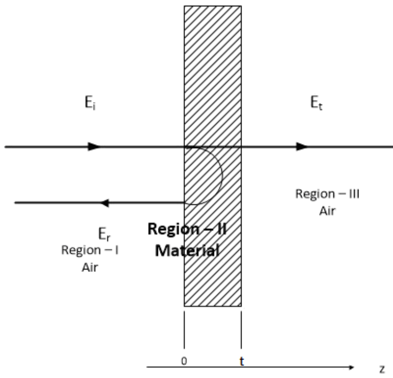

Figure 1: Wave Propagation through Dielectric Material

Transfer function

It is assumed that there are no scattering from the edges of the sample material under test and the receiver is in the far-field region of the transmitting antenna. The insertion transfer function H(jω) is obtained by assuming that a plane wave in the far-field of a transmitting antenna is incident normally on the material slab under test. Let't' be the thickness of the material and its complex dielectric constant is

$$\varepsilon_r = \varepsilon_r^{'} - j\varepsilon_r^{''}$$

In Fig. (1) components of the wave incident on the material are shown.

E_i – Incident wave in medium I

E_r – Reflected wave in medium II

E_t – Transmitted wave in medium III

Region – I is free space under the fields are represented by

$$\overline{E}_1 = \overline{a}_x \left[E_{io} e^{-j\beta_\circ z} + E_{ro} e^{+j\beta_\circ z} \right] \quad (14)$$

$$\overline{H}_1 = \overline{a}_y \frac{1}{\eta_1} \left[E_{io} e^{-j\beta_\circ z} + E_{ro} e^{+j\beta_\circ z} \right] \quad (15)$$

Where $\beta_\circ = \omega\sqrt{\mu_\circ \varepsilon_\circ} = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} \,\&\, \eta_1 = \sqrt{\frac{\mu_\circ}{\varepsilon_\circ}} = 120\pi\,\Omega$

Region-II constitutes the material under test and the fields are expressed as follows

$$\overline{E}_2 = \overline{a}_x \left[E_2^{+} e^{-\gamma z} + E_2^{-} e^{+\gamma z} \right] \quad (16)$$

$$\overline{H}_2 = \overline{a}_y \frac{1}{\eta_2}\left[E_2^+ e^{-\gamma z} - E_2^- e^{+\gamma z}\right] \tag{17}$$

The other parameters in medium-II are expressed as follows.

$$\gamma = \alpha + j\beta = j\omega\sqrt{\mu_\circ \varepsilon_\circ\left(\varepsilon_r^{'} - j\varepsilon_r^{''}\right)} \ \& \eta_2 = \sqrt{\frac{\mu}{\varepsilon_\circ \sqrt{\varepsilon_r^{'} - j\varepsilon_r^{''}}}} \tag{18}$$

γ-is the propagation constant
□-is the attenuation constant
β-is the phase constant
Region-III is free space and the fields are expressed as follows.

$$\overline{E}_3 = \overline{a}_x \ E_3^+ e^{-j\beta_\circ z} \ \& \ \overline{H}_3 = \overline{a}_y \frac{1}{\eta_1} E_3^+ e^{-j\beta_\circ z} \tag{19}$$

At the boundary Z=0 and Z=t the tangential components of E and H are continuous.

$$E_1(0) = E_2(0) \Rightarrow E_{i0} + E_{r0} = E_2^+ + E_2^- \tag{20}$$

$$H_1(0) = H_2(0) \Rightarrow E_{i0} - E_{r0} = \frac{\eta_1}{\eta_2}\left(E_2^+ - E_2^-\right) \tag{21}$$

$$E_2(d) = E_3(t) \Rightarrow E_2^+ e^{-\gamma t} + E_2^- e^{\gamma t} = E_3^+ e^{-j\beta_\circ t} \tag{22}$$

$$H_2(t) = H_3(t) = E_2^+ e^{-\gamma t} - E_2^- e^{+\gamma t} = \frac{\eta_2}{\eta_1} E_3^+ e^{-j\beta_\circ t} \tag{23}$$

The transmission coefficient '□' is expressed as follows.

$$\tau = \frac{E_3^+ e^{-j\beta_\circ t}}{E_{i0}} = S_{21} \tag{24}$$

Adding Eqs. (20)& (21)

$$2E_{i0} = E_2^+\left(1 + \frac{\eta_2}{\eta_1}\right) + E_2^-\left(1 - \frac{\eta_1}{\eta_2}\right) \tag{25}$$

Adding Eqs. (6.22)& (6.23)

$$2E_2^+ e^{-\gamma t} = E_3^+ e^{-j\beta_\circ t}\left(1 + \frac{\eta_2}{\eta_1}\right) \tag{26}$$

Subtracting Eq. (6.23) from Eq.(6.22)

$$2E_2^- e^{\gamma t} = E_3^+ e^{-j\beta_\circ t}\left[1 - \frac{\eta_2}{\eta_1}\right] \tag{27}$$

Substituting Eq. (6.26) & (6.27) in to Eq.(6.25)

$$2E_{i0} = \frac{1}{2}E_3^+ e^{(\gamma - j\beta_\circ)t}\left(1+\frac{\eta_2}{\eta_1}\right)\left(1+\frac{\eta_1}{\eta_2}\right)+\frac{1}{2}E_3^+ e^{(-\gamma - j\beta_\circ)t}\left(1-\frac{\eta_2}{\eta_1}\right)\left(1-\frac{\eta_1}{\eta_2}\right) \quad (28)$$

$$\tau = \frac{E_3^+ e^{-j\beta_\circ t}}{E_{i0}} = \frac{4}{e^{\gamma t}\left[2+\frac{\eta_1}{\eta_2}+\frac{\eta_2}{\eta_1}\right]+e^{-\gamma t}\left[2-\frac{\eta_1}{\eta_2}-\frac{\eta_2}{\eta_1}\right]} \quad (29)$$

By definition the insertion transfer function is expressed as

$$H(j\omega) = \frac{E_3 / E_{i0}}{E_{fs} / E_{i0}} = \frac{\tau}{e^{-j\beta_\circ t}} = \tau e^{j\beta_\circ t} \quad (30)$$

In Region-I $E_{fs} = E_{i0}$

$$H(j\omega) = \tau e^{j\beta_\circ t} = \frac{4e^{j\beta_\circ t}}{e^{\gamma t}\left[2+\frac{\eta_1}{\eta_2}+\frac{\eta_2}{\eta_1}\right]+e^{-\gamma t}\left[2-\frac{\eta_1}{\eta_2}-\frac{\eta_2}{\eta_1}\right]} \quad (31)$$

Equation (31) may be rewritten in terms of ε.

$$\beta_\circ = \omega\sqrt{\mu_\circ \varepsilon_\circ} = \frac{2\pi}{\lambda} = \frac{2\pi\ f}{c}$$

$$\eta_2 = \sqrt{\frac{\mu_\circ}{\varepsilon_\circ\left[\varepsilon_r^{'} - j\varepsilon_r^{''}\right]}} \approx \sqrt{\frac{\mu_\circ}{\varepsilon_\circ \varepsilon_r^{'}}} = \frac{\eta_1}{\sqrt{\varepsilon_r^{'}}} \quad (32)$$

Hence $\frac{\eta_1}{\eta_2}+\frac{\eta_2}{\eta_1} = \sqrt{\varepsilon_r^{'}}+\frac{1}{\sqrt{\varepsilon_r^{'}}} = \frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}$ (33)

Substitute Eq. (33) in to Eq. (31)

$$H(j\omega) = \frac{4e^{j\beta_\circ t}}{e^{\gamma t}\left[2+\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right]+e^{-\gamma t}\left[2-\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right]} \quad (34)$$

$$H(j\omega) = \frac{4e^{j\beta_\circ t}}{e^{(\alpha + j\beta)t}\left[2+\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right]+e^{-(\alpha + j\beta)t}\left[2-\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right]} \quad (35)$$

The magnitude of $|H(j\omega)|$ is determined for numerator and denominator and then the over all magnitude is obtained.

The magnitude of numerator is $4\angle\beta_\circ t$ (36)

Denominator is expanded and the real and imaginary parts are separated. The magnitude becomes

$$\left\{e^{2\alpha t}\left(2+\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)^2+e^{-2\alpha t}\left(2-\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)^2+2\cos(2\beta t)\left[4-\left(\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)^2\right]\right\}^{1/2} \quad (37)$$

$$|H(j\omega)|=\left[\frac{16}{\left\{e^{2\alpha t}\left(2+\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)^2+e^{-2\alpha t}\left(2-\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)^2+2\cos(2\beta t)\left[4-\left(\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)^2\right]\right\}}\right]^{1/2} \quad (38)$$

The phase angle of H(jω) is

$$\theta=\tan^{-1}\left[\frac{e^{\alpha t}\left(2+\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)-e^{-\alpha t}\left(2-\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)}{e^{\alpha t}\left(2+\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)+e^{-\alpha t}\left(2-\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)}\right]\tan(\beta t) \quad (39)$$

$$\theta=\tan^{-1}\left[\frac{\left(\sqrt{\varepsilon_r^{'}}+1\right)^2-e^{-2\alpha t}\left[-\left(\sqrt{\varepsilon_r^{'}}-1\right)^2\right]}{\left(\sqrt{\varepsilon_r^{'}}+1\right)^2+e^{-2\alpha t}\left[-\left(\sqrt{\varepsilon_r^{'}}-1\right)^2\right]}\right]\tan(\beta t) \quad (40)$$

$$\theta=\tan^{-1}\left[\frac{1-e^{-2\alpha t}Q}{1+e^{-2\alpha t}Q}\right]\tan(\beta t) \quad (41)$$

$$\angle H(j\omega)=\beta_{\circ}t-\theta$$

For many applications the value of Q is small.

Let $X=e^{-2\alpha t}$ & $\frac{1}{X}=e^{2\alpha t}$

Substitute in Eq. (6.38)

$$|H(j\omega)|^2=\frac{16\varepsilon_r^{'}}{\frac{1}{X}\left(\sqrt{\varepsilon_r^{'}}+1\right)^4+X\left(\sqrt{\varepsilon_r^{'}}-1\right)^4-2\cos(2\beta t)\left(\varepsilon_r^{'}-1\right)^2} \quad (42)$$

Rewriting the above equation

$$X^2\left(\sqrt{\varepsilon_r^{'}}-1\right)^4-2\left[\cos(2\beta t)\left(\varepsilon_r^{'}-1\right)^2+\frac{8\varepsilon_r^{'}}{|H(j\omega)|^2}\right]X+\left(\sqrt{\varepsilon_r^{'}}+1\right)^4=0 \quad (43)$$

Eq.(43) is quadratic in X and is solved as

$$X=e^{-2\alpha t}=\frac{\left[\cos(2\beta t)\left(\varepsilon_r^{'}-1\right)^2+\frac{8\varepsilon_r^{'}}{|H(j\omega)|^2}\right]\pm\sqrt{\left[\cos(2\beta t)\left(\varepsilon_r^{'}-1\right)^2+\frac{8\varepsilon_r^{'}}{|H(j\omega)|^2}\right]^2-\left(\sqrt{\varepsilon_r^{'}}-1\right)^4}}{\left(\sqrt{\varepsilon_r^{'}}-1\right)^4} \quad (44)$$

In Eq. (44) the positive sign before the square root results in X greater than unity and is not acceptable. Hence the sign before the square root must be negative.

$$X = e^{-2\alpha t} = \frac{\left[\cos(2\beta t)(\varepsilon_r^{'}-1)^2 + \frac{8\varepsilon_r^{'}}{|H(j\omega)|^2}\right] - \sqrt{\left[\cos(2\beta t)(\varepsilon_r^{'}-1)^2 + \frac{8\varepsilon_r^{'}}{|H(j\omega)|^2}\right]^2 - \left(\sqrt{\varepsilon_r^{'}}-1\right)^4}}{\left(\sqrt{\varepsilon_r^{'}}-1\right)^4} \quad (45)$$

In order to obtain a solution for the Eq. (45) the second term in the numerator is to be greater than zero. Hence

$$\left[\cos(2\beta t)(\varepsilon_r^{'}-1)^2 + \frac{8\varepsilon_r^{'}}{|H(j\omega)|^2}\right]^2 - (\varepsilon_r^{'}-1)^4 > 0 \quad (46)$$

Re writing

$$\left[\cos(2\beta t)(\varepsilon_r^{'}-1)^2 + \frac{8\varepsilon_r^{'}}{|H(j\omega)|^2} + (\varepsilon_r^{'}-1)^2\right].\left[\cos(2\beta t)(\varepsilon_r^{'}-1)^2 + \frac{8\varepsilon_r^{'}}{|H(j\omega)|^2} - (\varepsilon_r^{'}-1)^2\right] > 0 \quad (47)$$

The first term Eq. (47) is always positive

$$\cos(2\beta t)(\varepsilon_r^{'}-1)^2 + \frac{8\varepsilon_r^{'}}{|H(j\omega)|^2} - (\varepsilon_r^{'}-1)^2 > 0$$

$$\cos(2\beta t)(\varepsilon_r^{'}-1)^2 + \frac{8\varepsilon_r^{'}}{|H(j\omega)|^2} > (\varepsilon_r^{'}-1)^2 \quad (48)$$

The assumption of negative sign in Eq. (45) gives a solution for 'X' greater than zero and it must be less than one as it is the attenuation of the signal propagating through the material under test. Substituting Eq. (45) into Eq. (41).

$$\theta = \tan^{-1}\left\{\left[\frac{1-QX}{1+QX}\right]\tan(\beta t)\right\} \quad (49)$$

Substituting Eq. (49) into $\angle H(j\omega) = \beta_{\circ} t - \theta$

$$\tan[\beta_{\circ} t - \angle H(j\omega)] - \left[\frac{1-QX}{1+QX}\right]\tan(\beta t) = 0 \quad (50)$$

Eq. (50) contains $\varepsilon_r^{'}$ hence solving this equation numerically and substituting the value we can apply X and □. The $\varepsilon_r^{''}$ can be calculated using the equation of propagation constant for complex medium.

$$p = \alpha + j\beta = j\omega\sqrt{\mu_{\circ}\varepsilon_{\circ}\left(\varepsilon_r^{'} - j\varepsilon_r^{''}\right)}$$

Expanding and neglecting higher order terms

$$p = j\beta_{\circ}\sqrt{\varepsilon_r^{'}}\left[1 + j\frac{1}{2}\frac{\varepsilon_r^{''}}{\varepsilon_r^{'}}\right]$$

Equating real and imaginary parts

$$\alpha = \frac{1}{2}\beta_\circ \frac{\varepsilon_r^{"}}{\sqrt{\varepsilon_r^{'}}}$$

$$\varepsilon_r^{"} = \frac{2\alpha\sqrt{\varepsilon_r^{'}}}{\beta_\circ} = \frac{2c\alpha\sqrt{\varepsilon_r^{'}}}{\omega} \quad (51)$$

Where $\beta = \beta_\circ \sqrt{\varepsilon_r^{'}}$

It can be assumed that $e^{-2\alpha t} << 1$ then Eq.(41) becomes

$$\theta \approx \tan^{-1}(\tan \beta t) = \beta t$$

$$\angle H(j\omega) = \beta_\circ t - \beta t = \beta_\circ t - \beta_\circ t\sqrt{\varepsilon_r^{'}} = \beta_\circ t\left[1 - \sqrt{\varepsilon_r^{'}}\right]$$

$$\varepsilon_r^{'} = \left[1 - \frac{\angle H(j\omega)}{\beta_\circ t}\right]^2 \quad (52)$$

Attenuation Constant

Applying the condition $e^{-2\alpha t} << 1$ to Eq.(6.38)

$$\left|H(j\omega)\right|^2 = \frac{16}{e^{2\alpha t}\left(2 + \frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)^2 + 2\cos(2\beta t)\left[4 - \left(\frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)^2\right]} \quad (53)$$

Solving for □ gives

$$\alpha = \frac{1}{2t}\ln\left\{\frac{\frac{16}{\left|\mathrm{H}(\mathrm{j}\omega)\right|^2} + 2\cos(\beta t)\left[\frac{(\varepsilon_r^{'}-1)^2}{\varepsilon_r^{'}}\right]}{\frac{\left(\sqrt{\varepsilon_r^{'}}+1\right)^4}{\varepsilon_r^{'}}}\right\} \quad (54)$$

Eq.(34) may be solved in terms of the scattering parameter S_{21}

$$S_{21} = \frac{4}{e^{\gamma t}\left(2 + \frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right) + e^{-\gamma t}\left(2 - \frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\right)} \quad (55)$$

Expanding and rearranging

$$2\left(e^{\gamma t} + e^{-\gamma t}\right) + \frac{\varepsilon_r^{'}+1}{\sqrt{\varepsilon_r^{'}}}\left(e^{\gamma t} - e^{-\gamma t}\right) = \frac{4}{S_{21}} \quad (56)$$

$$p = \alpha + j\beta = j\omega\sqrt{\mu_\circ \varepsilon_\circ \varepsilon_r} = j\beta_\circ\sqrt{\varepsilon_r}$$

Substituting in Eq. (55)

$$\left(e^{j\beta_\circ\sqrt{\varepsilon_r}t}+e^{-j\beta_\circ\sqrt{\varepsilon_r}t}\right)+\frac{\varepsilon_r^{'}+1}{2\sqrt{\varepsilon_r^{'}}}\left(e^{j\beta_\circ\sqrt{\varepsilon_r}t}-e^{-j\beta_\circ\sqrt{\varepsilon_r}t}\right)-\frac{2}{S_{21}}=0$$

When □=0, $\beta=\beta_\circ\sqrt{\varepsilon_r}$

Put $y=\sqrt{\varepsilon_r}$ *and* $q=j\beta_\circ t$

$$\left(y+\frac{1}{y}\right)\sinh(\mathrm{qy})+2\cosh(qy)-\frac{2}{S_{21}}=0 \quad (57)$$

The insertion transfer function is determined using S_{21} for each material using Eq. (13). The real value of the permittivity is obtained from Eq. (52) using the angle of H(jω). The attenuation constant is obtained by substituting Eq. (52) and magnitude of H(jω) in to Eq. (51) and the imaginary value of the permittivity is determined.

Measurements are conducted using MS2024B Anritsu vector network analyzer and the S_{21} are measured for concrete and bricks from 3.0 GHz to 4.0 GHz. The measured values of the S_{21} are used to compute the path loss, attenuation and dielectric constants of these materials and are listed below.

Material: Ply Wood Thickness (t)=1.8 cm					
Frequency (GHz)	S_{21}	H (jω)	Path Loss (dB)	Attenuation (dB/m)	Dielectric Constant (ε_r)
3.0	0.65-0.69i	-0.86-0.39i	-0.58	27.57	2.57
3.5	-0.31-0.86i	-0.91-0.07i	-0.74	27.58	2.56
4.0	-0.99-0.04i	-0.93+0.36i	-0.74	27.65	2.56

Material: Clay Brick Thickness (t)=7.0 cm, length=21cm, width=10cm					
Frequency (GHz)	S_{21}	H (jω)	Path Loss (dB)	Attenuation (dB/m)	Dielectric Constant (ε_r)
3.0	-0.59-0.67i	-0.45+0.77i	-3.89	19.41	3.80
3.5	-0.57+0.68i	0.38+0.88i	-3.85	12.24	3.94
4.0	0.56+0.69i	0.77+0.42i	-3.93	18.67	4.02

Material: Concrete Block Thickness (t)=19.45cm					
Frequency (GHz)	S_{21}	H (jω)	Path Loss (dB)	Attenuation (dB/m)	Dielectric Constant (ε_r)
3.0	0.69+0.67i	0.83+0.38i	-1.99	25.58	2.2
3.5	-0.779-0.58i	0.67-73i	-1.95	27.62	2.25
4.0	0.82+0.52i	-0.39-0.89i	-1.98	29.87	2.28

Conclusion

By measuring the received signals with and without the material under test, a transfer function is obtained in frequency domain. This function is used to obtain the dielectric constant at different frequencies and also the attenuation offered and the path loss of the signal in the material. But it is to be ensured that there are no reflections from the surroundings as well as from the material under test. The accuracy of the material constants depends on the accuracy of the measurement of the received signals in the frequency domain. Similar measurements can be conducted using the proposed method for other materials such as glass, cloth materials and so on.

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References

[1] Federal Communications Commission (FCC) 02-48, "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems", First Report & Order, Washington DC, Adopted 14 Feb 2002, Released 22 April 2002.

[2] James Baker-Jarvis, Richard G.Geyer, John H.Grosvenor et. al., “Dielectric Characterization of Low-loss Materials A Comparison of Techniques,” IEEE Transactions on Dielectrics and Electrical Insulation, Vol.5, No. 4, August 1998, pp. 571-577.

[3] Kailash P.Thakur and Wayne S.Holmes, “An Inverse Technique to Evaluate Permittivity of Material in a Cavity,” IEEE Transactions on Microwave Theory and Techniques, Vol. 49, No.6, June 2001, pp.1129-1132.

[4] Bill Riddle, James Baker-Jarvis, and Jerzy Krupka, “Complex Permittivity Measurements of Common Plastics Over Variable Temperatures,” IEEE Transactions on Microwave Theory and Techniques, Vol. 51, No.3, March 2003, pp.727-733.

[5] A. Kumar and S. Sharma, “Measurement of Dielectric Constant and Loss Factor of the Dielectric Material at Microwave Frequencies,” Progress in Electromagnetics Research, PIER 69, 2007, pp.47-54.

[6] B. K. Chung, “Dielectric Constant Measurement for Thin Material at Microwave Frequencies,” Progress in Electromagnetics Research, PIER 75, 2007, pp.239-252.

[7] E. Li, Z.Nie, G.Guo, and Q. Zhang, “Broadband Measurements of Dielectric Properties of Low-loss Materials at High Temperatures Using

Circular Cavity Method," Progress in Electromagnetics Research, PIER 92, 2009, pp.103-120.

[8] Jose C.A. Santos, Mauricio H. C. Dias et.al., "Using the Coaxial Probe Method for Permittivity Measurements of Liquids at High Temperatures," Journal of Microwaves, Optoelectronics and Electromagnetic Applications, Vol. 8, No.1, pp.78-91, June 2009