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ANALYSIS OF METHOD TO DETERMINE DIELECTRIC CONSTANT OF SHEET MATERIALS USING APERTURE COUPLED MSA

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ABSTRACT
Apart from application in communication systems, microstrip patch antennas are also used as resonators in estimation of dielectric properties of substrate materials required for design of microwave circuits. In addition to patch antennas, the striplines, ring and cavity resonators are widely popular for evaluation of dielectric constant of microwave substrate materials in laminate or sheet form. Four aperture coupled microstrip antennas have been designed using CST Microwave studio, which resonate at 3, 5, 7 and 10 GHz frequency respectively. Firstly the resonance frequency of each antenna is first measured with the reference dielectric material and then again measured with material under test (MUT) which is a part of dielectric medium. Effective dielectric constant is estimated by computing ratio of the two frequencies. From which dielectric constant of the MUT is extracted using capacitance model of the multilayer dielectric structure. The antenna design for 5 GHz has been fabricated using dielectric substrate of ε_r = 2.94 and 0.4 mm thickness. Jig fixture assembly has also been fabricated for mounting of antenna structure and measurement set up. The method has been validated by simulation and measurements.

KEYWORDS: Aperture coupled, dielectric constant, non destructive method, patch antenna, measurement.

INTRODUCTION
The dielectric characterization of a material of low electrical conductivity is a vital phenomenon in the field of microwave and communication engineering [1]. It helps in the designing of electrical insulation in the equipments, satellite, antenna, and various radio frequency (RF) and microwave frequency devices using a dielectric material. The evaluation of dielectric constant is the main parameter for characterization of any dielectric material. The response of a dielectric material in an alternating current (ac) electric field is expressed by its complex permittivity. The general expression for the complex permittivity is given by

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (1)$$

in which the real part (ε') is the dielectric constant (relative permittivity) and the imaginary part (ε'') represents the dielectric loss in the material.

The Institute for interconnecting and Packaging Electronic Circuits (IPC) has reported the dielectric constant measurement techniques at microwave frequencies, under IPC TM 650, section 2.5. A stripline test is made for measurement of permittivity and loss tangent of metal clad substrates at microwave X-band. This method can be modified for L, S, and C bands. Another technique is a full sheet resonance (FSR) method for non destructive measurement of relative permittivity of clad laminates [2-3].

For a good design of antenna and related circuits, it is essential to know accurate value of the dielectric constant [4-5] of the material used as substrate. It is highly desirable to measure dielectric constant of such engineered dielectric medium, with relative ease method and making use of simple calculations.

MATERIALS AND METHOD

The detailed method used in present study has been described elsewhere [4]. The aperture coupled antenna was used as patch resonator which has multilayer dielectric structure. It consists of air dielectric layer between patch and ground. The air medium provides easy insertion of a sheet material. The method requires resonance frequencies f_{r1} and f_{r2} with reference material and material under test (MUT). Four aperture coupled antennas of different resonance frequency have been designed based on this structure (Fig.1).

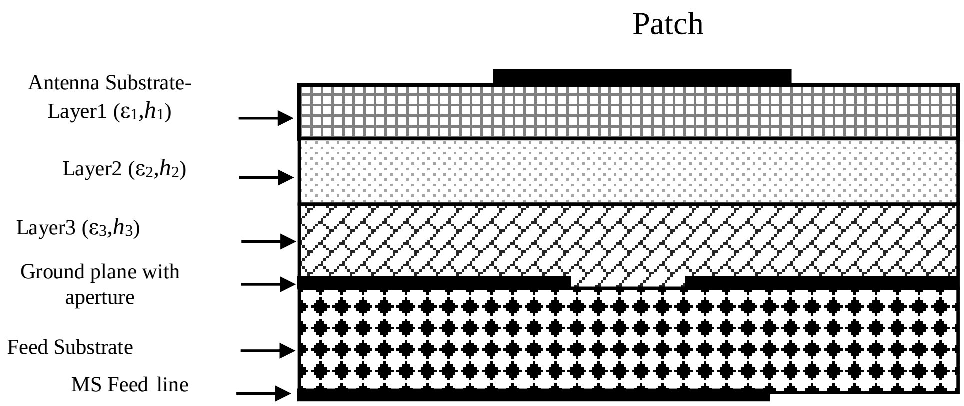

Fig.1 A Multilayer Dielectric Structure

DESIGN AND SIMULATION

The structure of proposed three layer aperture coupled patch resonator is shown in Fig.1.Four aperture coupled microstrip antennas are designed and simulated at 3, 5, 7 and 10 GHz resonance frequencies respectively using CST Microwave studio. These antennas have same structures with different dimensions because of different resonance frequencies. Therefore a common structure is discussed here. The dielectric medium consists of three layers in each patch antenna. First layer ($\varepsilon_r = \varepsilon_1$) having thickness, h_1 supports the patch material under test (MUT). Middle layer ($\varepsilon_2 = 1$) of thickness h_2 which has air as a medium lies between first and third layer. Third layer (ε_3) having thickness, h_3 is situated on the ground plane of patch antenna. Thus the three layers are specified by dielectric constants and thickness as $\varepsilon_1 = h_1; \varepsilon_2 = h_2$ and $\varepsilon_3 = h_3$ respectively [5].

Table 1 Values of Different Antenna Parameters

Notations	Parametric values (mm) at different resonance frequencies (GHz)			
	3	5	7	10
W_p	44.81	25.00	18.9	13.00
L_p	36.70	21.20	14.6	9.62
W_{sub}	144.00	82.00	58.00	43.00
L_{sub}	139.00	82.00	56.00	41.00
$X_{aperture}$	14.80	10.10	8.30	8.00
$Y_{aperture}$	1.48	1.010	0.83	0.80
L_{stub}	86.00	49.00	33.00	24.52
$\varepsilon_{rpatch} = \varepsilon_{rfeed}$	2.94	2.94	2.94	2.94
h	0.40	0.40	0.40	0.40
h_t	1.60	1.60	1.60	1.60
ε_c	1.49	1.49	1.49	1.49

Table 1 shows the dimensions of aperture coupled antennas. Each antenna is simulated at composite dielectric constant of 1.49, which contains dielectric constant of patch, air and MUT reference layer. Now MUT is changed by unknown dielectric material one by one and different values of composite dielectric constant are achieved .Thus combined return loss plots are achieved for different resonance frequencies.

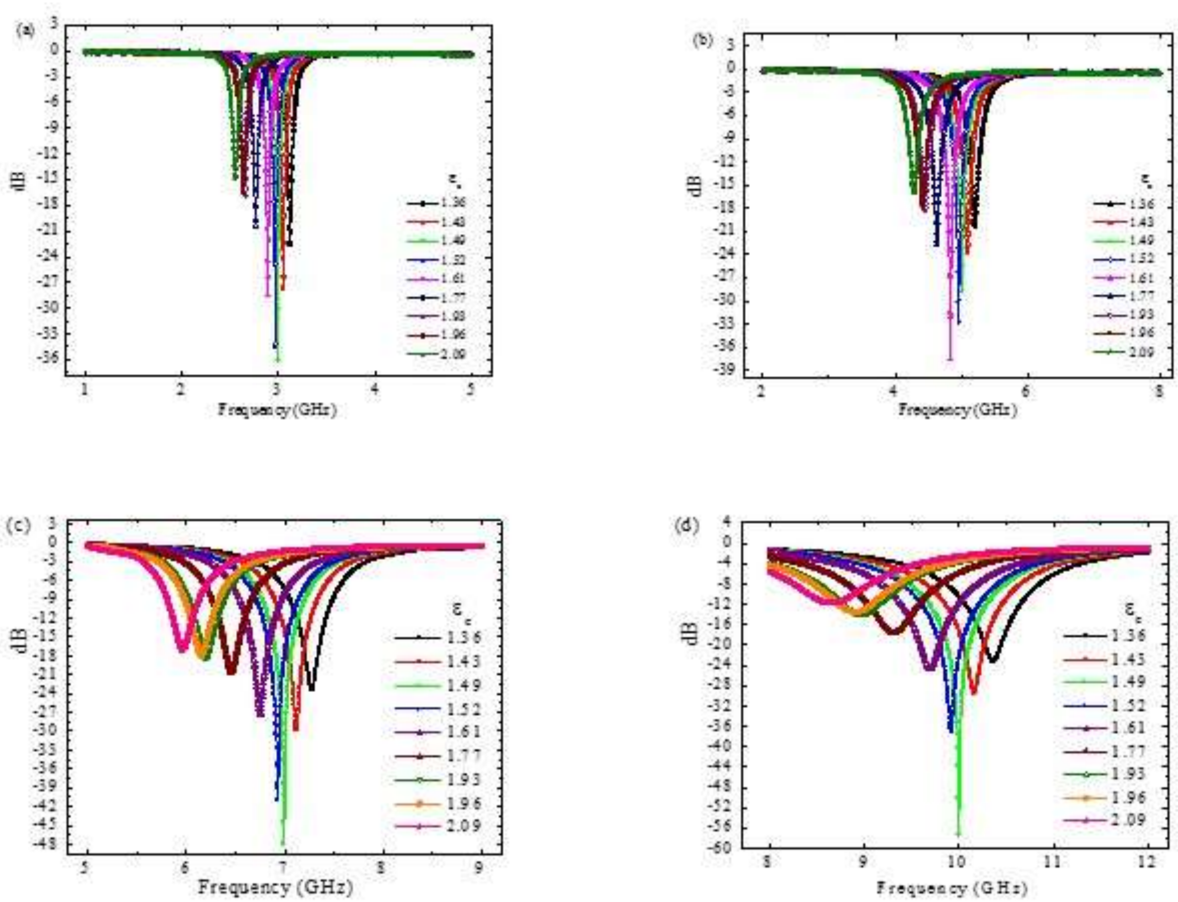

Fig. 2: Combined Return Loss Plots Of Different MUTs (a) 3 GHz (b) 5 GHz (c) 7GHz (d) 10GHz

Table 2: Simulation Results

S.NO.	MUT ε_3^*	h (mm)	calculated ε_c	Simulated values of f_{r1} (GHz) at different resonance frequencies			
				3	5	7	10
1	2.20	0.40	1.43	3.052	5.096	7.128	10.168
2	2.33	0.50	1.52	2.968	4.958	6.932	9.920
3	2.94	0.04	1.49	3.000	5.000	7.000	10.000
4	3.00	0.25	1.36	3.120	5.024	7.280	10.376
5	3.20	0.50	1.61	2.890	4.830	6.752	9.680
6	2.33	0.76	1.77	2.768	4.628	6.456	9.320
7	2.94	0.77	1.93	2.656	4.440	6.190	8.970
8	3.20	0.76	1.96	2.636	4.400	6.148	8.900
9	9.40	0.64	2.09	2.556	4.274	5.968	8.652

*Typical value of ε_3 as per manufacturer's data sheet. Simulated Results are presented in Table 2. For different MUTs each antenna is simulated at composite dielectric constant which changes corresponds to new MUT. There are nine MUTs with dielectric constant and heights. For each MUT the value of f_{r1} is achieved from the return loss plot.

Table 3 shows the calculated values of effective dielectric constant at different resonant frequencies.These values are different at different frequencies because of different antenna dimensions. Variation in ε_{ce} and simulated values of f_{r1} suggests the two groups of dielectric samples. Four references MUT's are selected for the extraction of ε_3 .Thus the value of dielectric constant is extracted for each sample. Table 4 presents the extracted values of ε_3 at different resonant frequency.

Table 3 Effective Dielectric Constant

S.No.	MUT	h (mm)	ε_{ce} at different frequencies (GHz)			
			3	5	7	10
1	2.20	0.40	1.39	1.37	1.36	1.35
2	2.33	0.50	1.48	1.45	1.44	1.42
3	2.33	0.76	1.71	1.67	1.65	1.63
4	2.94	0.04	1.45	1.43	1.41	1.40
5	2.94	0.77	1.85	1.81	1.79	1.76
6	3.00	0.25	1.33	1.32	1.31	1.30
7	3.20	0.50	1.56	1.53	1.52	1.50
8	3.20	0.76	1.88	1.84	1.82	1.79
9	9.40	0.64	2.00	1.95	1.92	1.89

Table 4 Extracted ε_3 for Different MUTs

S.No.	MUT	h (mm)	Extracted value of ε_3 at different frequencies (GHz)			
			3	5	7	10
1	2.20	0.40	2.24	2.21	2.14	2.25
2	2.33	0.50	2.31	2.31	2.33	2.29
3	2.94	0.04	2.86	2.94	2.97	2.90
4	3.00	0.25	3.04	3.01	2.88	3.14
5	3.20	0.50	3.18	3.13	3.22	3.17
6	2.33	0.76	2.32	2.29	2.37	2.33
7	2.94	0.77	1.32	2.97	2.96	2.94
8	3.20	0.76	1.53	3.25	3.18	3.19
9	9.40	0.64	1.95	9.37	9.60	9.40

Table 5 Fabrication Result

S.No.	ε_3	h_3 (mm)	f_{r_mea} (GHz)	ε_3	%error
1	2.2	0.4	5.080	2.17	1.28
2	2.33	0.5	4.940	2.29	1.39
3	3.0	0.25	5.180	3.12	-4.24
4	2.94	0.4	4.664	2.91	0.92
5	2.94	0.77	4.982	2.90	1.19
6	3.2	0.76	4.616	3.20	-0.28
7	9.8	0.62	4.526	9.69	1.02

FABRICATION AND MEASUREMENTS

The antenna design for 5 GHz has been fabricated. A wooden jig assembly has also been fabricated. The purpose of this jig is to hold the entire aperture coupled patch resonator. The height of patch substrate over the feed substrate is maintained by means of a specially machined rectangular strip of required thickness and length which is fixed by screw over the edge of feed substrate where SMA connector is mounted. Care must be taken that the mechanical force of the cable does not disturb the set up. Now only one side is open so sheet material can be inserted. Jig assembly is designed in such a way that the air gap between feed and patch substrate maintains accurately.

Measurement of seven samples has been performed using Agilent Technologies PNA N5224A (10MHz-43.5GHz).The set up is shown in figure 3. Measured results are shown in Table 5. Measured values have been compared with the original values and a good intimacy is found between these values

RESULTS AND DISCUSSION

Designing an antenna with multilayer structure is quite challenging task, therefore aperture coupled feeding technique is used. Because there are certain problems with probe feeding and direct inset feeding [8]. Four antennas have been designed and for each antenna the extracted values of different MUT's are achieved. From the simulation results, it is found that the accuracy of this method for determination of dielectric constant of MUT lies within $\pm$1.9%, $\pm$1.42%, $\pm$ 2.84% and $\pm$3.3% of the values given by manufacture at four different resonance frequencies mentioned above. Measurement of resonant frequency is performed using Agilent Technologies PNA Network Analyzer N5224A. Dielectric constant of seven different samples has been measured. The measured results were found to be within $\pm$1.46%, except for one which shows -4.24% of the dielectric constant's value given by manufacture.

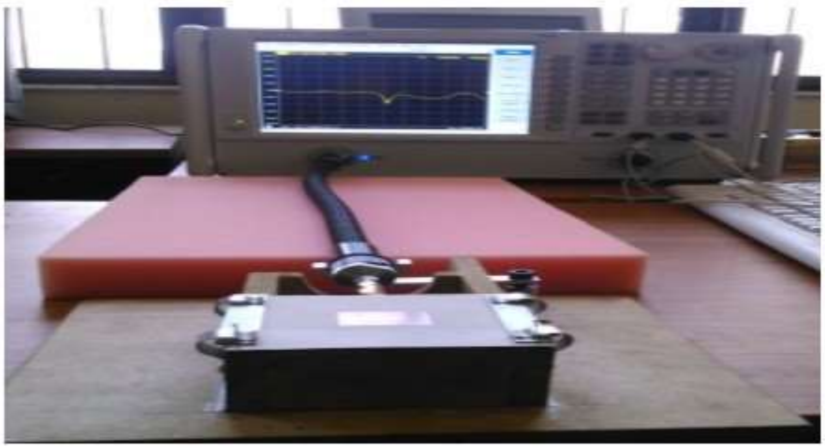

Fig.3 Measurement Set Up

CONCLUSION

Simulation results of antennas are obtained and compared. The method has been validated by simulation and measurements. Based on the structure of aperture-coupled antenna as resonator and the specially designed jig-fixture assembly, standard equipment can be fabricated. Such equipment should be very useful as it provides simple and quick means of measuring substrate dielectric constant. Due to uneven surface of substrate material, some errors have been associated with the measured results. The air medium and height of the MUT play significant role in determining the value of dielectric constant. If the thickness of MUT is greater than air gap between the substrates, different jig assembly will be required for thicker substrates. So to evaluate the dielectric constant of such sheet materials we have to design another aperture coupled antenna, considering the thickness of sheet material. Based on this method a better equipment can be designed to achieve better accuracy. As four aperture coupled antenna have been designed at different frequencies, the study of behaviour of dielectric constant on frequency is possible. Estimation of loss tangent (tanδ) may be added to complete characterization of dielectric constant.

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