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High Frequency Measurements of Dielectric Behavior of Ceramic Materials Using free Space Method

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Abstract – The dielectric properties measurements of some dielectric materials, used in microwave and millimeter wave technology, are performed in F band (90-140 GHz) by using free space technique. A system, which consist a Performance Network Analyzer, two pyramidal horn antennas, a quasi-optical bench and an in house developed code TTDS are used in measurements. The measurement results are also verified by the simulation results obtained by CST-Microwave Studio

Keywords: F Band, Dielectric Behavior, Ceramics

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1. INTRODUCTION

The measurement of dielectric properties is related to the response of a material for the storage and loss of electromagnetic energy which further define the various physical and chemical properties of the material. The dielectric behavior is defined as the capability of a material to be polarized under the influence of the electric field. The dielectric behavior of a material can be defined in terms of the relative permittivity and loss factor. The relative permittivity can be expressed by the following equation [1-3]:

$$K = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = \varepsilon_r^{'} - j\varepsilon_r^{''}$$

Relative permittivity (εr), also known as a material's dielectric constant (K), depicts the interaction of a material with Relative permittivity (ε_r), also known as a material's dielectric constant (*K*), depicts the interaction of a material with the electric field. The dielectric constant is the ratio of the absolute permittivity (ε)to the free space permittivity (ε_0), which is also known as the relative permittivity. The real part of the relative permittivity ($\varepsilon_r^{'}$) represents the stored electromagnetic energy in a material due to influence of the applied external electric field. The imaginary part of permittivity ($\varepsilon_r^{''}$), also known as the loss factor, quantifiesthe loss of the electromagnetic energy by the material under the influence of the external electric field [1-3].

Free space technique (FST) is a well-known method to determine the dielectric behaviour because it can be used up to the millimeter wave band [4,5]. In other conventional methods, the operational freedom of the high frequency measurements is limited to thecomponent dimensions [1] but not critical in case of free space method. InFST,the measurements are performed completely non-destructive and contact-less (as shown in Fig. 1) and also the measurements can be carried out in strong electric and magnetic fields [4, 5].

The materials such as Alumina (96% Al_2O_3) and Teflon exhibit numerous high frequency applicationsin microwave components, devices and systems [6-9]. Alumina disk are used widely in the microwave vacuum tubes as RF window material due its good dielectric and thermo-mechanical properties [8]. The high frequency measurements of dielectric behavior of Alumina and Teflon are carried out to updatethe data sheet more accurately and also to verify the free space measurement technique. The Vector Network Analyzer (VNA) of the frequency range from 110 GHz to 170 GHz is used as the high frequency source in the measurement [9]. The loss tangent and dielectric permittivity are estimated directly using the data of reflection and transmission of high frequency wavedirectly received from the VNA. An indigenously developed (TTDS)is used for the estimation of the dielectric behavior of Alumina and Teflon. The computer program is based on the theory described in Refs [10] and discussed in next section in detail. The measured results of dielectric behavior of Alumina and Teflon are also validated by the CST simulations. Both the results shows good similarity and discussed in detail in section IV.

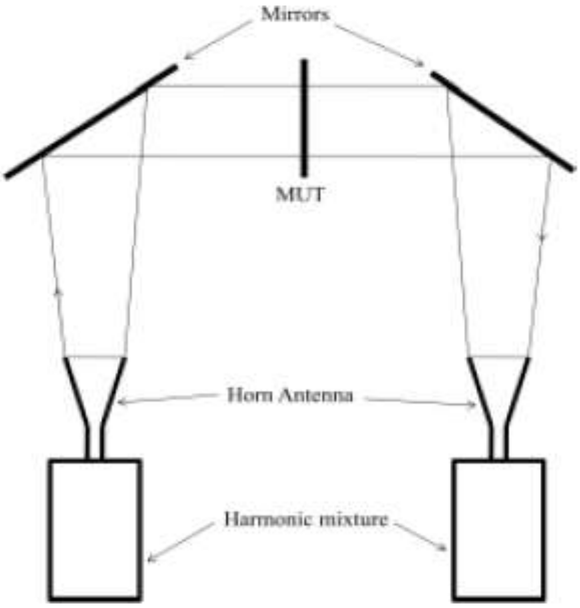


Fig. 1: Schematic view of free space method.

2. BASIC THEORY

The experimental technique used here is based on a high performance machine network analyzer. The network analyzer measures the high frequency response by the material under consideration in terms of reflection and transmission. Basically, the high frequency signal is transmitted through a horn antenna directed towards the solid sample and reflected signal received back by another horn antenna. Both the horn antenna are connected with the network analyzer and works as the transmitter and receiver. The relation of S-parameters with reflection and transmission coefficient can be defined as [8,10]:

$$S_{21} = \frac{(1-\tau^2)z}{(1-\tau^2 z^2)} \qquad (1)$$

$$S_{11} = \frac{(1-z^2)\tau}{(1-\tau^2 z^2)} \qquad (2)$$

Where τ and z are used for the reflection and transmission coefficient. For the easy calculation, three parameters can be defined as:

$$V_1 = S_{21} + S_{11} \qquad (3)$$

$$V_2 = S_{21} - S_{11} \qquad (4)$$

$$x = \frac{1-V_1 V_2}{V_1 - V_2} \qquad (5)$$

The reflection and transmission coefficient are defined as:

$$\tau = x \pm \sqrt{x^2 - 1} \qquad (6)$$

$$z = \frac{V_1 - \tau}{1 - V_1 \tau} \qquad (7)$$

Further complex propagation constant:

$$\gamma = \alpha + i\beta \qquad (8)$$

Here, the real part is attenuation constant.

$$\alpha = \frac{1}{d} \log \frac{1}{|z|} \qquad (9)$$

Where *d* is the sample size. The imaginary part is phase constant and given as:

$$\beta = -\frac{(2\pi\delta + \Phi)}{d} \qquad (10)$$

where, δ and ϕ are the phase of reflected and transmitted signals, respectively. The attenuation and phase constant are given as:

$$\varepsilon' = \frac{(\beta^2 - \alpha^2)}{k_0^2} \qquad (11)$$

$$\tan\delta = \frac{2\alpha\beta}{(\beta^2 - \alpha^2)} \qquad (12)$$

The theory discussed above is used in the calculation of dielectric properties by using the S matrix data obtained experimentally.

3. METHODOLOGY

A. Measurement Setup and equipment

The free-space measurement technique consists of: (1) a VNA, (2) a sample holder, (3) quasi optical test bench consisting two mirrors and (4) two horn antennas. In this case, an Agilent Performance Network Analyzer (PNA) ranging from 110 GHz to 170 GHz is used. Two horn antennas (WR08) are used as the transmitter and receiver and the ceramic sample will be placed in between them as the material under test (MUT). The dimensions of horn antenna are 39.65 mm x 19.68 mm x 14.96 mm with the frequency range between 90 GHz to 140 GHz and VSWR is less or equal to 1.25. The Network Analyzer provides S parameters (S11 and S21) which further used in the in-house developed code TTDS for the calculation of permittivity ε' (or dielectric constant) and the loss factor of materials.

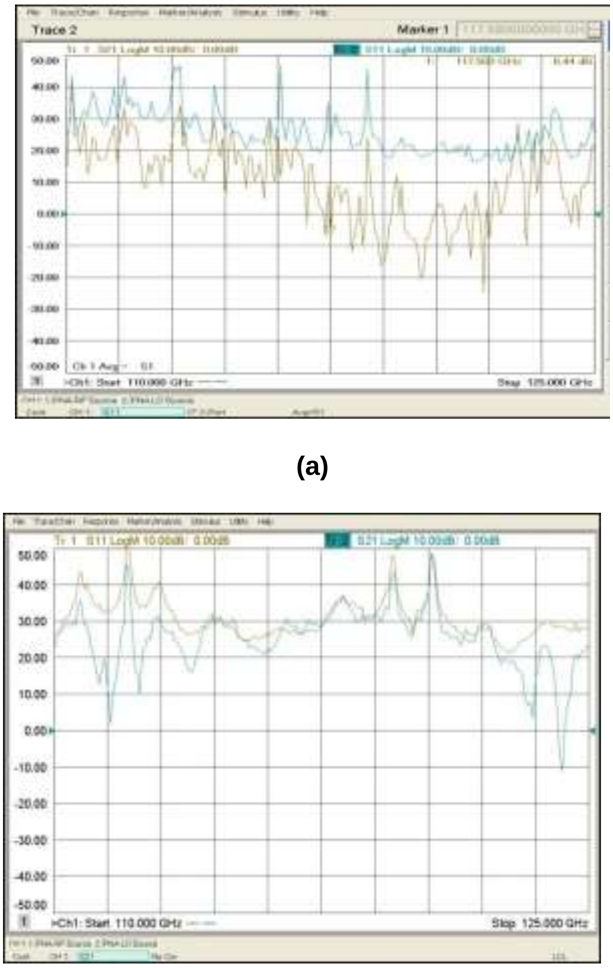
Results were displayed as a function of frequency with 1 to 2% accuracy (typical). Depending on the Agilent network analyzer and harmonic mixture used, test frequencies can also be extended. Fig. 3 shows the complete measurement set-up consisting a base unit of VNA (200 MHz-20 GHz), the harmonic mixtures (for the frequency band 110-170 GHz), diamond polished quasi-optical mirrors (minimum scattering), two WR08 horn antenna, and the material under test (MUT). The S matrix results with respect to frequency are displayed directly on the VNA screen.

B. Calibration

Measurement errors are happened most probably due to the mismatching of waveguide components, source phase noise, sampler noise and instrument noises. These undesired errors must be removed for the accurate measurements. Due to the high frequency testing of the dielectric samples, the need of perfect calibration becomes more essential and thus two port calibration is done before the measurements. Two-port calibration can be done by different calibration techniques such as the through-reflect-match (TRM), the line-reflect-line (LRL) and the through-reflect-line (TRL). The LRL calibration technique is used as it shows maximum calibration quality. After the calibration, the measurements on MOT are performed and the dielectric properties can be determined by the post processing of measured S matrix by using the program TTDS.

4. RESULTS AND DISCUSSION

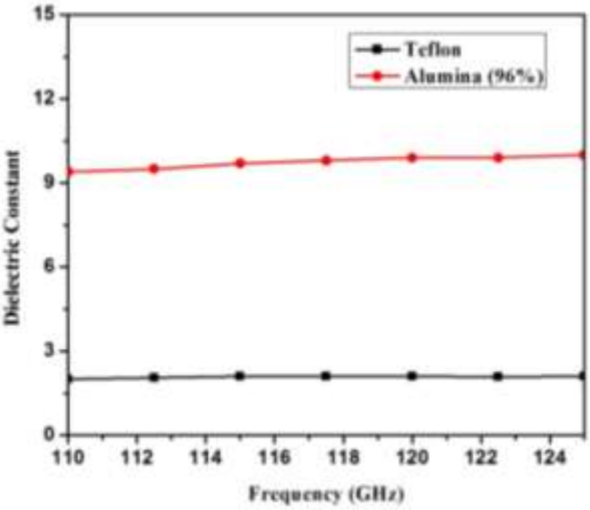
The measurements are performed for the dielectric materials Teflon and Alumina in the frequency range of 110 GHz to 125 GHz (center frequency of WR08 horn antenna). Fig. 2 shows the results of measured S parameters. Using the S parameters data, the relative permittivity and loss tangent are post processed for both the materials. Fig. 3 shows the dielectric constant and loss tangent with respect to the frequency. The simulation tool CST is used to verify the measured data of dielectric behavior of the considered materials. A model of the free space measurement set-up is made in CST and shown in Fig. 4. The RF is excited through the port define on the horn antenna waveguide (shown in red color in Fig. 4). The dielectric material is located just between both the horn antennas. The dielectric properties assigned to the material in the simulations are taken from the measured results (Fig. 3). Further the S parameter results obtained from CST simulations are compared with the measured results and shown in Table 1. The results show good similarities and verify the measured results of dielectric properties of considered materials.



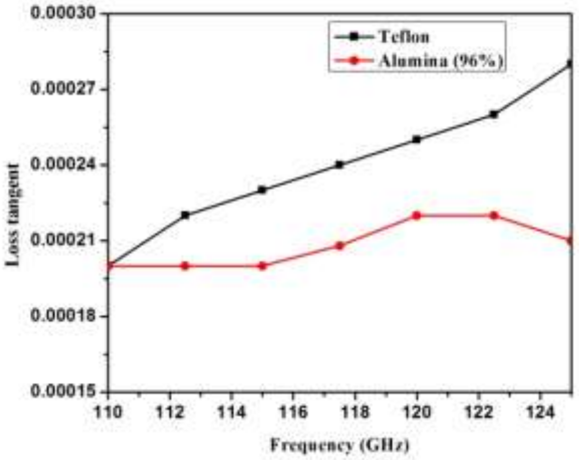
(a)

(b)

Fig. 2: S-parameters for (a) Teflon sample (b) Alumina (96% Al2O3) sample.



(a)



(b)

Fig. 3: (a) Variation in dielectric constant with frequency (b) Variation in loss tangent with frequency.

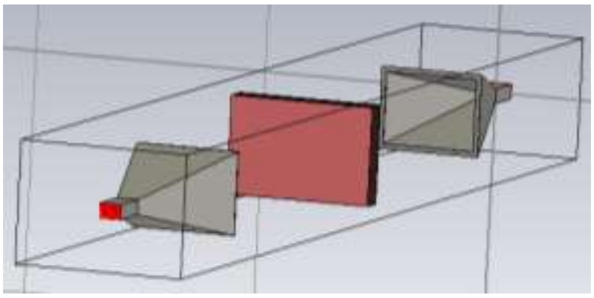


Fig. 4: Model of free space method in CST.

Table 1: Measured and simulated S matrix results for Teflon and Alumina

Material	Frequency (GHz)	Simulated S parameters (dB)		Measured S parameters (dB)	
		S11	S21	S11	S21
Teflon	110	-8	-13	-5	-15
	115	-13	-23	-10	-23
	120	-7.5	-21	-7	-24
	125	-8	-15	-5	-12
Alumina (96%)	110	-16	-20	-14	-18
	115	-10	-12	-12	-16
	120	-12	-20	-10	-15
	125	-8	-18	-15	-22

5. CONCLUSION

The dielectric behavior is measured for Alumina and Teflon in high frequency range using the free space technique. It is a non-destructive technique and provides the real time measurements. We achieved appropriate values of dielectric constant and dielectric loss. The measured values of dielectric constant and loss tangent are used further in the CST simulation to verify the measurement approach. The measured and simulated results show good similarity. The measured data for Alumina and Teflon in high frequency range certainly would be helpful in the development of components, devices and systems for high frequency applications.

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