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Tunable Slit Loaded Stacked Circular Microstrip Antenna for Multiband applications

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Abstract:- In the present endeavor a tunable (frequency agile) stacked slit loaded circular microstrip antenna has been presented for wireless systems. The frequency agility has been achieved by loading a varactor diode. The antenna is able to operate in five bands. One of these bands hopes over different bands while others are fixed at 1.9611GHz, 2.1179GHz, 2.3018GHz and 2.6203GHz. The bands are useful for different wireless applications. The mathematical model presented here is very accurate and gives clear picture of facts happening in the antenna. Antenna parameters like return loss, resonant frequency, gain, directivity, co and cross polar patterns have been obtained from simulation and numerically. The simulated results agree well with the numerical data. The gain of 6.78dBi and directivity of 7.53 dB has been achieved from the proposed tunable structure.

Keywords:- Stacked, slit, resonant frequency, frequency agile, cavity model etc.

I. INTRODUCTION

With the advent of different services, the need for multiband antenna is increasing day by day. Due to low profile, light weight, low cost and integration capability with MMICs, the microstrip antennas are becoming popular for wireless communication systems. But low band width and single band of operation has been inherent problem with them. Also, they suffer from low gain and low power handling capacity. Various techniques [1-5] have been evolved by researchers to enhance the bandwidth. In [1], two H-shape stacked microstrip antennas have been analyzed using transmission line model. In this the stacking has been helpful to increase the radiation efficiency to 87% from 23% and bandwidth from 0.42% to 5.5%. An inverted-F antenna has been presented in [2] with the gain of 5 dBi and bandwidth of 15.8%. By shorting the edges of the stacked slot loaded rectangular microstrip antennas (RMSA), Broadband operation (impedance bandwidth of 76.25%) is achieved [3]. In [4] the author moved coaxial feed in different positions to obtain circular polarization in rectangular microstrip antenna (RMSA). The antenna is useful for satellite and terrestrial application by proper biasing of PIN diodes.

An E-shaped patch is stacked in [5] on RMSA to improve the impedance bandwidth from 33.8% to 44.9%. There are several other advantages of stacked microstrip antennas like- stacking provides many degrees of freedom like gap between layers feed point, substrate and superstrate parameters. The coaxial feeding technique has been extensively used in stacked patches. The inductive nature of the probe feed limits the bandwidth of the antenna [6]. Recently the frequency agile microstrip antennas have been seen as solution to the low bandwidth [7-8]. They hop over different frequency bands at different time to cover a larger band. The two layered stacked microstrip antenna has two resonant frequencies, by including an active device between ground plane and lower patch lower resonant frequency could be varied to hop over. A dual band operation is achieved in [8] by cutting two identical notches in RMSA. But loading of tunnel diode ceases the upper band of operation. This may be restored by using staked structure.

In the present paper, the varactor loaded stacked circular microstrip antenna is analyzed and presented for multi band operation and may be varied to other bands for wireless application. The structure has four bands of operation out of which upper three bands of the structure remains unaffected while the lower band is agile in nature. The theoretical and simulated return loss, gain directivity etc. are studied, the details of which are given in the following sections.

II. THEORETICAL CONSIDERATION

In this design the stacked patch has two layers of circular microstrip antennas, placed vertically and center aligned. The lower patch with radius a_1 is supported by a substrate of dielectric constant ε_{r1} and the upper one with radius a_2 residing on substrate with dielectric constant ε_{r2}. Two pairs of narrow slits are cut diagonally in the upper patch at 90^0 angles. The width of each slit is 1 mm, the length of slit along horizontal axis is 5 mm and that along vertical axis is 10 mm. The thickness of the lower substrate layer is h_1 and that of the upper is $h_2,$ both 1.6 mm. In the present design both layers are filled with FR4 substrate with relative dielectric constant of

4.4. A varactor diode is embedded between lower circular patch (LCP) and ground plane. The center conductor of coaxial probe is electrically connected to the upper circular patch (UCP) through a hole in the lower patch as shown in fig. 1. The 3D view of the structure from full wave electromagnetic simulation software ADS is shown in figure 2. The numerical analysis of antenna is presented in five parts. First part describes design of upper cavity with lower patch as ground plane. Secondly, an analysis is given to incorporate the four slits in the upper patch.. In the third part, the lower cavity has been analyzed with superstrate, neglecting effect of upper patch. In the fourth part the combined effect of lower and upper cavity i.e. stacked antenna is investigated. Lastly, varactor diode loaded stacked circular microstrip antenna has been investigated. The theoretical and simulated results are found and there is good agreement between them.

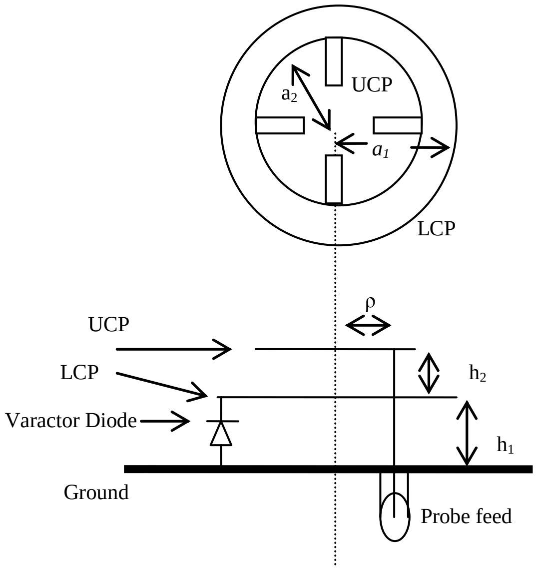


Fig. 1: Structure of proposed antenna

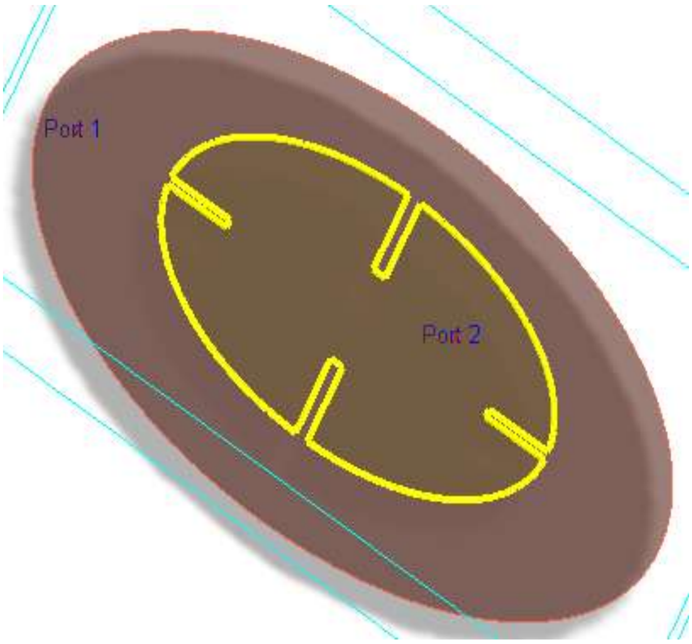


Fig 2: 3D view from ADS

Analysis of upper patch

The resonant frequency of upper patch is determined by taking substrate height h_2 [9], since lower patch acts as ground plane for upper patch. The size of lower patch is small and acts as finite ground plane. This assumption causes error in the model, since lower patch does not provide sufficient ground.
The input impedance of upper cavity is given as

$$Z_{in2} = \frac{1}{\left\{\left(\frac{1}{R_2}\right) + (j\omega C_2) + \left(\frac{1}{j\omega L_2}\right)\right\}} \tag{1}$$

Where resistance R_2, capacitance C_2 and inductance L_2 are equivalent circuit components for circular microstrip antenna expressed as parallel combination for TM_{np} mode.
The resonance resistance (R_2) is given by [10]

$$R_2 = \frac{1}{G_T} \frac{J_n^2(k\rho)}{J_n^2(ka_2)} \tag{2}$$

Where ρ is probe position from center, J_n is the first kind of Bessel function of order n with argument $k\rho$ or ka, G_T is total conductance for upper cavity associated with dielectric loss, radiation loss, and conduction loss.
The capacitance associated with upper cavity patch is given by

$$C_2 = \frac{Q_T}{2\pi f_{res2} R_2} \tag{3}$$

and inductance L_2 of upper layer is given as

$$L_2 = \frac{R_2}{2\pi f_{res2} Q_T} \tag{4}$$

Where Q_T is total quality factor [11] of upper cavity, which includes radiation loss, dielectric loss and conductance loss. Then resonant frequency (f_{res2}) of upper cavity circular microstrip antenna is given [12] by

$$f_{res2} = \frac{c\alpha_{mn}}{2\pi a_{eff2}\sqrt{\varepsilon_{reff2}}} \tag{5}$$

Where c is velocity of light in free space, α_{mn} is m^{th} zero of first kind Bessel function of order n, a_{eff2} is effective radius of the upper patch and ε_{reff2} is effective permittivity [12] of upper substrate considering fringing effect of upper patch.

Analysis of slit loaded Circular microstrip antenna

The effect of slits may be incorporated in the design by taking the multiple radius of the circular microstrip patch. Due different lengths of the slits, there would be three resonant frequencies [13]
The i^{th} resonant frequency may be given as

$$f_{ri} = \frac{1.841c}{P_e\sqrt{\varepsilon_{reff2}}} \tag{6}$$

Where P_e is effective circumference due to slits and is governed by

$$P_e = P_i\left\{1 + \frac{2h_2}{\pi a_2 \varepsilon_{r2}}\left(\ln\frac{\pi a_2}{2h_2} + 1.7726\right)\right\}^{1/2} \tag{7}$$

In the above equation Pi is physical circumference associated to different resonant frequency and is given by

$$P_i = \begin{Bmatrix} 2\pi a_2 - 4w...............for - i = 1 \\ 2\pi a_2 + 2l_x..............for - i = 2 \\ 2\pi a_2 + 2l_y.............for - i = 3 \\ 2\pi a_2 + 2l_y + 2lx.....for - i = 4 \end{Bmatrix} \tag{8}$$

For each value of resonant frequencies given in equation (6) the associated physical radius is calculated by dividing equation (8) by 2π.

Analysis of lower patch

Lower circular patch is analyzed as circular microstrip antenna with superstrate and neglecting the effect of upper patch. One or more dielectric layer above radiating patch disturbs fringing fields thus changing the effective radius of lower patch. Resonant frequency of rectangular microstrip antenna with superstrate has been calculated in [14] taking filling fraction into consideration. In this, an antenna system with one or more

superstrate is represented as antenna with one substrate with same radiation characteristics. Moreover, the formulation provided in [12] along with analysis carried out in [15] is used to analyze the present problem more accurately.
The effective dielectric constant of equivalent substrate is given as

$$\varepsilon reff = \varepsilon_{r1} p_1 + \varepsilon_{r1}(1-p_1)^2 \times [\varepsilon_{r2}{}^2 p_2 p_3 + \varepsilon_{r2}\{p_2 p_4 + (p_3+p_4)^2][\varepsilon_{r2}{}^2 p_2 p_3 p_4 + \varepsilon_{r1}(\varepsilon_{r2} p_3 + p_1) \times (1-p_1-p_4)^2 + \varepsilon_{r2} p_4\{p_2 p_4 + (p_3+p_4)^2]^{-1} \tag{9}$$

Where

$$p_1 = 1 - \frac{h_1}{2w_e}\ln\left(\frac{\pi w_e}{h_1} - 1\right) - p_4 \tag{10}$$

$$p_2 = 1 - p_1 - p_3 - 2p_4 \tag{11}$$

$$p_3 = \frac{h_1 - g}{2w_e}\ln\left[\frac{\pi w_e}{h_1}\frac{\cos\left(\frac{\pi g}{2h_1}\right)}{\pi(0.5+\frac{h_2}{h_1}) + \frac{g\pi}{2h_1}} + \sin\left(\frac{g\pi}{2h_1}\right)\right] \tag{12}$$

$$p_4 = \frac{h_1}{2w_e}\ln\left(\frac{\pi}{2} - \frac{h_1}{2w_e}\right) \tag{13}$$

$$g = \frac{2h_1}{\pi}\arctan\left[\frac{\frac{\pi h_2}{h_1}}{\left(\frac{\pi}{2}\right)\left(\frac{w_e}{h_1}\right) - 2}\right] \tag{14}$$

$$w_e = \sqrt{\frac{\varepsilon_r'}{\varepsilon_{reff}}}\left[\left\{w + 0.882h_1 + 0.164h_1\frac{(\varepsilon_r'-1)}{\varepsilon_r'^2}\right\} + h1\frac{(\varepsilon_r'-1)}{\pi\varepsilon_r'}\left\{\ln\left(0.94 + \frac{w}{2h_1}\right) + 1.451\right\}\right] \tag{15}$$

$$\varepsilon_r' = \frac{2\varepsilon_{reff} - 1 + \left(1 + \frac{10h_1}{w_e}\right)^{-0.5}}{1 + \left(1 + \frac{10h_1}{w_e}\right)^{-0.5}} \tag{16}$$

$$w = a(\pi - 2) \tag{17}$$

The parameters w_e and ε_r' are calculated by iteration method [14] with initial value $\varepsilon_r' = \varepsilon_{r1}$ and $\varepsilon_{reff} = \varepsilon_r'$. In the above equation (17) w is width of RMSA equivalent to CMSA with same radiation characteristics [16]. These equations may be calculated by assuming equal fringing field for both structures. When the relative dielectric constant of superstrate is greater than that of substrate, the surface wave may be reduced to a certain extent by choosing appropriate thickness. To accommodate this, a new dielectric constant is defined as

$$\varepsilon_{re} = \frac{\varepsilon_{r1}}{\varepsilon_{reff}} \tag{18}$$

Now effective radius of LCP is calculated as

$$a_{eff1} = a_1\sqrt{(1+q)} \tag{19}$$

In this q is calculated as given in [12] where in equations (9)-(14) the result of above equation (17) is used. Using a_{eff1} as calculated in equation (16), the input impedance of LCP Z_{in1} is calculated. The antenna is assumed to be edge fed in above calculation.

Staked Circular Patch

There is no variation of electric field in z direction so total electric field is sum of the electric fields in LCP and UCP. Moreover, LCP is represented as parallel combination of a resistance (R_1), an inductance (L_1) and a capacitance (C_1). The equivalent circuit of stacked microstrip antenna may be represented as series combination of input impedances of the two antennas i.e. LCP and UCP as shown in fig. 3.
Hence

$$Z_{in} = Z_{in1} + Z_{in2} \tag{20}$$

Varactor Diode Integrated Stacked Microstrip Patch:

The varactor diode is connected between LCP and ground plane and is positioned opposite to coaxial feed. The diode is kept at the edge of the antenna. The equivalent circuit of varactor diode is shown in fig. 4. It contains a series resistance (R_s) due to semiconductor material, inductance (L_s) due to connection from external terminal, a junction capacitance (C_j) due to space charge in depletion region and packaging capacitance (C_p).
The junction capacitance of varactor diode varies with reverse bias as

$$C_j = \frac{C_{j0}}{\left(1+\frac{v}{V_T}\right)^n} \tag{21}$$

C_{j0} is zero bias junction capacitance, v is bias voltage, V_T is built in voltage (threshold voltage) and n is a constant (tuning slope) which depends upon doping type. For abrupt junction the value of n is less than 0.5 and for hyper-abrupt junction its value is taken more than 0.5.
The impedance of diode is calculated from fig. 4 as

$$Z_d = Z_s /(1+ j\omega C_p Z_s) \tag{22}$$

where

$$Z_s = R_s + j\omega L_s + (1/ j\omega C_j) \tag{23}$$

Hence total input impedance of varactor loaded stacked circular microstrip antenna as shown in fig. 5 is given as

$$Z_{\text{int}} = Z_{in2} + Z_{in1} Z_d /(Z_{in1} + Z_d) \tag{24}$$

and return loss is given as

$$RL = 20\log|\Gamma| \tag{25}$$

Where reflection coefficient (Γ) for coaxial probe of 50 ohms characteristic impedance is given as

$$\Gamma = (Z_{\text{int}} - 50) \big/ (Z_{\text{int}} + 50) \tag{26}$$

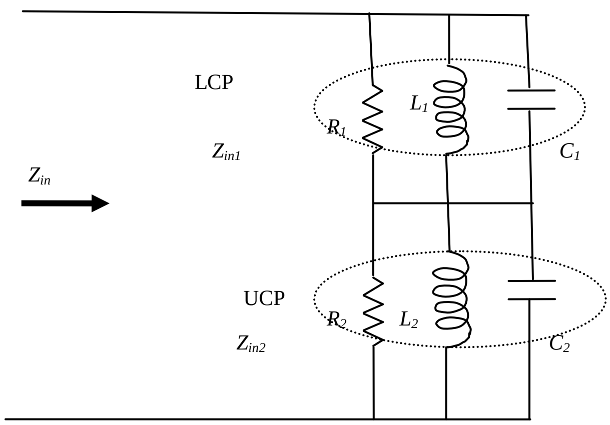


Fig. 3: Equivalent circuit of stacked CMSA

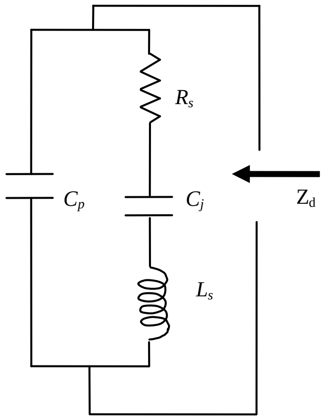


Fig. 4: Equivalent circuit of Varactor diode

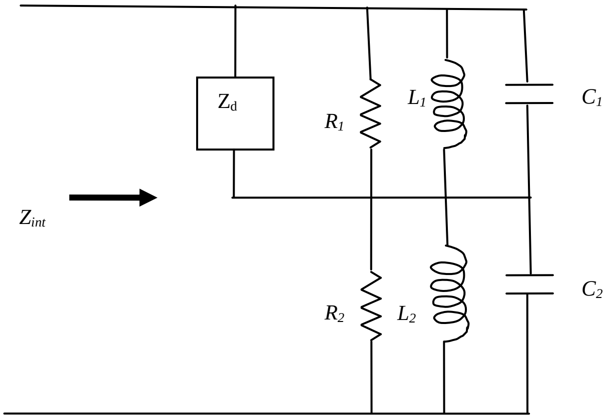


Fig. 5: Equivalent circuit of stacked CMSA loaded with varactor diode

III. DESIGN PARAMETERS

The stacked circular microstrip antenna is designed to operate on two resonant frequencies - 2.2 GHz and 3.5 GHz without any slit in the upper patch. The motive is to design an antenna that could operate for WiMAX as well as one of PCS, DCS and UTMS bands. For these operating frequencies the antenna design parameters are given in Table I. The radius for UCP is calculated assuming LCP as ground plane. Commercially available varactor diode (MA 46473) is taken to simulate the antenna. For calculation, the values of equivalent discrete components which are given in table II are used.

Table I Stacked CMSA Specification

Parameters	**Value**
Radius of LCP (a_1)	**26mm**
Radius of UCP (a_2)	**16.25mm**
Height of LCP(h_1)	**1.6mm**
Height of UCP(h_2)	**1.6mm**
Relative dielectric constant of substrate & superstrate ($\varepsilon_{r1}=\varepsilon_{r2}$)	**4.4 (FR4)**
Width of slit (w)	**1 mm**
Length of slits (lx, ly)	**5mm, 10mm**
Loss Tangent ($tan\ \delta$)	**0.0012**

Table II Varactor diode specification

Parameters	Value
Model	MA46473
Material	GaAs
Junction Type	Hyper abrupt
Series Resistance (R_s)	0.1ohm
Series inductance (L_s)	0.4nH
Peak Junction capacitance(C_0)	6pf
Threshold voltage (V_T)	1.1Volts
Package capacitance (C_p)	0.13pf

IV. RESULTS AND DISCUSSIONS

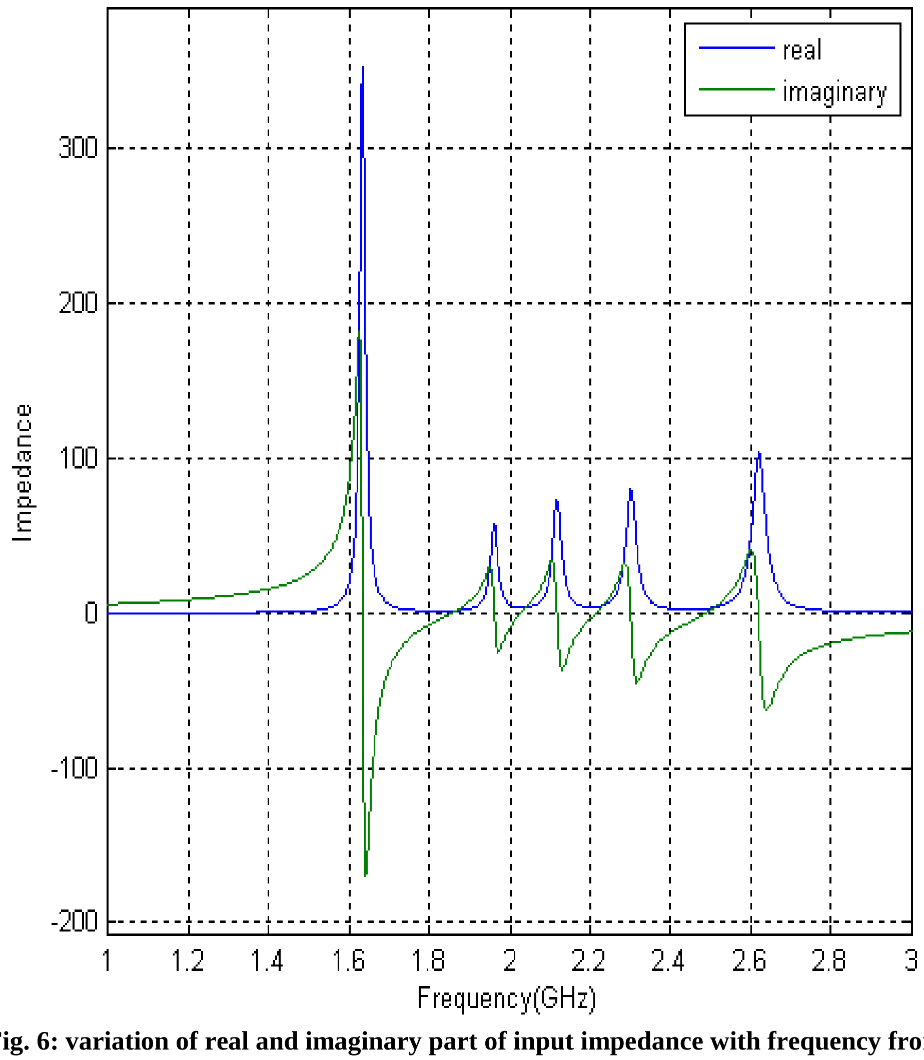


Fig. 6: variation of real and imaginary part of input impedance with frequency from MATLAB for SLSCMSA

Fig. 6 shows computed real and imaginary part of input impedance from MATLAB for slit loaded stacked circular microstrip antenna (SLSCMSA) without loading any varactor diode. The figure shows that there are five resonance frequencies in the stacked antenna at 1.6339GHz, 1.9611GHz, 2.1179GHz, 2.3018GHz and 2.6203GHz. The lowest resonant frequency corresponds to lower CMSA while highest one corresponds to CMSA excluding all the four slits. Figure 7 shows impedance variation with frequency from simulation software. The resonant frequencies from the graph are 1.54GHz, 2.06GHz, 2.4GHz and 2.56GHz. It is noticeable that the two lower resonant frequencies coincide at 1.54GHz. The calculated and simulated resonant frequencies are very close to each other.

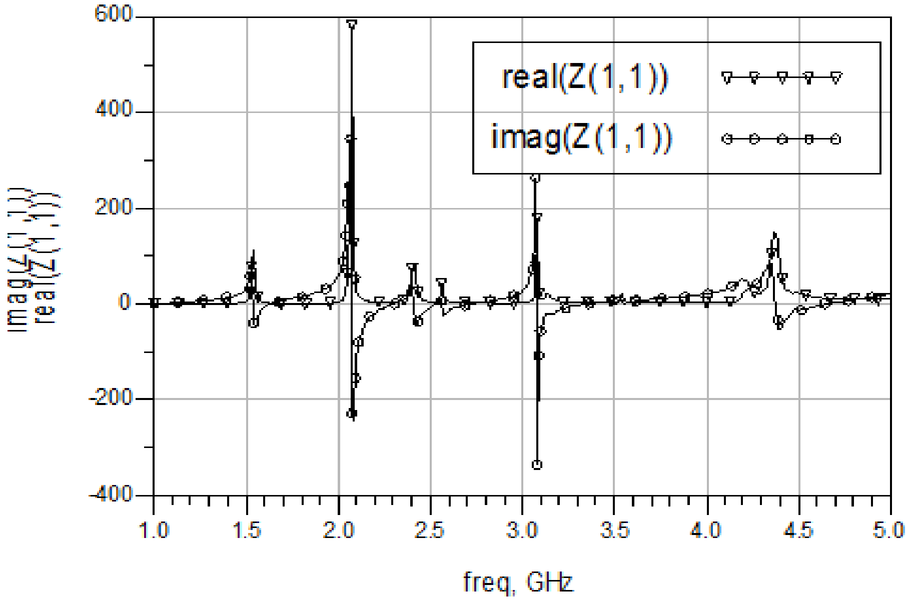


Fig. 7: variation of real and imaginary part of input impedance with frequency from ADS for SLSCMSA

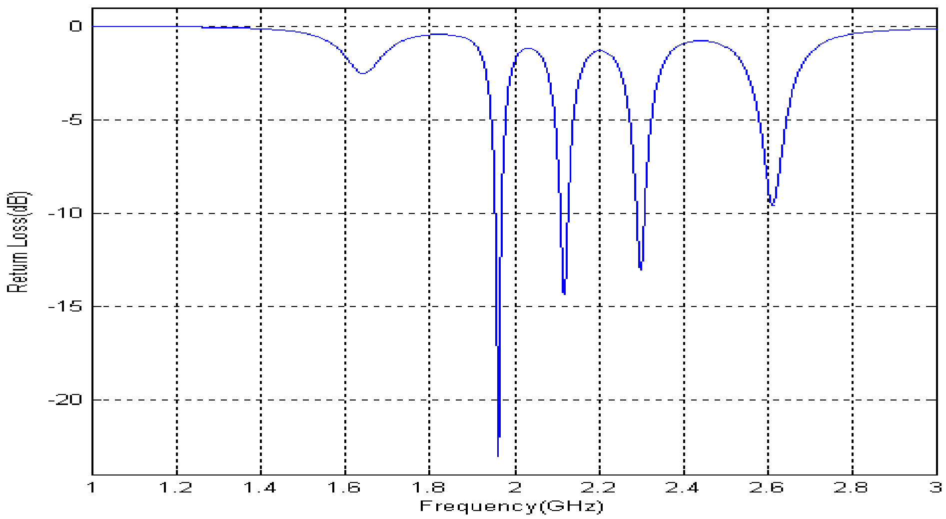


Fig. 8: Return loss variation with frequency from MATLAB for SLSCMSA

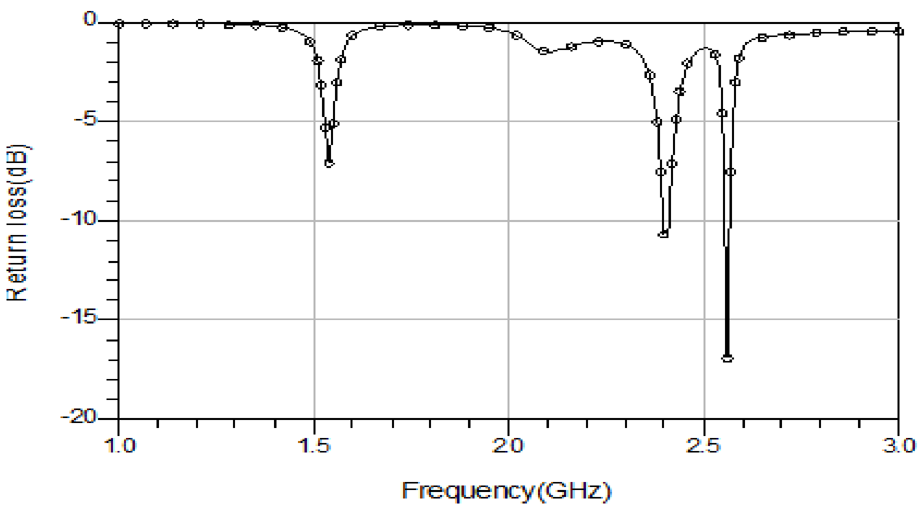
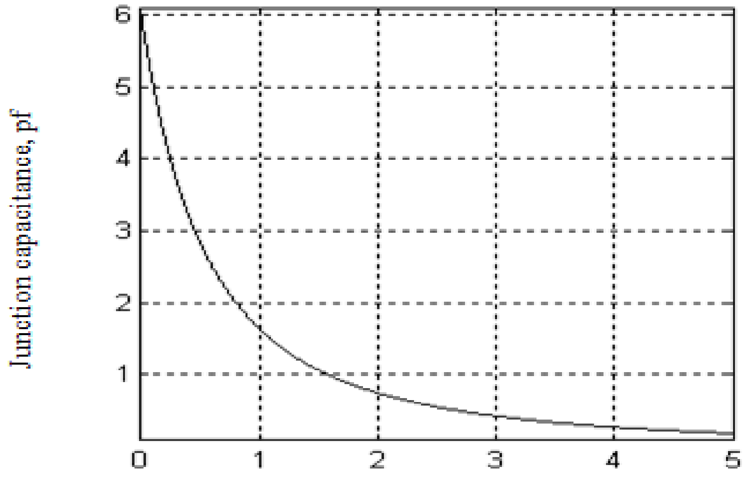


Fig. 9: Return loss variation with frequency from ADS for SLSCMSA

Figures 8 and 9 show computed and simulated return loss variation with frequency.



Reverse Bias Voltage, volts

Figure 10: Variation of Junction capacitance with reverse bias voltage

Figure 10 shows variation of junction capacitance with reverse bias of varactor diode. A steep variation in the junction capacitance is observed around 1V and the peak value of junction capacitance is 6pf.

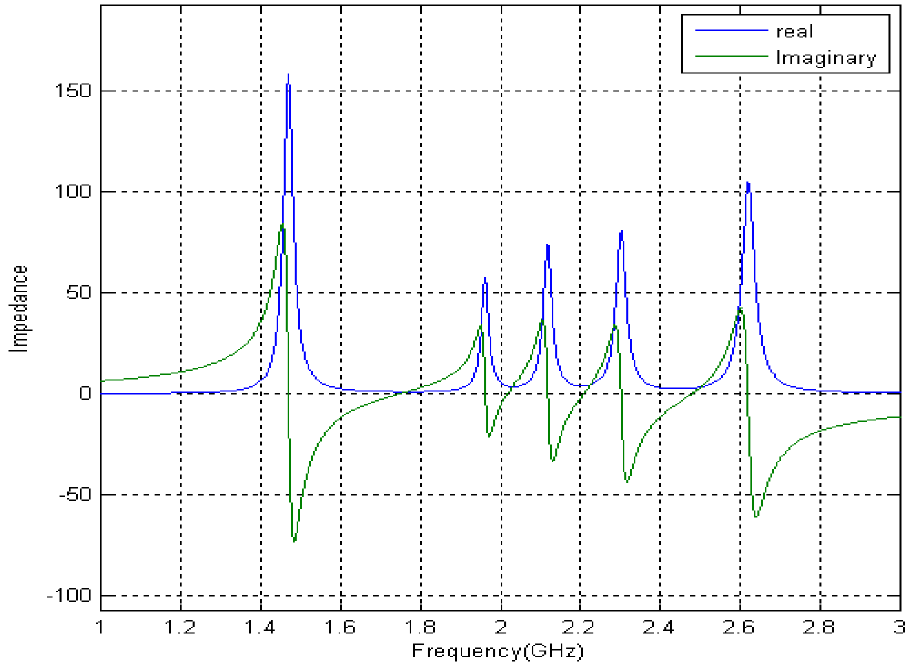


Fig. 11: Impedance variation with frequency for Varactor loaded antenna at 0V from MATLAB

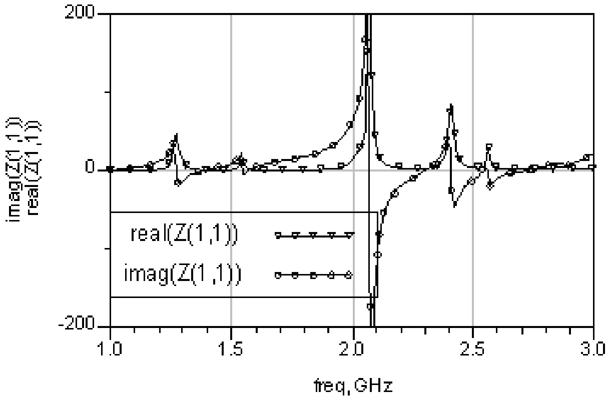


Fig. 12: Impedance variation with frequency for Varactor loaded antenna at 0V from ADS

Figure 11 and 12 show the variation of input impedance of varactor diode loaded antenna at 0V reverse bias. The lowest resonant frequency which is associated with lower patch is shifted towards lower side at 1.27GHz (simulated) and 1.474GHz (calculated).

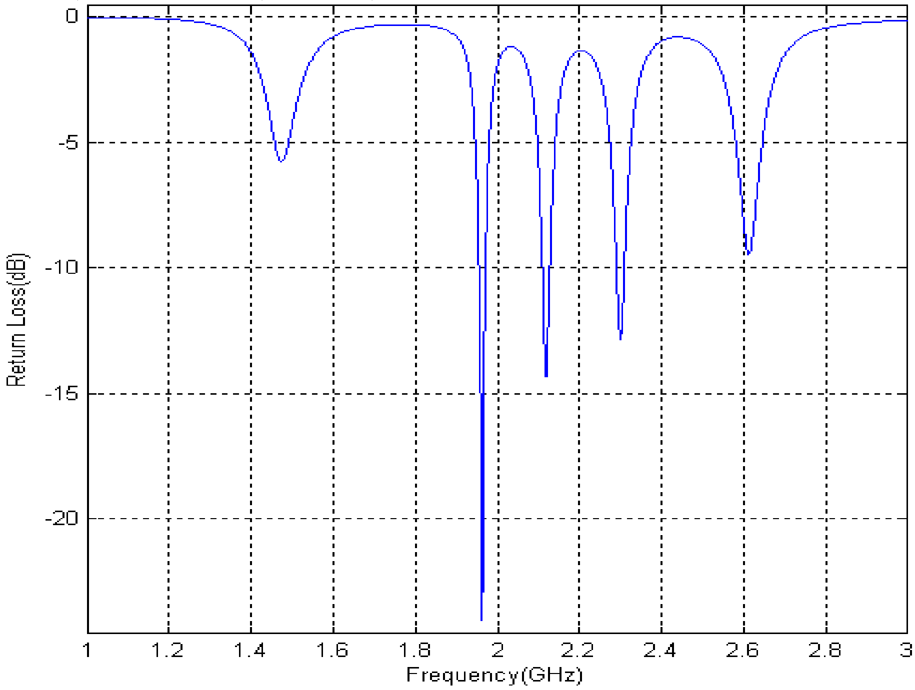


Figure 13: Return loss variation of varactor diode loaded microstrip antenna at 0 V from MATLAB

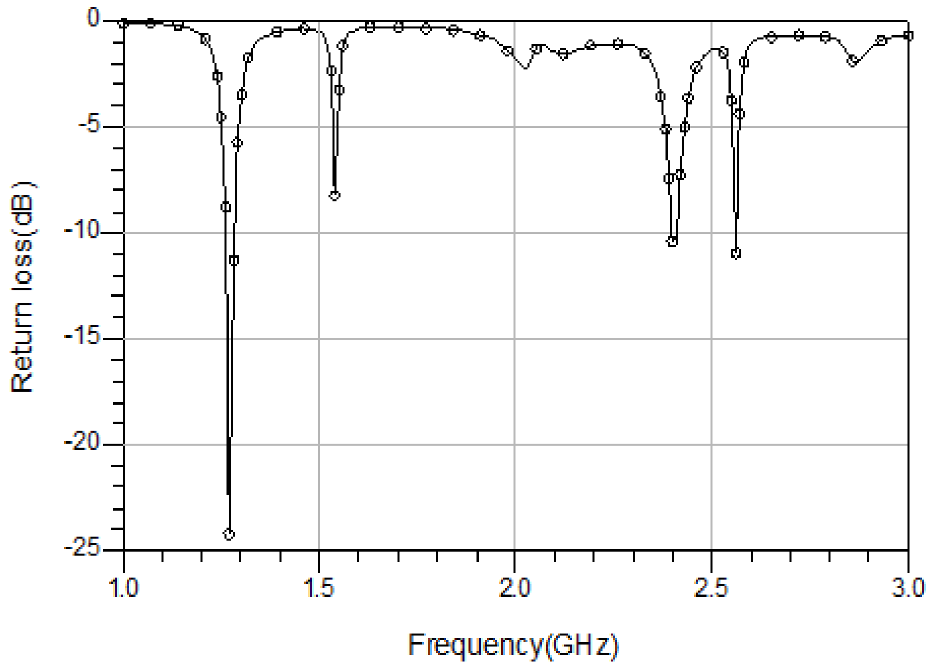


Figure 14: Return Loss variation of Varactor diode loaded microstrip antenna at 0 V from ADS

Figures 13 and 14 show returns loss variation of the Varactor loaded SLSCMSA at 0V reverse bias. Higher order mode may be observed near 2GHz which is associated with lower patch. This mode also moves towards lower side of the frequency spectrum as reverse bias is varied. Figure 15 and 16 show the variation of input impedance of varactor diode loaded antenna at 0.5V reverse bias. The lowest resonant frequency which is associated with lower patch is shifted towards lower side at 1.39GHz (simulated) and 1.545GHz (calculated). It is noticeable that the other bands remain fixed.

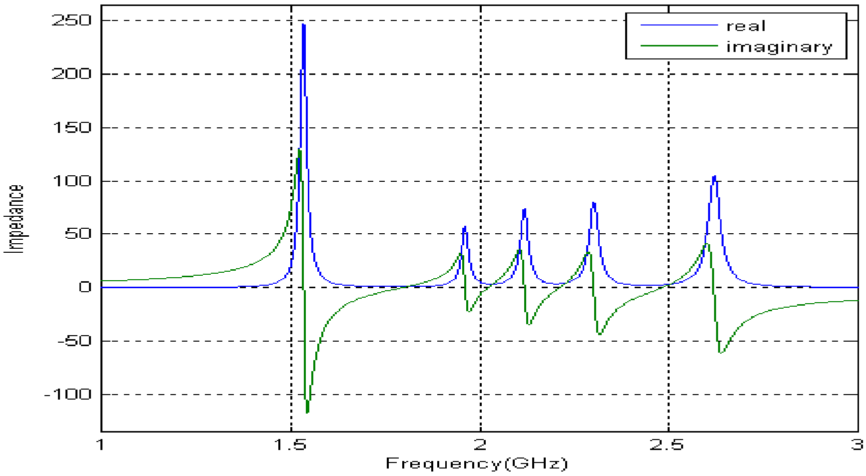


Figure 15: Input impedance variation of varactor diode loaded microstrip Antenna at 0.5 V from MATLAB

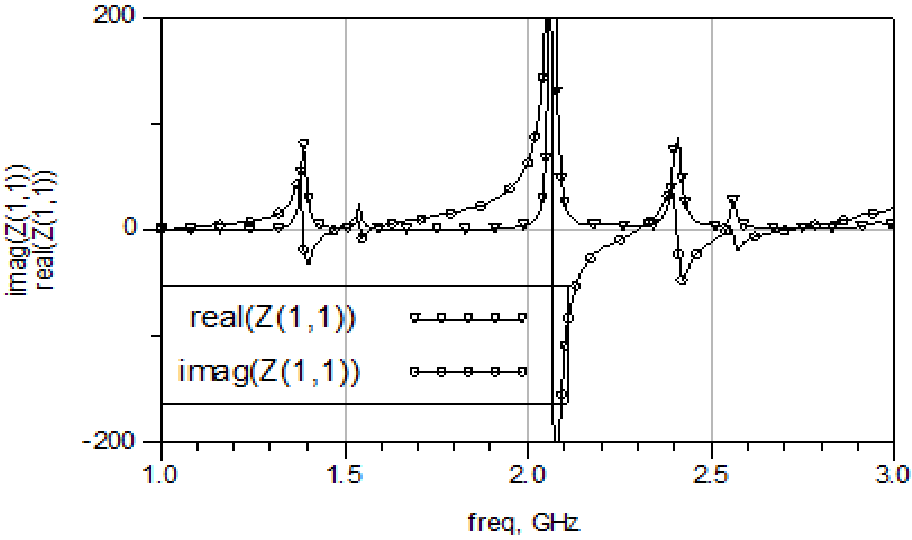


Fig. 16: Input impedance variation of Varactor diode loaded microstrip antenna at 0.5 V from ADS

Figures 17 and 18 show returns loss variation of the Varactor loaded SLSCMSA at 0.5 V reverse bias. Higher order mode may be observed near 2.2 GHz which is associated with lower patch. The movement of higher order mode may be seen again towards higher side of the frequency spectrum as reverse bias is increased.

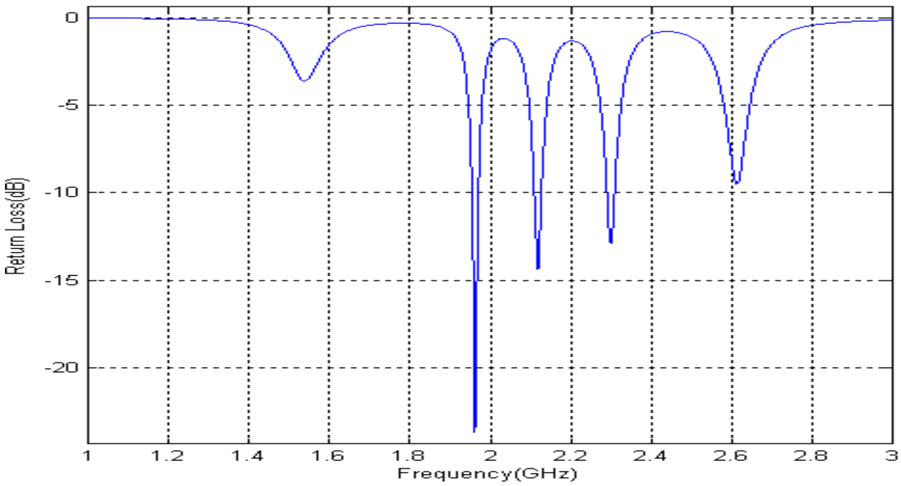


Fig. 17: Variation of computed return loss with frequency at 0.5V for Varactor diode loaded SLSCMSA

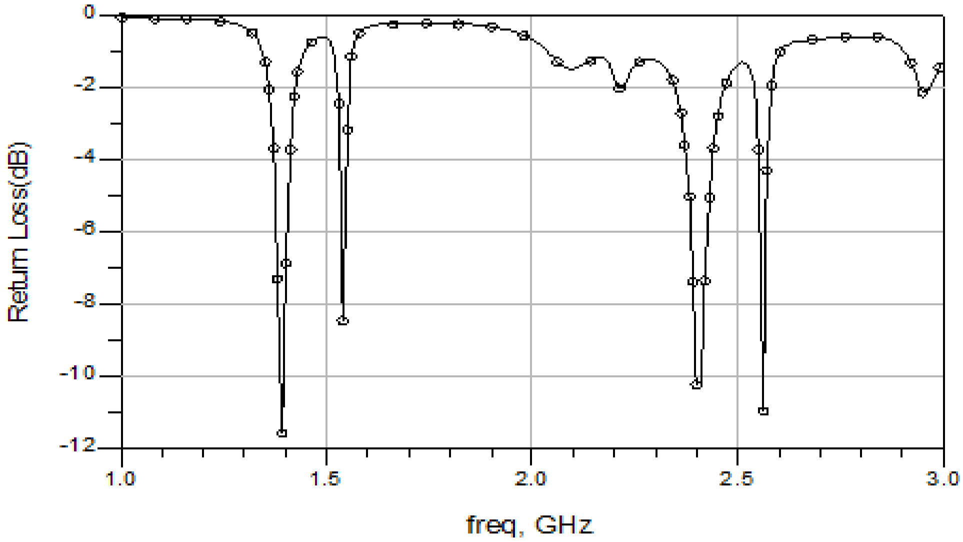


Fig. 18: Variation of simulated return loss with frequency at 0.5V for Varactor diode loaded SLSCMSA

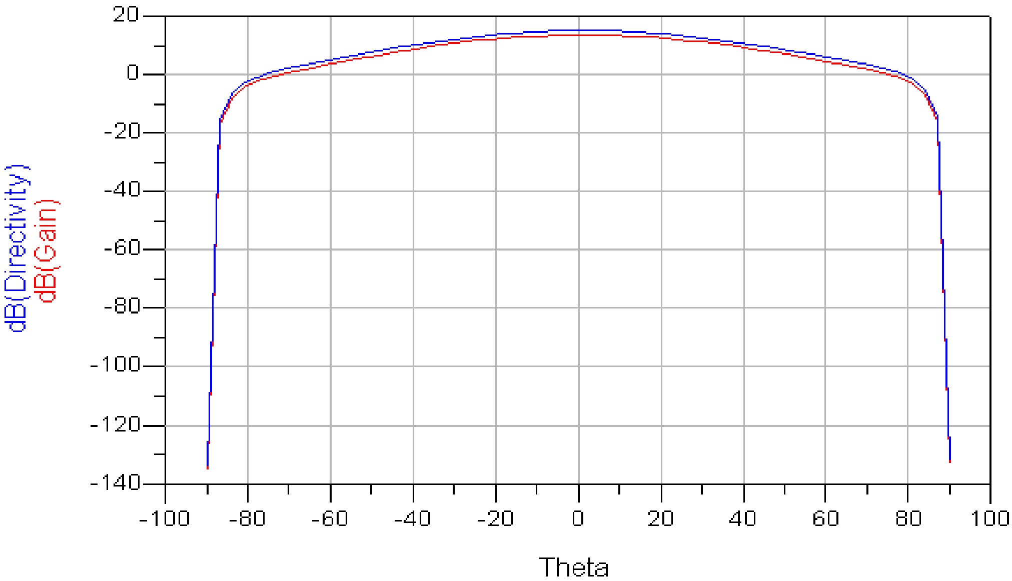


Fig. 19: Directivity and gain variation at at 2.4GHz

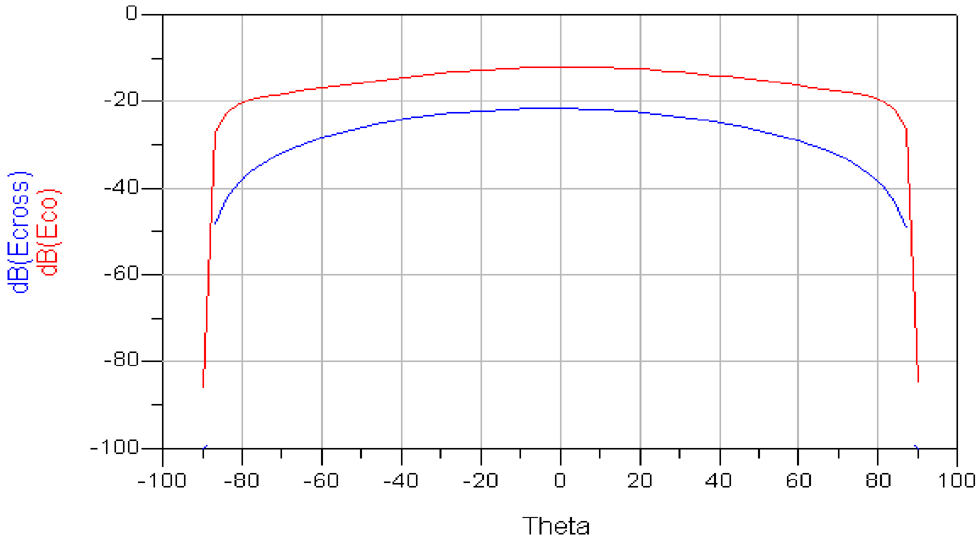


Fig. 20: Co and cross polar radiation pattern at 2.4GHz

Figure 19 shows gain directivity properties of the tunable proposed antenna. The graph shows these parameters with respect to elevation theta. It may be observed that the peak occurs at 0^0 indicating a broadside radiation pattern. Maximum directivity of the antenna is found to be 7.5334dB and maximum gain is 6.78dBi. These parameters are similar to an ordinary stacked microstrip antenna i.e. no effect of loading of varactor diode is seen. Figure 20 shows co-polar and cross polar radiation pattern of the proposed antenna. Again a broadside radiation pattern is confirmed. The cross polar pattern suppression of more than 12dB is achieved in the antenna suggesting a linearly polarized radiation pattern. Table III shows comparison of resonant frequencies from MATLAB and ADS. The results are in close agreement.

Table III: Comparison of resonant frequencies form MATLAB and ADS

	without varactor diode				
	f1	f2	f3	f4	f5
MATLAB	1.6339	1.9611	2.1179	2.3018	2.6203
ADS	1.54	1.54	2.06	2.4	2.56
	with varactor at 0V bias				
MATLAB	1.474	1.9611	2.1179	2.3018	2.6203
ADS	1.27	1.54	2.06	2.4	2.56
	with varactor at 0.5V				
MATLAB	1.545	1.9611	2.1179	2.3018	2.6203
ADS	1.39	1.54	2.06	2.4	2.56

V. CONCLUSION

A varactor diode and slit loaded stacked circular microstrip antenna has been designed and analyzed using extended cavity model. Four slit on the upper patch provide multiband operation to the antenna. Tuning property has been achieved using varactor diode which makes antenna suitable for wireless communication like WiMAX, UTMS and PCS bands. The gain, directivity, efficiency etc. have been like any normal stacked circular microstrip antenna i.e. the frequency agility has been achieved without any significant loss in its other radiation properties. The antenna may operate at all bands simultaneously even after varactor loading.

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