Design of Frequency and Polarization Tunable Microstrip Antenna

M. S. Nishamol, V. P. Sarin, D. Tony, C. K. Aanandan, P. Mohanan, K. Vasudevan

Abstract − **A novel compact dual frequency microstrip antenna with frequency and polarization tunability is presented. The tuning is realized by varying the effective electrical length of slot with an embedded capacitor at the center of X-slot. Design equations of the antenna are developed and validated on different substrates.**

Key words − **Microstrip antenna, Multi-frequency antenna, Polarization diversity antenna, Reconfigurable antenna.**

I. INTRODUCTION

Frequency agile systems must be able to receive signals over a large frequency range and therefore, requires either wide-band or tunable antennas. However, conventional microstrip patch antennas have disadvantage of narrow bandwidth and the instantaneous bandwidth of efficient antennas is limited as they become small with respect to the wavelength. Hence, tunable narrow-band antennas can be advantageous if small efficient antennas are required to cover a large frequency range. In addition, tunable narrow-band antennas provide frequency selectivity which relaxes the requirement of the receiver filters. Frequency and polarization reconfigurable antennas extend the flexibility of a system even further.

Several interesting approaches to change the resonant frequency of a microstrip antenna are available in literature. In the dual-frequency stacked circular disc microstrip antenna [1], the upper resonance is mechanically tunable by adjusting the air gap width between the substrate and the ground plane. Slot antennas are common for frequency tuning because their resonant frequency can be changed easily with lumped capacitors (or varactors), inductors or switches. Slot-ring antennas that are tunable over a small frequency range either using capacitor loading for a single frequency linearly polarized (LP) radiation or using varactors for dual frequency orthogonal polarized radiation [2-3]. The dual band antenna [4] designed by loading chip capacitors across two pairs of unequal-length slots on a square patch have a frequency ratio ranging from 1.25 to1.73 for right hand circular polarized (CP) radiation. Peroulis *et al*. proposed a slot antenna that can be switched to four different frequency bands over a 1.7:1 bandwidth using four PIN diodes [5] has a polarization mismatch of 25% as the frequency is changed.

In the single-polarized dual-band slot antenna [6] both of the bands can be tuned independently with frequency ratio ranging from 1.3 to 2.67. An electronically reconfigurable antenna using varactors [7] achieves tuning of two orthogonally polarized modes with an added advantage of size reduction up to 85% and 65% respectively. A F Sheta *et al*. demonstrated the tuning of four frequency bands using an array of three switches and posts in different states [8]. The frequency tunable U-slot patch antenna [9] using a variable chip capacitor (trimmer) soldered to the microstrip line at the position where the feeding probe is connecting to the line. By varying the trimmer capacitance value from 0.37 to 1.26 pF a frequency ratio of 1.28 between highest and lowest frequency is achieved. These approaches, however, can only be used to design antennas that have multi-band characteristics with either single (LP or CP) or orthogonal polarized radiation with frequency ratio greater than 1.2.

In this paper, a novel compact microstrip antenna achieving frequency and polarization tunability is presented. The proposed antenna utilizes an etched "X" shaped slot on the center of a rectangular patch with square slits on its four corners result in a dual frequency dual polarized operation. The X shape is chosen to induce symmetric current distributions for TM_{10} and TM_{01} modes and can be easily modified to obtain a tunable antenna with greater area reduction. A chip capacitor inserted at the center of the X-slot is used to tune the operating frequency and polarization of the antenna. Polarization of the antenna is switchable between LP and CP by resoldering the right value for the lumped element without changing the geometrical parameters of the antenna. The frequency ratio can assume any value in the range $1.025 \leq f_R \leq 1.21$. The important aspect of this design is that it provides an area reduction of 79% for the first frequency and 66% for the second frequency when compared with a standard rectangular patch operating at the same frequencies. The location of the capacitor is chosen to minimize the variations of one mode and therefore obtain a dual frequency antenna with adequate control over its frequency ratio. The validity of this concept is demonstrated by simulated and measured results which show low cross polar level for linear polarization and good axial ratio for circular polarization.

II. ANTENNA GEOMETRY AND DESIGN

As shown in Fig. 1, the proposed antenna is fabricated on a substrate of thickness h (1.6 mm) and relative permittivity ε_r (4.2). The antenna structure is obtained by removing the four square regions of side dimension L_s mm from the corners of a

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rectangular patch of size L x W mm^2. An X-slot of arm length L_x mm and width W_x mm is then carved at the centre of the cross patch and the antenna is electromagnetically coupled using a 50Ω microstrip line fabricated using the same substrate. A chip capacitor C inserted into the center of the slot is oriented normal to the feed line. The ground plane dimension is 65 mm x 65 mm.

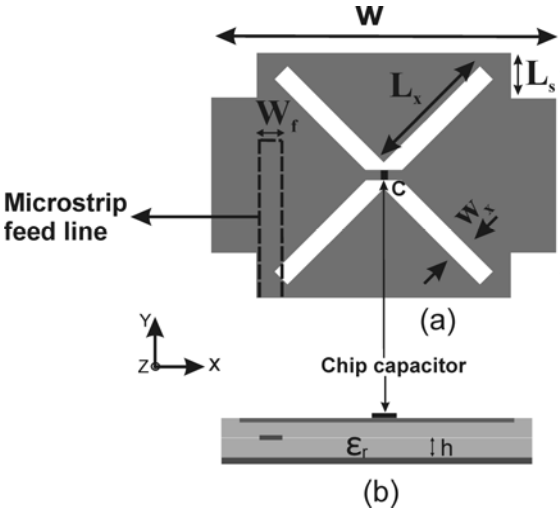

Fig. 1. Geometry of the proposed antenna (a) Front view (b) Side view.

A. *Effect of X- Slot*

The fundamental resonant modes (TM_{10} andTM_{01}) of the unslotted cross shaped patch are at 1.6 GHz and 2.1 GHz with orthogonal polarizations. The proper selection of the X-slot size modifies the horizontal and vertical electrical lengths of the patch equally so that the two resonant frequencies are lowered to 1.12 GHz and 1.44 GHz. To attain an insight on the effect of slot geometry on the antenna performance, the proposed antenna is designed with three different slot sizes and the results are tabulated in Table I.

The X-slot length (L_x) modifies the first and second resonant modes equally while slight variations in resonant frequencies are observed when the width (W_x) is increased but this change is found to be negligible compared to that of slot length. The change in the resonant frequencies with slot length is shown in Fig 2. The antenna gives an area reduction of 79% for the first frequency and 66% for the second frequency when compared with a standard rectangular patch operating at the same frequencies. Bandwidth of 1.53% and 1.56% for the first and second resonant frequencies respectively with a frequency ratio of 1.29 is obtained. To understand the dependence of slot geometry on the antenna behavior the surface current distributions of the antenna are simulated using Ansoft HFSS and plotted at their resonant frequencies in Fig.3. In both the cases the surface current is following along the slot edges and a half wavelength variation in current is observed. Hence the slot geometry is empirically related to the antenna resonance.

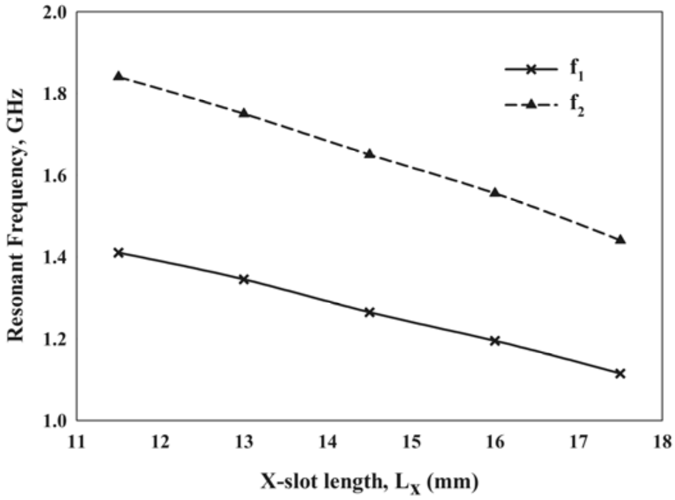

Fig. 2 The response of first and second resonant modes with X-slot length

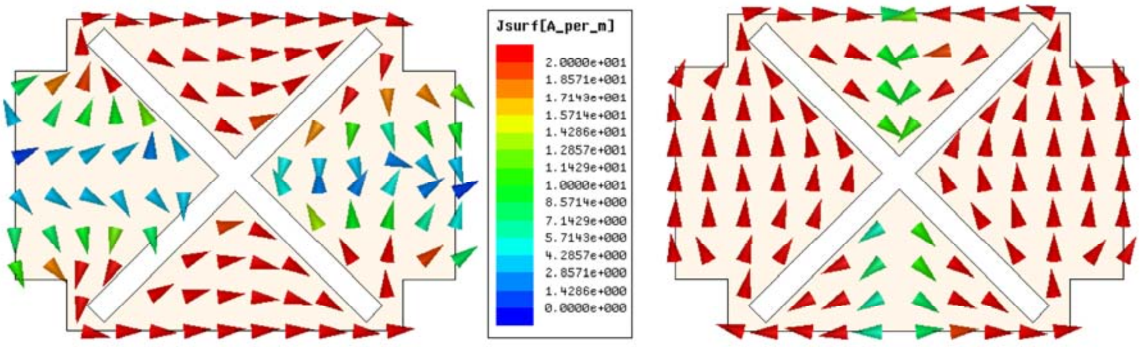

Fig. 3 Simulated current distribution on the antenna (a) at f_1=1.12GHz (b) at f_2=1.44 GHz

TABLE I PERFORMANCE OF THE ANTENNA FOR DIFFERENT SLOT DIMENSION

X-Slot Length L_x (mm)	X-Slot Width W_x (mm)	f_1 (TM_{10}) (GHz)	f_2 (TM_{01}) (GHz)	Input Impedance (Ω)				Frequenc y Ratio, f_2/f_1	% Impedance bandwidth		% Area Reduction	
				TM_{10}		TM_{01}			TM_{10}	TM_{01}	TM_{10}	TM_{01}
				Re.	Im.	Re.	Im.					
17.5	3.29	1.07	1.4	51	-15	56	1	1.3	1.57	1.57	82.4	69.9
	2.29	1.11	1.44	63	-10	53	-2	1.29	1.53	1.56	79.6	65.9
	1.29	1.17	1.5	52	-6	56	-12	1.28	1.6	1.62	75.8	60.2
14.5	3.29	1.22	1.61	54	-8	46	-7	1.32	1.65	1.75	76	58.3
	2.29	1.26	1.65	54	-8	39	-2	1.3	1.74	1.85	73	54
	1.29	1.31	1.7	51	-12	37	-6	1.29	2.28	1.76	69	48.5
11.5	3.29	1.37	1.81	50	-8	42	-0.5	1.32	1.93	2.15	68.7	45
	2.29	1.41	1.84	42	-3	42	-2.5	1.3	1.86	2.17	65.6	41.2
	1.29	1.46	1.89	45	0.6	43	-0.12	1.29	2.02	2.3	61.5	35.3

B. Design

Based on the above observations, equations for designing the antenna are summarized as follows:

(i) *Substrate and feed lines*: Choose the width of the microstrip feed line W_f for a 50Ω impedance on a substrate with permittivity ε_r and thickness h.

(ii) *Patch length and width*: For the desired dual frequencies of operation, calculate the dimensions of the rectangular patch corresponding to f_{r10} and f_{r01}. Due to the effect of fringing, the patch antenna look electronically wider compared to its physical dimensions [10]. The effect of fringing fields along the width and length direction of the patch is ΔL_{10} and ΔL_{01} respectively. This line extension lengths as well as the addition of X-slot modifies the patch dimensions as

$$W = \frac{c}{2f_{r10}\sqrt{\varepsilon_{re}}} - 2\Delta L_{10} - \frac{c}{9.02 f_{r10}} \qquad (1)$$

$$L = \frac{c}{2f_{r01}\sqrt{\varepsilon_{re}}} - 2\Delta L_{01} - \frac{c}{8.126 f_{r01}} \qquad (2)$$

where ε_{re} is the effective dielectric constant. The last term account for the effect of X-Slot.

(iii) *Slot Geometry:* The dimensions of the slot is deduced in terms of guided wavelength as follows,

$$\lambda_{g10} = \frac{\lambda_{10}}{\sqrt{\varepsilon_{re}}} \text{ and } \lambda_{g01} = \frac{\lambda_{01}}{\sqrt{\varepsilon_{re}}}$$

$$L_s = \frac{\lambda_{g10}}{29} \qquad (3)$$

$$L_x = 0.123\lambda_{g10} \qquad (4)$$

and

$$W_x = 0.019\lambda_{g01} \qquad (5)$$

The above design equations of the antenna are validated on different substrates and the computed dimensions are simulated using HFSS. The antenna parameters along with their resonances is tabulated in Table II.

III. RESULTS AND DISCUSSIONS

A prototype of the antenna is fabricated on a substrate of ε_r= 4.2 and h=1.6mm with the parameters L=30.9mm, W=43.47mm, L_s=5.145mm, L_x=18.3mm and W_x=2.289mm. The measurements of the antenna are done using HP8510C vector Network Analyzer. The simulated and measured reflection characteristics of the antenna with and without X-slot plotted in Fig.4 show good agreement. The resonant frequencies of the antenna can be reconfigured by loading a chip capacitor at the center of the X-slot. The location of the capacitor is chosen normal to the feed line to minimize the variations of one mode and to obtain a frequency tunable antenna with adequate control over its frequency ratio. However, the decrease is not uniform and depends on the orientation of the capacitor along the slot.

TABLE II COMPARISON BETWEEN THE COMPUTED AND SIMULATED RESONANCES OF THE DESIGNED ANTENNAS

Antenna	ε_r	h (mm)	W_f (mm)	W (mm)	L (mm)	L_s (mm)	L_x (mm)	W_x (mm)	f_{r10}, GHz		f_{r01}, GHz	
									Computed	Simulated	Computed	Simulated
1	4.2	1.6	3	43.47	30.9	5.14	18.3	2.29	1.12	1.12	1.44	1.44
2	3.8	1.6	3.3	46.49	33.34	5.35	19.05	2.39	1.12	1.12	1.44	1.44
3	3.38	1.57	3.5	50.38	36.37	5.62	20	2.51	1.12	1.11	1.44	1.42
4	2.65	1.59	4.35	58.79	42.89	6.21	22.09	2.77	1.12	1.11	1.44	1.41
5	2.32	1.6	4.7	63.8	46.78	6.56	23.34	2.92	1.12	1.11	1.44	1.4

Hence, the capacitor is placed along x-direction to minimize the variations of TM_{01} mode and at the same time TM_{10} mode can be tuned by changing the value of the capacitor. The reflection characteristics of the antenna for different capacitor values are shown in Fig. 5. Only a few variations are shown for brevity. The variation of resonant frequency and return loss characteristics of the antenna for different values of chip capacitor is given in Table III.

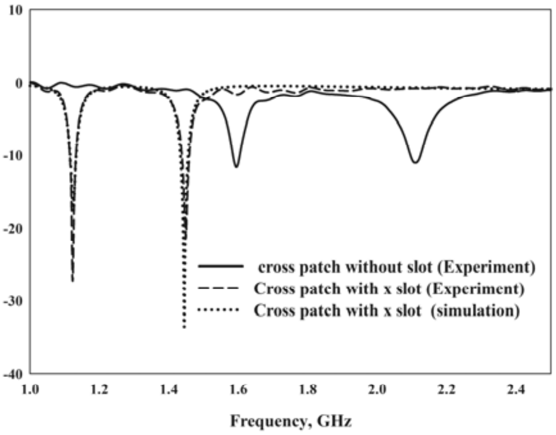

Fig. 4 Simulated and measured reflection characteristics of cross patch antenna with and without X-slot

It can be seen that the fundamental resonant mode (TM_{10}) is tuned to 672 MHz from 1.118GHz with capacitor value C=3.3pF. The effective resistance of this mode decreases drastically and is suppressed due to very low impedance (4.7-j2.5 Ω) by increasing the capacitor values from 10pF onwards. Also, loading a chip capacitor generates an additional TM_{10} mode at higher frequency due to shortest electrical path through the capacitor along x-direction. This third resonant frequency is not matched for low C values due to high inductive reactance (68+ j58 Ω) and achieves impedance matching by increasing the value of C from 2.2pF to 100pF. In addition, increase in C offers tuning to 1.594GHz from 1.748GHz and all the frequencies are well matched, except for C=1pF, with a linearly polarized radiation along x-direction.

The second resonant frequency (TM_{01}) is well matched for all values of capacitance ranging from 1pF to 100pF, which gives a linearly polarized radiation along y-direction. A slight variation is observed when the value of C is increased, but this change is negligible compared to that of third resonant frequency. Hence, it is found that the second resonance is determined by the cross patch antenna with X-slot while the first and third resonance is excited with respect to the chip capacitor value. Thus, the antenna offers a frequency ratio of 1.66 and 1.09 for first and second resonances with linearly polarized radiation along x-direction and y-direction respectively. With capacitor value equal to 15pF, the 2:1 VSWR bandwidth is measured to be 90 MHz, which amounts to 6% with respect to the centre frequency of 1.49 GHz. In addition, the second and third modes come close together which results a circularly polarized radiation at1.465GHz. The measured resonant frequencies f_1, f_2 and f_3 along with frequency ratio f_R (f_3/f_2) with various capacitances is shown in Fig. 6.

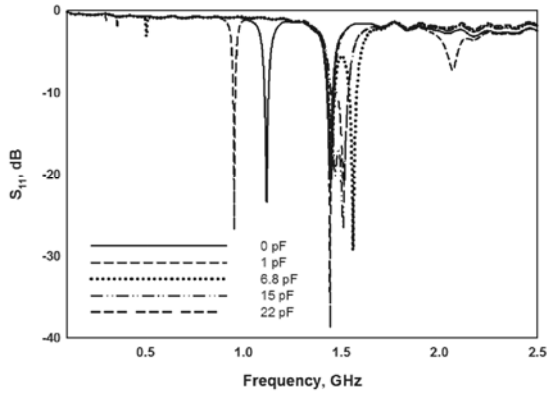

Fig. 5 Measured return loss for the proposed antenna with various capacitances

TABLE III PERFORMANCE OF THE ANTENNA AGAINST VARIOUS CAPACITANCES

Capacitor (pF)	f_1(G HZ), S_{11}(-dB)	f_2(G HZ), S_{11}(-dB)	f_3(G HZ), S_{11}(-dB)	Input Impedance (Ω)					
				f_1		f_2		f_3	
				Re.	Im.	Re.	Im.	Re.	Im.
0	1.12,23	1.44,20	-	56	3.6	49.9	9.5	-	-
1	0.95,26	1.45,21	2.07,6.7	46	-2	49	9	68	58
2.2	0.77,10.7	1.44,18	1.75,14	27.6	-9.8	52	12	73	-7.5
3.3	0.67,9.5	1.46,18.5	1.64,23	72.8	35	62.7	3.3	44.5	-3.8
4.7	0.59,5	1.46,23	1.62,20	13	-4	56	4	49	-10
6.8	0.5,3	1.45,19	1.56,29	169	133	57	9	53	1
8.2	0.45,2.5	1.46,17	1.55,28.5	9.5	28	64	6.5	52	3
10	0.42,1.6	1.44,17	1.54,46	4.7	-2.5	54	13	50.6	0.3
15	1.44-1.53			-	-	57.5	-8	54.5	3.4
22	-	1.44,38	1.51,21	-	-	50.9	0.8	49.3	-9
47	-	1.44,20	1.59,26	-	-	60	4.3	51.7	-4.7
100	-	1.49,25	1.59,32	-	-	50.5	-5.5	51.5	-2

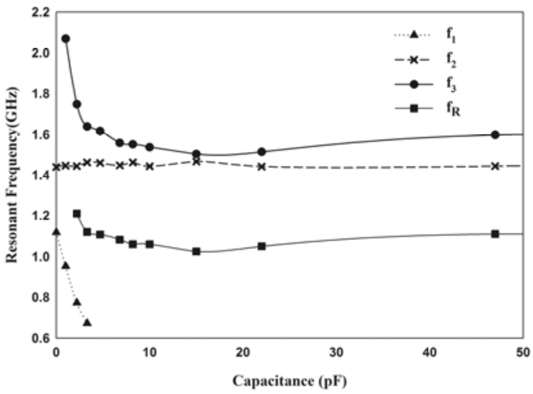

Fig. 6 Measured resonant frequencies and frequency ratio f_R (f_3/f_2) against various capacitances

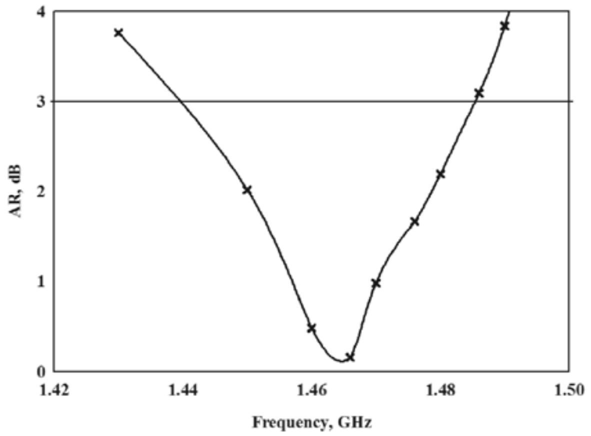

Fig. 7 Measured axial ratio of the antenna with capacitor value of 15pF

The measured axial ratio of the antenna when C=15pF is plotted in Fig. 7. The best CP performance in the broadside direction is achieved at 1.465GHz with 3% CP bandwidth. The measured radiation patterns of the antenna for capacitor values 1pF, 6.8pF and 15pF are plotted in Fig 8 (a), (b) and (c) respectively. It is observed that the antenna has similar radiation patterns at both the modes and the shape of the patterns remain unchanged as the capacitor value is changed. A broadside radiation characteristic in both X-Z and Y-Z planes with more than 100º half power beam width are obtained in all linear polarization states. Furthermore, low cross polar levels are achieved. The cross-polarization levels are, however, larger at 952MHz due to smaller electrical dimensions of the antenna at this frequency.

The gain is also measured using a double ridged horn as a reference and is shown in Fig. 9. The antenna shows a peak gain of 3.39dBi in the direction of maximum radiation. The lower gain of the antenna is a result of smaller electrical dimensions at lower frequencies that occurs due to capacitive loading.

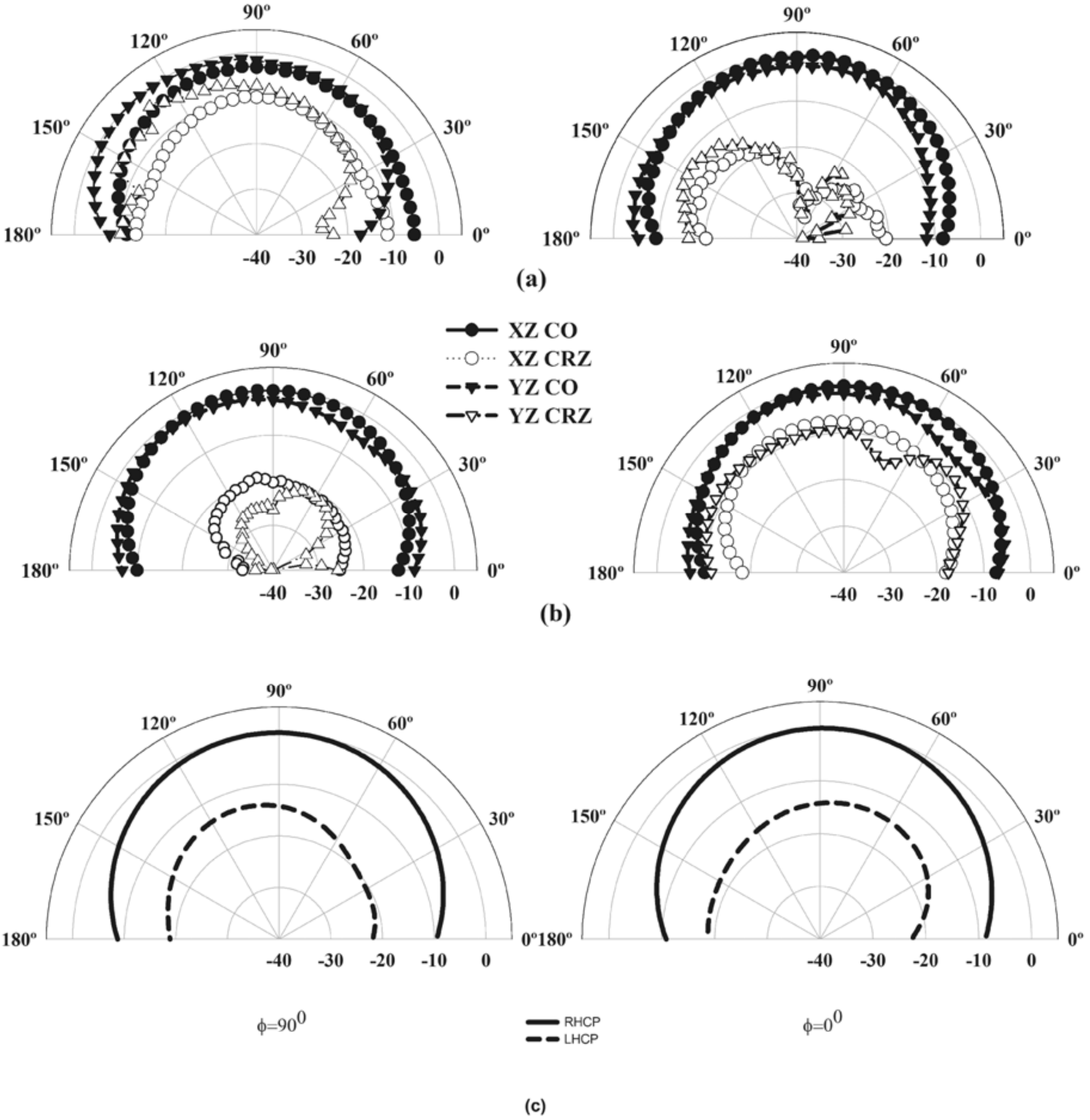

Fig. 8 Measured radiation pattern of the antenna with various capacitances
(a) 1pF at 952MHz and 1.447GHz
(b) 6.8pF at 1.448GHz and 1.559GHz and
(c) 15pF at 1.465GHz in $\varphi = 0^0$ and $\varphi = 90^0$ plane

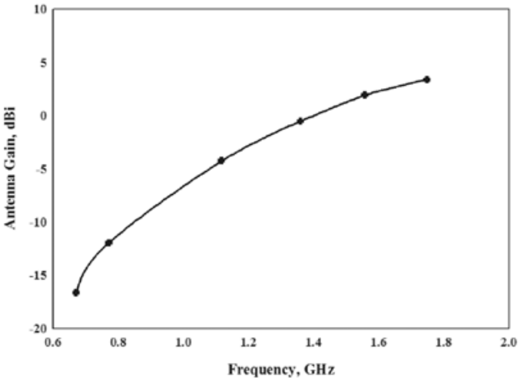

Fig. 9 The measured gain of the antenna

IV. CONCLUSION

A single feed design of novel compact frequency and polarization tunable microstrip antenna is proposed in this paper. The concept is based on the tuning of embedded slots in the patch antenna using a chip capacitor. A high tuning range of 34.48% and 14.3% is achieved for the first and third resonant frequencies respectively by minimizing the variations of second resonant frequency. Measurement results of the antenna indicate that its frequency ratio can assume any value in the range $1.025 \leq f_R \leq 1.21$with linear or circularly polarized radiation by changing the capacitor value from 1pF to 100pF. Furthermore the proposed antenna has an added advantage of size reduction, moderate gain, low levels of cross-polarized radiation and the radiation patterns of each frequency remain unchanged as the capacitor value is changed. Empirical equations are deduced and validated on different substrates. By replacing the chip capacitor with a varactor diode the proposed design can be extended to frequency agile polarization diversity antenna.

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