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Microwave Absorption Behavior of Ceramic Composites in X-Band Region

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Abstract— *A Theoretical investigation was conducted to examine the microwave absorption characteristics of La & Fe doped sample in X-Band. The sample is made by solid state ceramic method. Reflection transmission and absorption loss were calculated from sample using impedance concept as a function of frequency. The length of layer of sample are equal length are placed in parallel. The absorption losses are depending on frequency and doping concentration.*

Keywords— *Millimeter waves, reflection coefficient, transmission, absorption loss.*

I. INTRODUCTION

Recently considerable attention has been paid to evaluate the absorption characteristic of microwave in ceramic system. It affects the microwave and millimeter waves both in phase and amplitude. Earlier work investigated the limit in cascaded from and determined the reflections transmission coefficient and power loss. In the present paper an attempt has been made to evaluate the absorption loss of microwave while propagating through media having different chemical constituents. Utilizing the transmission line concept equation has been developed to evaluate the reflection coefficient, transmission coefficient and absorption loss.

II. MICROWAVE ABSORPTION BEHAVIOR

A. Theoretical Consideration

- *Geometry of problem*: The prepared sample of Ba and La doped Ceramic Material have been link in cascaded determined the power loss using transmission line model. The geometry of the problem has defined in following figure 1.

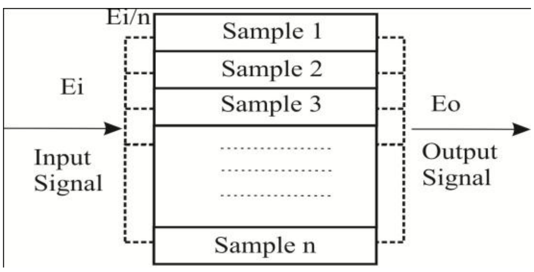

Fig. 1.

The length of sample with contain n types of chemical constitutes is taken. Since the waves are incident through mediums. Which has sparsely chemical constitutes it is quite logical to represent the entire length of the sample into n section in parallel having n different constitutes as show in fig 1. It is the assumed that all the n constituents have same number of chemical constituents per unit volume of the sample then each section of sample may have equal length. Let $\varepsilon_1, \varepsilon_2, \varepsilon_3, \ldots \varepsilon_n$, $\mu_1, \mu_2, \mu_3, \ldots\ldots \mu_n$, and $\sigma_1, \sigma_2, \sigma_3, \ldots\ldots \sigma_n$, denote the usual medium parameters (Permittivity, Permeability and conductivity) for n constituents, respectively. Further, let $\eta_1, \eta_2, \eta_3, \ldots\ldots \eta_n$, denote the characteristic impedance of individual sections. For calculating the various propagation parameter to cases have been taken separately, namely (i) Normal incidence and (ii) oblique incidence.

B. Normal Incidence

Figure 1 is the transmission line equivalent of a Sample in medium. In this, each section is characterized by a type of sample. The incident signal is divided into *n* equal parts.

If a microwaves is indicate at the interface, then transmission coefficients for each sample can be written as:

$$T_1 = \left[\frac{2\eta_1}{\eta_1+\eta_0}\frac{2\eta_0}{\eta_1+\eta_0}\right]\exp(-\gamma_1 L) \tag{1}$$

Where *L* is length of sample

$$T_2 = \left[\frac{2\eta_2}{\eta_2+\eta_0}\frac{2\eta_0}{\eta_2+\eta_0}\right]\exp(-\gamma_2 L) \tag{2}$$

$$T_3 = \left[\frac{2\eta_3}{\eta_3+\eta_0}\frac{2\eta_0}{\eta_3+\eta_0}\right]\exp(-\gamma_3 L) \tag{3}$$

$$T_n = \left[\frac{2\eta_n}{\eta_n+\eta_0}\frac{2\eta_0}{\eta_n+\eta_0}\right]\exp(-\gamma_n L) \tag{4}$$

Putting the value of

$$\eta_1 = \frac{\eta_0}{\sqrt{\varepsilon_{r_1}}}, \eta_2 = \frac{\eta_0}{\sqrt{\varepsilon_{r_2}}}, \eta_3 = \frac{\eta_0}{\sqrt{\varepsilon_{r_3}}}, \eta_n = \frac{\eta_0}{\sqrt{\varepsilon_{r_n}}} \quad and$$

$$\gamma_1 = \frac{2\pi}{\lambda_1}\left(1 - j\frac{\sigma_1}{2\omega\varepsilon_1}\right), \gamma_2 = \frac{2\pi}{\lambda_2}\left(1 - j\frac{\sigma_2}{2\omega\varepsilon_2}\right)$$

$$\gamma_3 = \frac{2\pi}{\lambda_3}\left(1 - j\frac{\sigma_3}{2\omega\varepsilon_3}\right), \ldots\ldots\ldots \gamma_n = \frac{2\pi}{\lambda_n}\left(1 - j\frac{\sigma_n}{2\omega\varepsilon_n}\right)$$

Following are obtained,

$$T_1 = \left[\frac{2\sqrt{\varepsilon_{r_1}}}{\left(\sqrt{\varepsilon_{r_1}}+1\right)^2}\right]\exp\left[-j\frac{2\pi}{\lambda_1}\left(1 - j\frac{\sigma_1}{2\omega\varepsilon_1}\right)L\right] \tag{5}$$

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$$T_2 = \left[\frac{2\sqrt{\varepsilon_{r_2}}}{\left(\sqrt{\varepsilon_{r_2}}+1\right)^2}\right]\exp\left[-j\frac{2\pi}{\lambda_2}\left(1-j\frac{\sigma_2}{2\omega\varepsilon_2}\right)L\right] \quad (6)$$

$$T_3 = \left[\frac{2\sqrt{\varepsilon_{r_3}}}{\left(\sqrt{\varepsilon_{r_3}}+1\right)^2}\right]\exp\left[-j\frac{2\pi}{\lambda_3}\left(1-j\frac{\sigma_3}{2\omega\varepsilon_3}\right)L\right] \quad (7)$$

$$T_n = \left[\frac{2\sqrt{\varepsilon_{r_n}}}{\left(\sqrt{\varepsilon_{r_n}}+1\right)^2}\right]\exp\left[-j\frac{2\pi}{\lambda_n}\left(1-j\frac{\sigma_n}{2\omega\varepsilon_n}\right)L\right] \quad (8)$$

C. Reflection Coefficients

The reflection coefficients for *n* La and Fe sample are calculated as:

$$R_1 = \frac{z_1-\eta_0}{z_1+\eta_0} = \left(\frac{z_1-\eta_0}{z_1+\eta_0}\right)$$

Where

$$z_1 = \frac{\frac{\eta_0}{\sqrt{\varepsilon_{r_1}}}\left(\eta_0 + \frac{\eta_0}{\sqrt{\varepsilon_{r_1}}}\tanh\gamma_1 L\right)}{\left(\frac{\eta_0}{\sqrt{\varepsilon_{r_1}}}\eta_0 \tanh\gamma_1 L\right)}$$

$$R_1 = \frac{\eta_0\left(\frac{A_1}{B_1}\right)-\eta_0}{\eta_0\left(\frac{A_1}{B_1}\right)+\eta_0} = \frac{A_1-B_1}{A_1+B_1} \quad (9)$$

Where

$$A_1 = \left(1+\frac{1}{\sqrt{\varepsilon_{r_1}}}\tanh\gamma_1 L\right)$$

$$B_1 = \left(1+\frac{1}{\sqrt{\varepsilon_{r_1}}}\tanh\gamma_1 L\right)$$

Similarly for

$$R_2 = \frac{A_2-B_2}{A_2+B_2}, R_3 = \frac{A_3-B_3}{A_3+B_3}, ...R_n = \frac{A_n-B_n}{A_n+B_n} \quad (10)$$

Where

$$A_n = \left(1+\frac{1}{\sqrt{\varepsilon_{r_n}}}\tanh\gamma_n L\right)$$

$$B_n = \left(1+\frac{1}{\sqrt{\varepsilon_{r_n}}}\tanh\gamma_n L\right)$$

D. Oblique Incidence

In this case, the electromagnetic wave is incident at an angle θ of surface and the sample. Then, θ_n will be the angle of refraction through the interface.

$\gamma_n \sin\theta_n = \gamma_n \sin\theta$ (from Snell's Law)

$$\cos\theta_n = \sqrt{1-\frac{\gamma_0\sin\theta}{\gamma_n}}$$

γ_0, Propagation constant for free space = $j.2\pi/\gamma_0$

The Maxwell's equation for dielectric medium having permittivity, ε is given as:

$$\nabla\times H = J_c + \frac{\partial D}{\partial t} = \sigma E + j\omega\sigma E = j\left(\frac{\sigma}{j\omega\varepsilon}+1\right)\omega\sigma E$$

Where $1+\frac{\sigma}{j\omega\varepsilon}$ denotes the complex effective permittivity of the lossy dielectric medium. The characteristics impedence of such sample will be:

$$\eta = \sqrt{\frac{\mu}{\varepsilon\left(1+\frac{\sigma}{j\omega\varepsilon}\right)}} = \sqrt{\frac{j\omega\mu}{(\sigma+j\omega\sigma)}}$$

The Propagation constant offered by the lossy dielectric sample is given by

$$\gamma = \{j\omega\mu(\sigma+j\omega\varepsilon)\}^{\frac{1}{2}}$$

Therefore,

$$\frac{\eta}{\gamma} = \frac{\sqrt{\frac{j\omega\mu}{\sigma+j\omega\varepsilon}}}{\sqrt{j\omega\mu\,(\sigma+j\omega\varepsilon)}} = \frac{1}{(\sigma+j\omega\varepsilon)}$$

Or

$$\eta = \frac{\gamma}{\sigma+j\omega\mu} \quad (11)$$

If the electromagnetic wave incident at an angle θ with the direction of propagation, the effective characteristics impedance offered by the various sections of dielectric sample can be given by

$$\eta_n = \frac{\gamma_n\cos\theta_n}{\sigma_n+j\omega\varepsilon_n} \quad (12)$$

θ_n = angle of refraction for n^{th} section of sample
σ_n = conductivity for n^{th} section of sample
n = 1,2,3, …………..

If θ_1, θ_2, θ_3, …….. θ_n denote the angle of refractions of each section then transmission coefficient from equation (1) will be.

$$T_1 = \left[\frac{2\eta_1}{\eta_1+\eta_0}\frac{2\eta_0}{\eta_1+\eta_0}\right]e^{\gamma_1\cos\theta_1 L}$$

Putting the value of

$$\eta_0 = \frac{\gamma_{0\cos\theta_0}}{(\sigma_0+j\omega\varepsilon_0)} \text{ and } \eta_1 = \frac{\gamma_{1\cos\theta_1}}{(\sigma_1+j\omega\varepsilon_1)}$$

Following are obtained,
Similarly reflection coefficients can also be obtained as:

$$T_1 = \frac{4\gamma_1\gamma_0(\sigma_1+j\omega\varepsilon_1)(\sigma_0+j\omega\varepsilon_0)\cos\theta_0\cos\theta_1}{[\gamma_1(\sigma_0+j\omega\varepsilon_1)\cos\theta_1+\gamma_0(\sigma_1+j\omega\varepsilon_1)\cos\theta_0]^2}\exp[-\gamma_1\cos\theta_1 L] \quad (13)$$

$$T_2 = \frac{4\gamma_1\gamma_0(\sigma_2+j\omega\varepsilon_2)(\sigma_0+j\omega\varepsilon_0)\cos\theta_0\cos\theta_2}{[\gamma_2(\sigma_0+j\omega\varepsilon_0)\cos\theta_2+\gamma_0(\sigma_2+j\omega\varepsilon_2)\cos\theta_0]^2}\exp[-\gamma_2\cos\theta_2 L] \quad (14)$$

$$T_3 = \frac{4\gamma_3\gamma_0(\sigma_3 + j\omega\varepsilon_3)(\sigma_0 + j\omega\varepsilon_0)\cos\theta_0\cos\theta_3}{[\gamma_3(\sigma_0 + j\omega\varepsilon_0)\cos\theta_3 + \gamma_0(\sigma_3 + j\omega\varepsilon_3)\cos\theta_0]^2}\exp[-\gamma_3\cos\theta_3 L] \quad (15)$$

$$T_n = \frac{4\gamma_n\gamma_0(\sigma_n + j\omega\varepsilon_n)(\sigma_0 + j\omega\varepsilon_0)\cos\theta_0\cos\theta_n}{[\gamma_n(\sigma_0 + j\omega\varepsilon_0)\cos\theta_n + \gamma_0(\sigma_n + j\omega\varepsilon_n)\cos\theta_0]^2}\exp[-\gamma_n\cos\theta_n L] \quad (16)$$

Similarly reflection coefficients can also be obtained as:

$$R_1 = \left(\frac{Z_1 - \eta_0}{Z_1 + \eta_0}\right)$$

Where

$$Z_1 = \frac{\eta_0\left(1 + \frac{1}{\varepsilon_{r_1}}\tan h\gamma_1 L\right)}{(1 + \sqrt{\varepsilon_{r_1}}\tan h\gamma_1 L)} = \frac{\eta_0 A_1}{B_1}$$

Therefore

$$R_1 = \frac{B_1 - A_1}{B_1 + A_1}; R_2 = \frac{B_2 - A_2}{B_2 + A_2}; R_3 = \frac{B_3 - A_3}{B_3 + A_3}; R_n = \frac{B_n - A_n}{B_n + A_n} \quad (17)$$

Where

$$A_n = 1 + \frac{1}{\sqrt{\varepsilon_{r_n}}}\tan h\left\{j\frac{2\pi}{\lambda n}\left(1 - \frac{j\sigma_n}{2\omega\varepsilon_n}\right)L\cos\theta_n\right\}$$

$$B_n = 1 + \frac{1}{\sqrt{\varepsilon_{r_n}}}\tan h\left\{j\frac{2\pi}{\lambda n}\left(1 - \frac{j\sigma_n}{2\omega\varepsilon_n}\right)L\cos\theta_n\right\}$$

Where

N=1, 2, 3, …………..

III. Effective Dielectric Constant

In Order to derive the equivalent dielectric constant, the distribution of chemical constitutions having permittivity ε_s embedded in back ground sample of permittivity ε_0 (air)[10], will be considered.

Thus

$$\varepsilon_{eff} = \frac{\varepsilon_0(1 + 2n_0 v(\varepsilon_s - \varepsilon_0))/\{(\varepsilon_s + 2\varepsilon_0)\}}{\{1 - vn_0(\varepsilon_s - \varepsilon_0)/\varepsilon_s + 2\varepsilon_0\}} \quad (18)$$

The equation (6.18) can be modified to

$$\varepsilon_{eff} = \frac{\varepsilon_0(1 + 2v_t y)}{(1 - v_t y)} \quad (19)$$

Where

$$y = \frac{(\varepsilon_s - \varepsilon_0)}{(\varepsilon_s + 2\varepsilon_0)}$$

v_t = total volume of n_0 Chemical constitutes in unit volume of sample the total volume of the number of chemical constitute in unit volume of sample is related to the visibility as [8]

$$v_t = \frac{9.43 \times 10^{-9}}{v^{r'}}$$

Where v is v-volume of each sample and r' is constant having value 1.07.

The transmission coefficient for sparsely distributed chemical constitute can be obtained by combined by combining equations (5) and (19) as;

$$T_1 = \frac{\left[2\sqrt{\varepsilon_{r_{eff}}}\right]}{(\sqrt{\varepsilon_{r_{eff}}} + 1)^2}\exp - j\frac{2\pi}{\lambda_1}\left(1 - j\frac{\sigma_1}{2\omega\varepsilon_{r_{eff}}}\right)$$

Where

$$\varepsilon_{r_{eff}} = \frac{\varepsilon_0(1 + 2v_t y_1)}{(1 - v_t y_1)} = m_1^2$$

Therefore,

$$T_1 = \left[\frac{2m_1}{(m_1 + 1)^2}\right]\exp\left[-j\frac{2\pi}{\lambda_1}\left(1 - j\frac{\sigma_1}{2\omega m_1^2}\right)L\right] \quad (20)$$

Similarly

$$T_2 = \left[\frac{2m_2}{(m_1 + 1)^2}\right]\exp\left[-j\frac{2\pi}{\lambda_2}\left(1 - j\frac{\sigma_2}{2\omega m_2^2}\right)L\right] \quad (21)$$

$$T_3 = \left[\frac{2m_3}{(m_3 + 1)^2}\right]\exp\left[-j\frac{2\pi}{\lambda_3}\left(1 - j\frac{\sigma_3}{2\omega m_3^2}\right)L\right] \quad (22)$$

$$T_n = \left[\frac{2m_n}{(m_n + 1)^2}\right]\exp\left[-j\frac{2\pi}{\lambda_n}\left(1 - j\frac{\sigma_n}{2\omega m_n^2}\right)L\right] \quad (23)$$

Similarly the, reflection coefficient is given by

$$R_1 = \frac{B_1 - A_1}{B_1 + A_1}$$

Where

$$A_1 = 1 + \frac{1}{m_1}\tanh\left\{j\frac{2\pi}{\lambda_1}\left(1 - j\frac{\sigma_1}{2\omega m_1^2}\right)L\right\} \quad (24)$$

Where

$$B_1 = 1 + m_1\tanh\left\{j\frac{2\pi}{\lambda_1}\left(1 - j\frac{\sigma_1}{2\omega m_1^2}\right)L\right\} \quad (25)$$

$$R_2 = \frac{B_2 - A_2}{B_2 + A_2}$$

$$R_n = \frac{B_n - A_n}{B_n + A_n}$$

$$A_n = 1 + \frac{1}{m_n}\tanh\left\{j\frac{2\pi}{\lambda_n}\left(1 - j\frac{\sigma_n}{2\omega m_n^2}\right)L\right\}$$

$$B_n = 1 + m_n\tanh\left\{j\frac{2\pi}{\lambda_n}\left(1 - j\frac{\sigma_n}{2\omega m_n^2}\right)L\right\}$$

IV. Power Calculation

In general total power dissipated (P_{abs}) within these sections can be calculated by utilizing the concept of energy balance. For general case the absorbed power can be written as:

$$P_{abs} = P_{inc}(1 - |R|^2 - |T|^2)$$

It may be mentioned that while dealing with transmission in the sample we have taken the sample separately in the system and the value of R and T are calculated taking the same input in each case. It is therefore, logical that to get the effective value of R and T, 3E has to be considered as the input to the system. Therefore,

$$E_{ref} = \left(\frac{R}{3}\right) \times E_{in}$$

$$E_{trans} = \left(\frac{T}{3}\right) \times E_{in}$$

Therefore, power absorbed

$$P_{abs} = P_{inc}(1 - |R|^2 - |T|^2)$$

V. Numerical Computation

The values of transmission coefficient (T), reflection coefficient (R) and absorption loss were calculated using equations (5), (6), (7), (9), (10), (20), (21), (22), (23) (24), (25) for different values of frequencies, angle of incidence, and visibility. The typical values of permittivity were

$\varepsilon_{r_1} = (3.776 - j0.20), \varepsilon_{r_2} = (4.021 - j0.214),$

$\varepsilon_{r_3} = (4.495 - j0.255),\ \mu_1 = \mu_2 = \mu_3 = 1, and$

$\sigma_1 = 2\times10^{-5}\ mho/mt,\ \sigma_1 = 2\times10^{-4}\ mho/mt$

for ceramic Material. The data obtained are shown is figure 2 to figure 8.

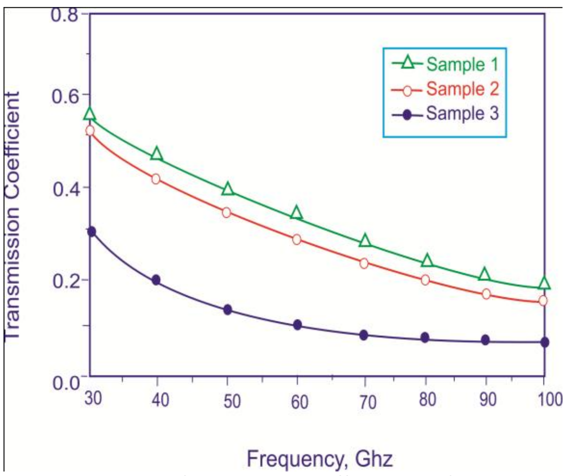

Fig. 2. Variation of transmission coefficient with frequencies

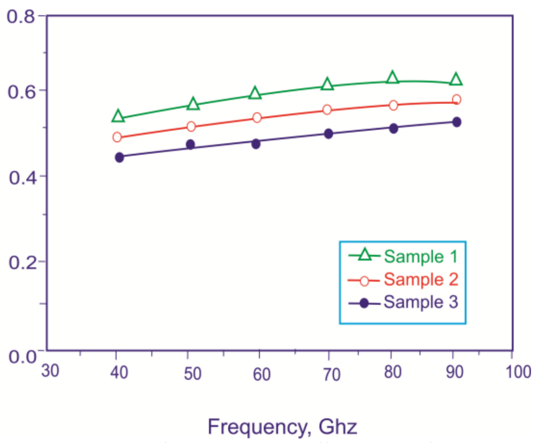

Fig. 3. Variation of transmission coefficient with frequencies

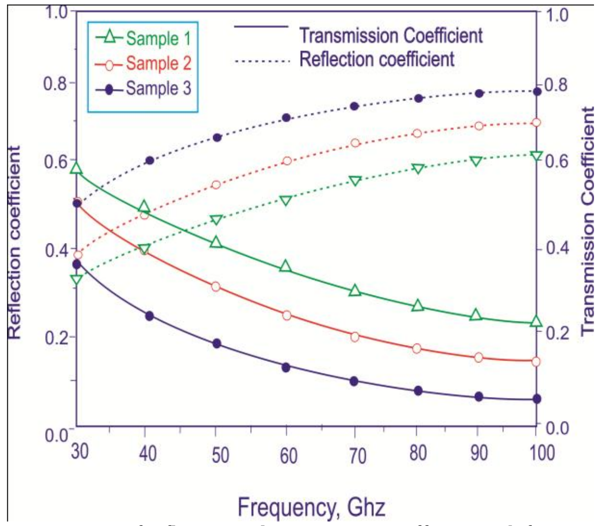

Fig. 4. Variation of reflection and transmission coefficient with frequencies for different sample

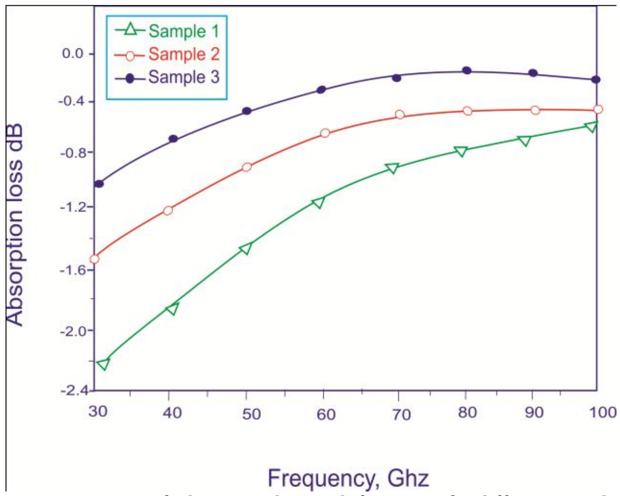

Fig. 5. Variation of Absorption loss with frequency for different sample

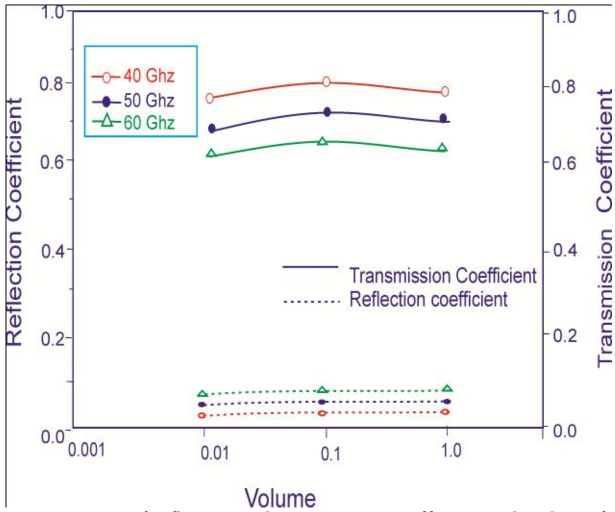

Fig. 6. Variation of reflection and transmission coefficient with volume for different frequencies

VI. Result and Discussion

Here the reflection and transmission coefficient for different sample have been calculated separately and then for overall System. The figures (2), (3), (4) reveal that with increasing frequency reflection coefficient increases whereas the transmission coefficient decreases. Further the loss due to absorption is found to increase with increasing frequency (Figure 5). The entire phenomenon can be explained as follows:

For zero volume the sample is almost completely packed with chemical particles. Any lossy dielectric medium will have a permittivity.

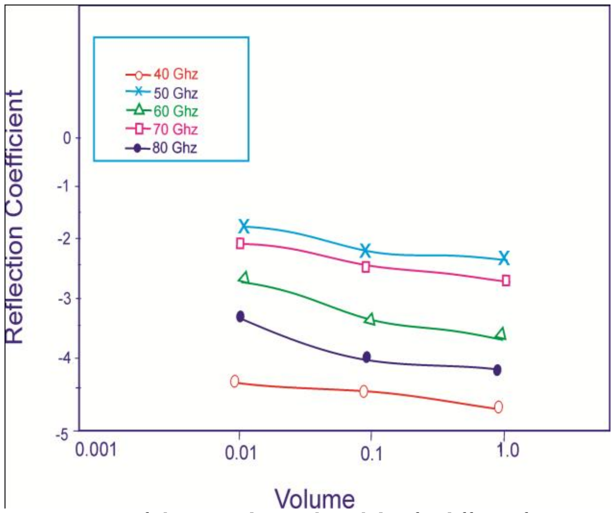

Fig. 7. Variation of absorption loss with visibility for different frequencies

The imaginary part of which is a function of conductivity and frequency. It may be mentioned that there are two types of loss mechanism which attenuate the wave in addition to reflection loss. First, the conductivity of the dielectric contributes the loss of energy in the form of heat. Secondly the dipoles created due to the polarization process experience certain amount of friction (damping) force when they flip back and forth in alternating electromagnetic fields. Consequently, these dipoles extract energy from the impressed field which is dissipated in the form of heat. Since the losses due to dielectric conductivity and polarization damping force are in the form of dissipated heat it is logical to represent the two losses in terms of conductivity. The effective conductivity:

$$\sigma_{eff} = \sigma + \omega\varepsilon''$$

dissipation factor

$$\tan\delta = \frac{\sigma_{eff}}{\omega\varepsilon'} = \frac{\sigma + \omega\varepsilon''}{\omega\varepsilon'}$$

It is clear that increasing frequency enhances the effective conductivity and loss tangent of the medium. These in turn, raise the effective absorption loss along with reflection in the system. This justifies the increase in absorption loss with increasing frequency. It may therefore, be concluded that it is the polarization damping force that predominantly controls the loss in the medium, when frequency of the propagating signal is increased. The reflection coefficient decreases with increasing angle of incidence, it attain minimum value near 75 of angle of incidence and thereafter rises. There are a clear Brewster's phenomena around 75^0 of angle of incidence. Similarly, transmission coefficient also corroborates the Brewster's Phenomena as given in figure 8. The absorption loss also decreases with increasing angle of incidence and minimum value is near 750 figure 9. This is due to increasing frequency which raises significantly the effective conductivity and dissipation factor.

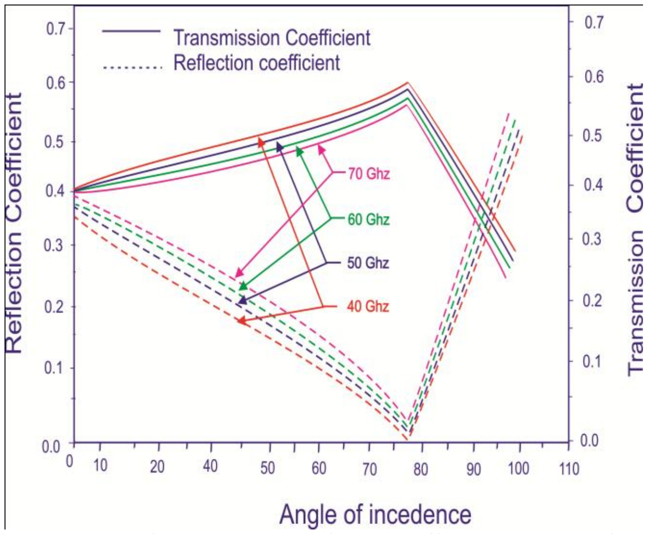

Fig. 8. Variation of transmission and reflection coefficients with angle of incidence for different frequencies (oblique incidence)

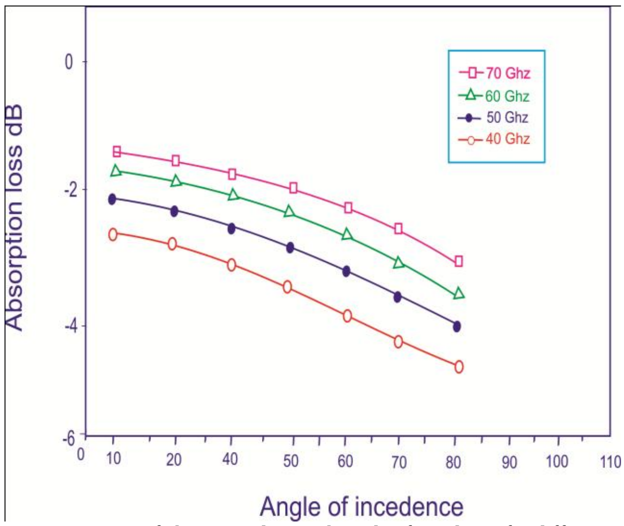

Fig. 9. Variation of absorption loss with angle of incidence for different frequencies

The reflection coefficient increases with increasing frequency whereas, transmission coefficient decreases with increasing frequency figure 3. This is in accordance with the fact that sparsely distributed particles can be taken embedded in the sample will be between the dust particles. The Variation of reflection and transmission coefficients is also shown in figure 7. This is due to the fact that at low visibilities particle concentration is very high which renders the effective permittivity of the dusty medium nearer to dust particle permittivity. This increase the loss of offering higher mismatch between air and dusty medium and hence higher reflection and low transmission. The increased number of particles at low visibility inherently enhances the dielectric loss. Figure 7 shows that loss in dusty medium increases with increasing frequency and decreasing visibility. Increasing frequency and decreasing visibility will raise the overall loss in the propagating field in sand and dust storms.

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