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Dielectric SUPERSTRATE Thickness VARIATIONON the Characteristics of Circular Patch Antenna

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Abstract: This paper focused about the coaxial probe fed circular patch of microstrip antenna characteristics have been studied with and without dielectric superstrate. The dielectric constant of the substrate and Superstrate material is used same for designing of circular microstrip patch antenna. The antenna designed frequency is 2.4GHz(ISM band) using cavity model. In this paper experimentally investigated the effect of single microstrip patch antenna(without Superstrate) and varying various thicknesses of Superstrate (radome) and same dielectric constant of the substrate on the patch antenna studied on the parameters such as bandwidth, beam-width, gain, resonant frequency, input impedance, return-loss and VSWR etc. Measured results shows when placing the superstrates material thickness above the substrate the antenna parameter will be changed and antenna resonant frequency will be shifted lower side, while other parameters have slight variation in their values. In particular, the resonant frequency increases with the dielectric constant of the Superstrates thickness. In addition, it has also been observed that return loss and VSWR increases, however bandwidth and gain decreases with the dielectric constant of the superstrates. Impedance characteristics are that both input impedance and the reactance are increased as superstrate become thick and its $\in_r$ increases.

KEYWORDS: Circular patch microstrip antenna, dielectric superstrate, VSWR, Gain, Beam- width, Bandwidth, Resonant frequency etc.

1. INTRODUCTION:

Circularmicrostrip antenna consists of radiating patch on the one side of the substrate having the ground plane on other side. The major advantages are light weight, low profile, conformable to planar and non-planar surfaces and easy to fabricate. The antenna is suitable for high speed vehicles, aircraft's, space crafts and missiles because of low profile and conformal nature of characteristics [2].

Microstrip antenna has inherent limitation of narrow bandwidth. So, Superstrate (radome) is used on a microstrip antenna as a cover to protect the antenna from external environmental conditions like temperature, pressure etc. When microstrip antenna covered with a dielectric Superstrate (radome) its properties like resonance frequency, gain, bandwidth and beam width are changed which may seriously degrading the antenna performance[1-4]. By choosing the thickness of the substrate superstrate layer, a very large gain can be achieved [5-9]. Coaxial probe fed circular microstrip antenna characteristics have been investigated using High Frequency Structure Simulator (HFSS) software and measured experimentally. When microstrip antennas are covered with protective dielectric Superstrates thickness are subjected to icing conditions, or come into contact with plasma, then the resonant frequency is altered and shifted to lower sides, causing detuning which may seriously degrading the antenna performance. In this paper experimentally investigated the effect of single microstrip patch antenna (without Superstrate) and varying various thicknesses of Superstrate (radome) on the patch antenna with same dielectric constant andstudied on the parameters such as bandwidth, beam-width, gain, resonant frequency, input impedance, return-loss and VSWR etc.

2. ANTENNA SPECIFICATION AND SELECTION OF SUBSTRATE MATERIALS:

The geometry of a probe fed circular patch microstrip antenna is shown in Fig1. The antenna under investigation is a patch with diameter (D) = 47.1mm which is fabricated on Arlondiclad 880 dielectric substrate, whose dielectric constant ($\in_{r1}$) is 2.2, loss tangent ($\tan\delta$) is 0.0009, thickness (h_1) is 1.6mm and substrate dimension is 100mm×100mm. The dielectric superstrate is Arlon diclad 880 dielectric substrate, whose dielectric constant ($\in_{r2}$) is 2.2, loss tangent ($\tan\delta$) is 0.0009, thickness (h_2) is 1.6mm and substrate dimension is 100mm×100mm. The antenna center frequency is 2.4GHz(ISM band) and corresponding feed location is X=0 and Y=5.5mm is shown in Figure1 and Figure 2 .Suitable dielectric substrate of appropriate thickness and loss tangent is chosen for designing the circular patch microstrip antenna. A thicker substrate is mechanically strong with improved impedance bandwidth and gain [10]. However it also increases weight and surface wave losses. The dielectric constant ($\in_r$) will play an important role similar to that of the thickness of the substrate. A low value of $\in_r$ for the substrate will be increase the fringing field of the patch and thus the radiated power. A high loss tangent ($\tan\delta$) increases the dielectric loss and therefore reduce the antenna performance.

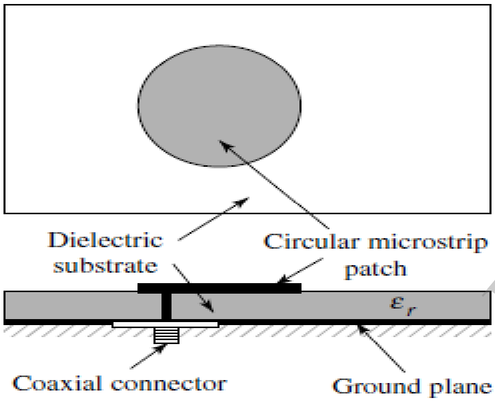


Figure1: The structure of circular patch antenna

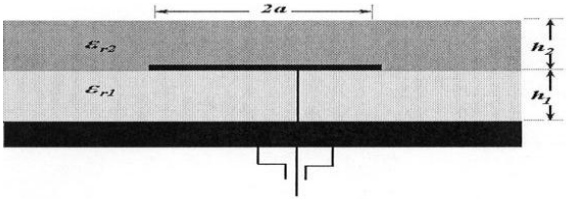


Figure2:Microstrip antenna with superstrate geometry

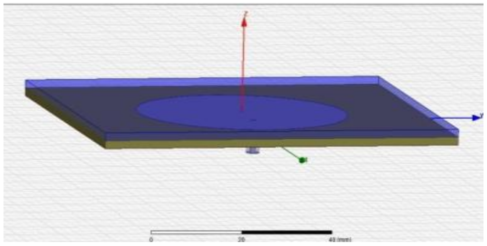


Figure3: Circular patch antenna with Superstrate thickness

3. DESIGN OF CIRCULA PATCH ANTENNA:

In the most basic form, a circularmicrostrip patch antenna consists of a radiating patch on one side of the dielectric substrate, which has ground plane on the other side and ground plane and radiating patch separated by dielectric substrate. The resonant length of the antenna can determine its resonant frequency. In fact the patch is electrically a bit larger than its physical dimension. The patch antenna can be designed at 2.4GHz and fabricated on Arlondiclad substrate, whose dielectric constant($\in_{r1}$) is 2.2.The substrate and Superstrate material is same whose dimensions are 100×100mm of the patch antenna.The coaxial probe feeding is given to the substrate at particular location of the point where input impedance is approximately 50 Ω. The main advantage of the coaxial probe feeding technique is that the feed can be placed at any desired location inside the patch in order to match with its input impedance. This feed method is easy to fabricate and also has low spurious radiation.

4. THEORITICAL FORMULATION:

The circular microstrip antenna can be analyzed using cavity model in cylindrical coordinates [18]. The cavity is composed of two perfect electric conductors at top and bottom to represent the patch and the ground plane.

4.1 Electric and magnetic fields:

To find the fields with in the cavity, we use the vector potential approach. For TM mode analysis need to calculate magnetic vector potential A_z . The cylindrical coordinates the homogeneous wave equation of[15]

$$\nabla^2 A_z(\varphi,\emptyset,z) + K^2 A_z(\varphi,\emptyset,z) = 0 \quad (1)$$

The electric and magnetic fields related to the vector potential A_z[15]

$$E_\rho = -j\frac{1}{\omega\mu\epsilon}\frac{\partial^2 A_z}{\partial\rho\partial z}, H_\rho = \frac{1}{\mu}\frac{1}{\rho}\frac{\partial A_z}{\partial\emptyset},$$

$$E_\emptyset = -j\frac{1}{\omega\mu\epsilon}\frac{1}{\rho}\frac{\partial^2 A_z}{\partial\emptyset\partial z} H_\emptyset = -\frac{1}{\mu}\frac{\partial A_z}{\partial\rho} E_z = -j\frac{1}{\omega\mu\epsilon}\left(\frac{\partial^2}{\partial z^2} + K^2\right) A_z , H_z = 0$$

(2) Subject to the boundary conditions of

$$E_\rho(0 \le \rho^1 \le a, 0 \le \emptyset^1 \le 2\pi, z^1 = 0) = 0$$

$$E_\rho(0 \le \rho^1 \le a, 0 \le \emptyset^1 \le 2\pi, z^1 = h) = 0, \quad H_\emptyset(0 \le \rho^1 \le a, 0 \le \emptyset^1 \le 2\pi, z^1 = h) = 0 \quad (3)$$

The magnetic vector potential $A_z$reduces to [15]

$$A_z = B_{mnp} J_m(k_\rho \rho^1)[A_2 cos(m\emptyset^1) + B_2 sin(m\emptyset^1)]cos(k_z z^1) \quad (4)$$

With the constraint equation of

$$(k_\rho)^2 + (k_z)^2 = k_r^2 = \omega_r^2 \mu\epsilon \qquad (5)$$

The primed cylindrical coordinates $\rho^1, \emptyset^1, z^1$ are used to represent the fields with in the cavity while $J_m(x)$ the Bessel function of the first kind of order m, and

$$k_\rho = \chi_{mn}^1 / a \qquad (6)$$

$$k_z = \frac{p\pi}{h} \qquad (7)$$

m= 0, 1, 2… (8)

n= 1, 2, 3… (9)

p= 0, 1, 2… (10)

Inχ_{mn}^1 represents the zeros of the derivative of the Bessel function$J_m(x)$, and they determine the order of the resonant frequencies. The first four values ofχ_{mn}^1, in ascending order, are

$$\chi_{11}^1 = 1.8412$$

$$\chi_{21}^1 = 3.0542 \qquad (11)$$

$$\chi_{01}^1 = 3.8318$$

$$\chi_{31}^1 = 4.2012$$

4.2. Resonant Frequencies:

Since for most typical microstrip antennas the substrate height is very small (typically h<$0.05\lambda_o$), the fields along z are essentially constant and are represented in (10) by p= 0 and in (7) by$k_z = 0$. Therefore the resonant freqencncies for the TM_{mn0}^z modes can be written using (5) as [15]

$$(f_r)_{mn0} = \frac{1}{2\pi\sqrt{\mu\epsilon}}\left(\frac{\chi_{mn}^1}{a}\right) \qquad (12)$$

Based on the values of (11), the first four modes in ascending order are TM_{110}^zwhose resonant frequency is[15]

$$(f_r)_{110} = \frac{1.8412}{2\pi a\sqrt{\mu\epsilon}} = \frac{1.8412}{2\pi a\sqrt{\epsilon_r}} \qquad (13)$$

Where $\vartheta_o$is the speed of light in free space.

The resonant frequency of (13) does not take into account fringing. As was shown for the rectangular patch. Fringing makes the patch look electrically larger. The circular patch a correction is introduced by using an effective radiusa_e[15]

$$a_e = a\left\{1 + \frac{2h}{\pi a \epsilon_r}\left[ln\left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{1/2} \qquad (14)$$

Therefore the resonant frequency of (13) for the dominant TM_{110}^Zshould be modified by using (14) and expressed as [15]

$$(f_r)_{110} = \frac{1.8412}{2\pi a\sqrt{\in_r}} \qquad (15)$$

4.3. Resonant input impedance:

The input impedance of a circular patch antenna at resonance is real and the input power is independent of the feed point position along the circumference. Taking the feed as a reference point, the radial distance $\rho = \rho_o$from the center of the patch for the dominant TM_{11} mode is [15]:

$$R_{in}(\rho^1 = \rho_o)\frac{1}{G_t}\frac{J_1^2(K\rho_O)}{J_1^2(Ka_e)} \qquad (16)$$

Since the resonant input impedance of a circular patch with coaxial probe fed is expressed as [15]:

$$R_{in}(\rho^1 = a_e) = \frac{1}{G_t}(17)$$

4.4.Fields radiated:

Applying the Equivalence principle to the circumferential wall of the cavity, the equivalent maganetic current density can be obtained and assuming a TM_{11} mode the field distribution under the patch. Since the thickness of the substrate is very small, the filamentary maganetic current becomes[15]: (18)

$$I_m = hM_a = \hat{a}_o 2hE_o J_1(Ka_e)cos\,\emptyset$$

Using equation(5), the patch antenna can be treated as a circular loop and using the radiation equation the expression is given[15]

$$E_r = 0 \qquad (19)$$

$$E_\theta = -j\frac{K_o a_e V_o e^{-jk_o r}}{2r}[cos\emptyset J_{02}^1] \qquad (20)$$

$$E_\emptyset = j\frac{K_o a_e V_o e^{-jk_o r}}{2r}[cos\theta sin\emptyset J_{02}] \qquad (21)$$

4.5 Designequations:

Based on the cavity model formulation, a design procedure is outlined which leads to practical designs of circular microstrip patch antennas for the dominantTM_{110}^Z mode. The procedure assumes that the specified information includes the dielectric constant of the substrate (ε_r), the resonant frequency (f_r) and height of the substrate h.

4.5.1 Circular patch radius and effective radius:

Since the dimension of the patch is treated a circular loop, the actual radius of the patch is given by[15]

$$a=\frac{F}{\left\{1+\frac{2h}{\pi \varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{1/2}} \qquad (22)$$

Where $F = \frac{8.791\times10^{9}}{f_r\sqrt{\varepsilon_r}}$

Equation (1) does not take into considerations the fringing effect. Since fringing makes the patch electrically larger, the effective radius of patch is used and is given by[15]

$$a_e = a\left\{1+\frac{2h}{\pi\varepsilon_r}\left[ln\left(\frac{\pi a}{2h}\right)+1.7726\right]\right\}^{1/2} \quad (23)$$

Hence, the resonant frequency for the dominant TM_{110}^{Z} is given by[15]

$$(f_r)_{110} = \frac{1.8412\, v_o}{2\pi a_e\sqrt{\varepsilon_r}} \quad (24)$$

Where vo is the velocity of light

5. DIELECTRIC SUPERSTRATE EFFECT ON CIRCULAR MICROSTRIP PATCH ANTENNA:

When circular patch microstrip antenna with the dielectric Superstrate or Radom is shown in Figure (3). The characteristics of antenna parameters change as a function of the dielectric Superstrate layer. The properties of a microstrip antenna with dielectric Superstrate layer have been studied theoretical formulation using cavity model analysis. The resonant frequency of a microstrip antenna covered with dielectric Superstrate layer can be determined when the effective dielectric constant of the structure is known. The change of the resonant frequency by placing the dielectric Superstrate thickness has been calculated using the following the expression [1].

$$\frac{\nabla f_r}{f_r} = \frac{\sqrt{\epsilon_e}-\sqrt{\epsilon_{eo}}}{\sqrt{\epsilon_e}} \qquad (25)$$

If $\epsilon_e = \epsilon_{eo} + \nabla\epsilon_e$ and $\nabla\epsilon_e \leq 0.1\ \epsilon_{eo}$, then

$$\frac{\Delta f_r}{f_r} = {}^{1}/_{2}\,\frac{{}^{\Delta\epsilon_e}/_{\epsilon e_o}}{1+{}^{1}/_{2}{}^{\Delta\epsilon_e}/_{\epsilon e_o}}$$

Where,

ϵ_e= Effective dielectric constant with dielectric superstrte

$\epsilon\ e_o$=Effective dielectric constant without dielectric superstrate

$\Delta\epsilon_e$= Change in dielectric constant due to dielectric superstrate

Δf_r =Fractional change in resonance frequency

f_r =Resonce frequency

Figure4: Fabricated Porto type circular patch with feed point location

Figure5: Structure of dielectric substrate and Superstrate materials

6. EXPERIMENTAL MEASUREMENTS:

The geometrical structure under consideration is shown in Figure1. A circular patch antenna, designed patch with diameter (D) =47.1mm was fabricated on thick dielectric substrate whose dielectric constant 2.2, loss tangent is 0.0009, thickness is 1.6mm and the dielectric superstrate is same substrate specification. The patch was fed through probe of 50Ω cable. The location of feed probe had been found theoretically and chosen as x=0, y= 5.5mm. Then the patch was covered with dielectric Superstrate thickness material such as ArlonDiclad 880 whose dielectric constant (ϵ_{r2}) is 2.2, loss tangent (tanδ) is 0.0009 and thickness (h_2) is 1.6mm. The impedance characteristics were measured by means of HP 8510B network analyzer. The radiation pattern measurements were performed in the anechoic chamber by the use of automatic antenna analyzer. The measured results were shown in Table4, Table5, Table6 and Table7.The measured far field radiation patterns and VSWR, return-loss, input impedance plots for various thickness such as 0.2mm,0.5mm,0.8mm,1.0mm, 1.3mm, 2.2mm, 2.4mm and 3.2mm is shown in Figure8 to Figure 20 and the corresponding data Tables is shown in Table4 to Table7.

6.1 RESULT OF CIRCULAR PATCH ANTENNA WITHOUT SUPERSTRATE:

In order to present the design procedure of antenna achieving impedance matching for the case, the first prototype of the antenna was designed using Arlondiclad 880 substrate resonating at 2.4GHz and corresponding the results are shown in Figure 6. The obtained results show that the value of VSWR is 1.4666, Bandwidth is 4.6GHz, the Gain is 4.8dB, half power beam-width is 108.16^0 in horizontal polarization and 105.45^0in vertical polarization, input impedance is 36.244Ω +j8.9070 and return-loss is -13.848dB.The corresponding data table is shown in Table4 and Table5.

6.2 RESULT OF CIRCULAR PATCH WITH SUPERSTRATE THICKNESS

In order to observe the effect of dielectric Superstrate thickness varying on the circular patch antenna characteristics such as bandwidth, gain, beam-width, resonant frequency, input impedance, return-loss andVSWR etc. The proposed antenna has been analyzed using various dielectric Superstrate thickness such as0.2mm,05mm, 0.8mm,1.0mm,1.3mm,1.5mm,2.2mm and 3.2mm, corresponding resonating frequency will be shifted at 2.40GHz, 2.40GHz, 2.38GHz, 2.369GHz, 2.87GHz,2.40GHz, 2.28GHz,2.31GHz and 2.21GHz. The gain is varied from 0.47GHz to 3.43GHz, the bandwidth is varied from 1.58GHz to 2.49GHz, the half power beam-width in vertical polarization is varied from 98.16^0to105.33^0, the half power beam-width in vertical polarization is varied from 74.86^0to90.20^0, the impedance is varied from 25.387Ω-j16.690Ω to 53.759Ω-j45.307, and the return-loss is varied from -8.286 dB to -12.142dB. The VSWR is varied from 1.656 to 2.253 based upon the various thickness of the dielectric Superstrates. The obtained the characteristics are shown in Figure 9 to Figure 20 and corresponding data are tabulated in Table 6 and Table 7 and also shown in Figures 7 to Figure 17.

TABLE1: Specification of dielectric substrate materials used in the design of circularpatch antenna

Dielectric constant(ε_{r1})	Loss tangent(tanδ)	Thickness (h_1),mm
2.2	0.0009	1.6

TABLE2: Specification of dielectric Superstrate material used in the design of circular patch antenna

Dielectric constant(ε_{r2})	Loss tangent(tanδ)	Thickness (h_2),mm
2.2	0.0009	1.6

TABLE 3: Calculated Diameter and Feed point location of circular patch antenna:

Type of Patch	Diameter(mm)	Feed Point(mm)
Circular patch antenna	47.1	5.5

TABLE 4: Experimental data for Gain, Bandwidth (BW)and half power beam-width (HPBW) of circular patch antenna without Superstrate:

$\in_{r1}$	f_r,GHz	BW(GHz	Gain dB	HPBW HP,(Deg)	HPBW (Deg)
2.2	2.40	0.03091	6.7	98.77	90.73

TABLE 5: Experimental data for impedance, return-loss and VSWR of circular patch antenna without Superstrate:

$\in_{r1}$	f_r(GHz)	IMPDANCE(Ω)	RL(dB)	VSWR
2.2	2.40	60.696+j15.164	-15.558	1.5654

TABLE6: Experimental measured data for gain, bandwidth (BW) and half power beam-width (HPBW)of circular patch antenna with Superstrate thickness (mm).

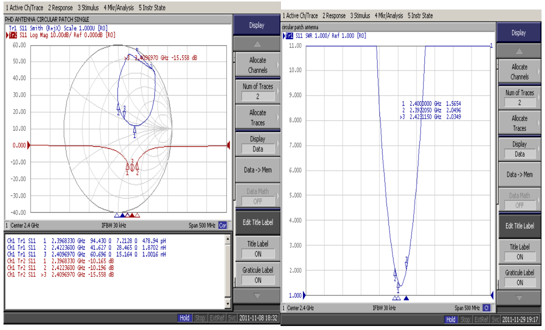
$\in_{r2}$	$\Delta f_r/f_r$ (GHz)	Gain (dB)	BW GHz)	HPBW(HP) ,Deg	HPBW(VP), Deg
0.2	2.41	3.92	0.012	84.26	77.47
0.5	2.419	4.01	0.031	85.70	73.02
0.8	2.41	3.64	0.012	84.32	76.99
1.0	2.419	5.88	0.012	88.33	75.49
1.3	2.419	5.29	0.031	90.0	76.84
1.5	2.419	5.21	0.012	90.0	76.80
2.2	2.394	2.87	0.033	89.06	74.51

2.4	2.341	3.91	0.023	92.89	75.84
3.2	2.213	3.29	0.023	92.78	79.34

TABLE7: Experimental measured data for inputimpedance(IMP), return-loss(RL) and VSWR of circular patch antenna with Superstrate thickness (mm).

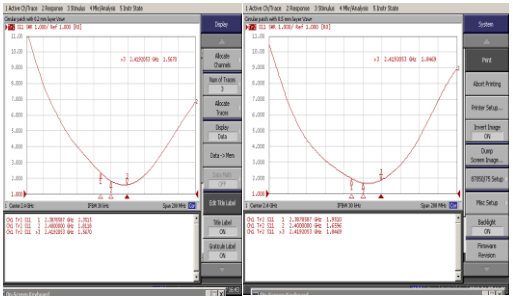
$\in_{r2}$	$\Delta f_r/f_r$(GHz)	IMP(Ω)	RL(dB)	VSWR
0.2mm	2.41	34.427 – j11.039	-12.857	1.567
0.5mm	2.419	27.784 – j7.3993	-10.423	1.846
0.8mm	2.41	21.980 – j12.968	-9.956	5.581
1.0mm	2.419	24.635 – j2.850	-9.11	2.021
1.3mm	2.419	21.582 +j1.3726	-10.075	2.355
1.5mm	2.419	21.248 +j3.7056	-7.673	2.497
2.2mm	2.394	19.24 +j3.215	-10.231	2.213
2.4mm	2.341	20.342 +j2.231	-12.211	1.912
3.2mm	2.321	25.212 – j1.2123	-13.231	2.341

7. EXPERMENTAL ANALYSIS OF CIRCULAR PATCH MICROSTRIP ANTENNA:



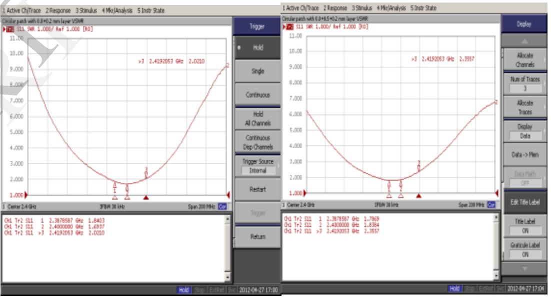
(a) (b)

Figure6: Experimental measured results (a) impedance and (b) VSWR plot of circular patch antenna without Superstrate at dielectric constant($\in_{r1}$) is 2.2



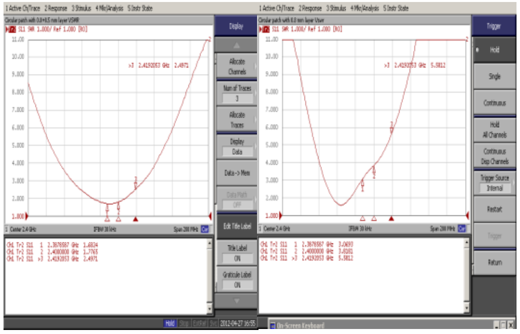
(a) 0.2mm (b) 0.5mm

Figure 7: Experimental measured VSWR plot of circular patch antenna with Superstrate thickness at 0.2mm and 0.5mm



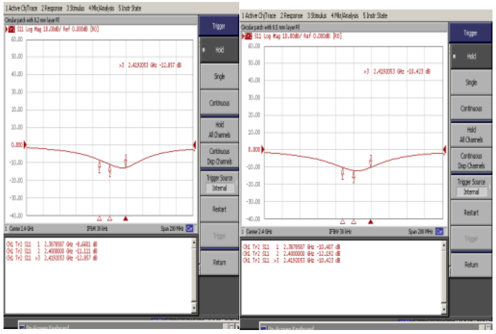
(a) 1.0mm (b) 1.5mm

Figure8: Experimental measured VSWR plot of circular patch antenna with Superstrate thickness at 1.0mm and 1.5mm



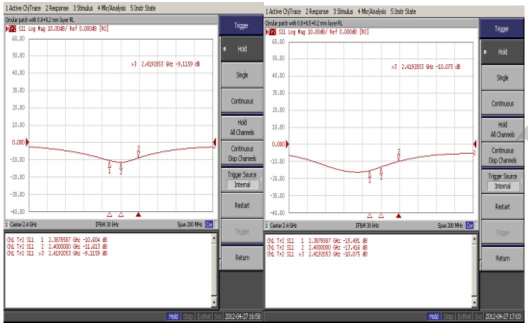
(a) 1.3mm (b) 0.8mm

Figure9: Experimental measured VSWR plot of circular patch antenna with Superstrate thickness at 1.3mm and 0.8mm



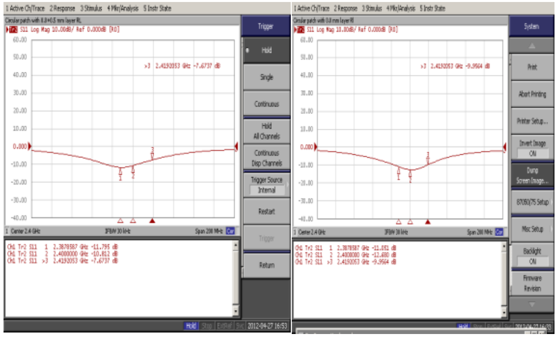
(a) 0.2mm (b) 0.5mm

Figure10: Experimental measured return-loss plot of circular patch antenna with Superstrate thickness at 0.2mm and 0.5mm



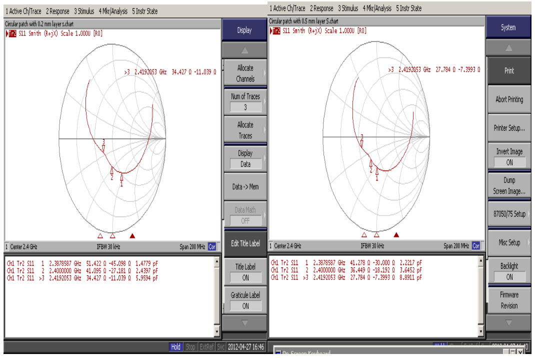
(a) 1.0mm (b) 1.5mm

Figure11: Experimental measured return-loss plot of circular patch antenna with Superstrate thickness at 1.0mm and 1.5mm



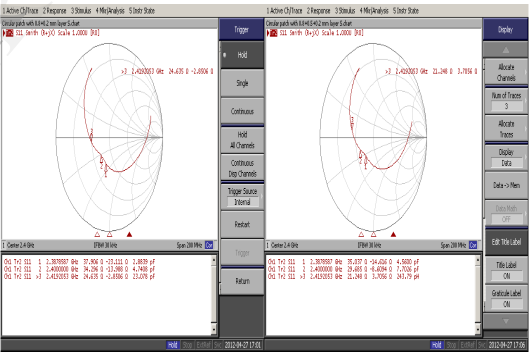
(a) 1.3mm (b) 0.8mm

Figure12: Experimental measured return-loss plot of circular patch antenna with Superstrate thickness at 1.3mm and 0.8mm



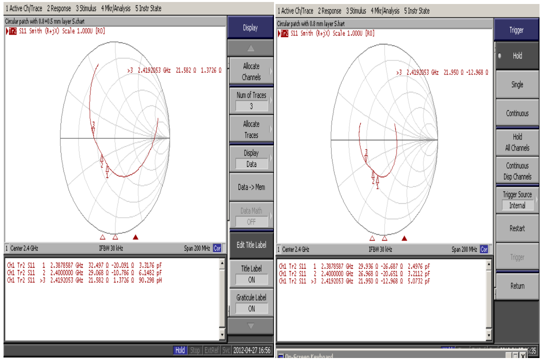
(a) 0.2mm (b) 0.5mm

Figure13:Experimental measured impedance plot of circular patch antenna with Superstrate thickness at 0.2mm and 0.5mm



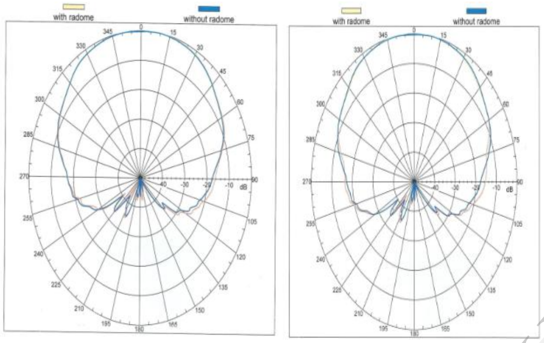
(a) 1.0mm (b) 1.5mm

Figur14:Experimental measured impedance plot of circular patch antenna with Superstrate thickness at 1.0mm and 1.5mm



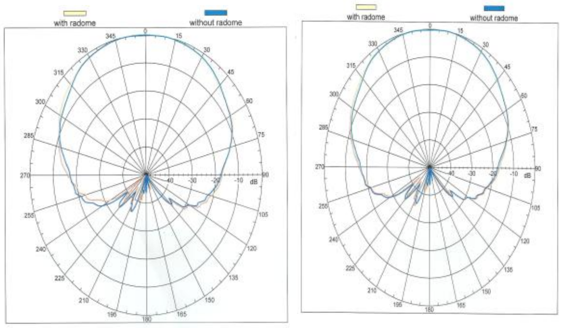
(a) 1.3mm (b) 0.8mm

Figure14:Experimental measured impedance plot of circular patch antenna with Superstrate thickness at 1.3mm and 0.8mm



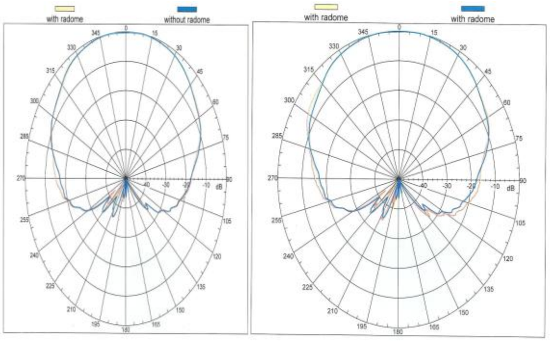
(a) 0.2mm (b) 0.5mm

Figure15: Experimental measured far field radiation pattern with and without Superstrate (radome)at 0.2mm and 0.5mm thickness in vertical polarization



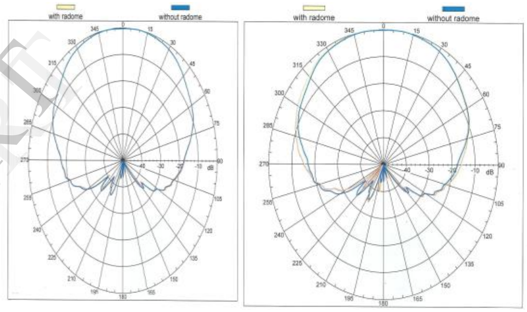
(a) 1.0mm (b) 1.3mm

Figure16:Experimental measured far field radiation pattern with and without Superstrate (radome) thickness at 1.0mm and 1.3mm invertical polarization.



(a) 2.2mm (b) 2.4mm

Figure17: Far field radiation pattern with and without Superstrate (radome)thickness at 2.2mm and 2.4mm in vertical polarization



(a) 0.8mm (b) 3.2mm

Figure18: Far field radiation pattern with and without radome at 0.8mm and 3.2mm thickness in vertical polarization.

8. RESULTS AND DESCUSSION:

A comparison of experimental results with and without dielectric Superstrate thicknessfor circular patch microstrip antenna is presented in Table4, Table5, Table6 and Table7. The data refer the highest gain 3.43dB is obtained for circularpatch antenna at Superstrate thickness at 2.2mm. The return- loss is first increases with increasing the dielectric constant of the dielectric Superstratethickness and decreases. The band width of microstrip antennas also increases with increasing thickness of dielectric Superstrate thickness for low dielectric constant materials, and decreases for high dielectric constant materials. The variation of VSWR with different dielectric

Superstratethickness, as dielectric Superstrate thickness increases, VSWR increases.Increase with high dielectric constant of the Superstrates. It is also observed that the resonant frequency f_r decreases monotonically with the increase in the superstrate thickness and dielectric constant of the Superstrates. The impedance characteristics are that both input impedance and the reactance are increased as Superstrates becomes thick and its $\in_r$increases. TheHPBW is also increases with the increasing thickness of the dielectric Superstrates.

9. CONCLUSION:

In particular, the resonant frequency increases with the dielectric constant of the Superstrates thickness. In addition, it has also been observed that return loss and VSWR increases, however bandwidth and gain decreases with the dielectric constant of the Superstrates. Impedance characteristics are that both input impedance and the reactance are increased as Superstrate become thick and its $\in_r$increases.The value of impedance, return loss and VSWR are minimum, whereas BW is maximum for Superstrate thickness at 2.2mm.

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