Design of a S Band Circularly Polarized Microstrip Patch Antenna Using Ferrite Disk

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Abstract – **The design of a microstrip patch antenna in the S band for nano-satellite application is presented. Two self biased ferrite disks are inserted in the resonant region of the patch to obtain circular polarization. The addition of ferrite disks results in gain enhancement, increase in bandwidth and decrease in axial ratio. Experimental results show that the antenna has a gain of 6.159 dB, an impedance bandwidth of 140 MHz at a resonant frequency of 2.455 GHz and an axial ratio of 1.016 which is in concurrence with the simulated results.**

Keywords – **Patch antenna; Nano-satellite; Ferrite; Circular-polarization; S-band.**

I. INTRODUCTION

As technology has progressed, there is a trend of miniaturization of equipments in different fields, especially in communication systems. One of the major components of the communication systems, the satellites, have undergone a significant improvement in design, weight, performance, power handling capacity and other factors over the past few years [1-5]. The core of any satellite based communication is the antenna; both at the ground station and the satellite. The earth stations use parabolic dishes for receiving as well as transmitting signals into the space [6, 7]. For small satellites an array of patch antennas forms an attractive alternative over conventional antennas such as Yagi-Uda, Horn antennas, as these are compact, light-weight and require significantly less power [8, 9].

Both the transmitting antennas as well as the receiving antennas are circularly polarized. It eliminates the need of orientation of the antennas since a circularly polarized antenna can receive equal power in the horizontal as well as the vertical plane (ideally AR =1, or 0 dB). However, practically, antennas should have AR less than 3 dB (1.412). There axial ratio bandwidth for circularly polarized antennas can vary anything from a few kilohertz (Reference no. ii and iii) to several megahertz depending on the application [10-12]. In case of amateur bands, the bandwidth is regulated by the country of operation [13]. Circular polarization in a patch antenna can be achieved by various means such as using a diagonal feed, truncating the edges or using magnetic substrates. The use of ferrites as magnetic substrates in patch antennas presents offers additional advantage in addition to circular polarization such as miniaturization, improvement in impedance matching and radiation efficiency [14-16]. Further the resonant frequency of the antenna can be tuned by applying suitable magnetic bias to the ferrite substrate [17-20].

A normally applied magnetic bias to a microstrip patch could be used to obtain a circular polarization from a square patch with a single feed probe which could be tuned by adjusting the bias field. The direction of polarization can be varied by altering the polarity of the bias field [21, 22]. M. Sigalov et al. investigated the effect of ferrite disks inserted in the resonant region of the patch. This was a significant improvement over the design which employed full ferrite substrate to control the radiation characteristics of the antenna. They were able to achieve a single and a dual band circular polarization due to the rotating field caused due to interaction of electromagnetic waves with the ferrite disk within the cavity region of the patch [24].

In our work, we have extended this concept to develop a prototype based on self-biased ferrite disks which can be further explored for use in space applications since nanosatellites such as cubesat have stringent weight and size requirements. The ferrite disk can be replaced by a stronger (large saturation magnetization and anisotropy) low loss ferrite and the square patch can be modified to suit the requirements. We propose to use self biased ferrite disks in the cavity region of the conventional rectangular patch to influence its radiation characteristics. There have been reports on the use of self biased ferrite thin films for tuning of antenna parameters [25-27]. Ferrite disks are convenient to fabricate compared to their thin film counterparts. The use of self biased ferrite disks offers an advantage of obtaining desired frequency and gain by placing the disks at various positions underneath the patch. Further, the height of the disk can be controlled which is quite inconvenient in case of thin films. The use of self bias ferrite disks eliminates the need of magnetic biasing source making the design lightweight and compact. In our case the axial ratio at the resonant frequency was found to be 1.02 in concurrence with the simulations, while the axial bandwidth obtained from simulations is greater than 300 MHz, encompassing the frequency bandwidth (122.7 MHz).

II. THEORY

A. Propagation of Plane Wave in Magnetized Ferrite

Consider a ferrite biased with a DC magnetic source in an arbitrary direction. Let an electromagnetic plane wave be incident on the ferrite such that its propagation vector **k** makes an angle θ with the direction of the applied dc magnetic bias.

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The effective permeability μ_{eff} of the ferrite derived from Polder's tensor is given as [28, 29]:

$$\mu_{eff}(\theta) = \\ = \frac{2+\left(\frac{\mu_\perp}{\mu_\parallel}-1\right)\sin^2\theta \pm \sqrt{\left(\frac{\mu_\perp}{\mu_\parallel}-1\right)^2 \sin^4\theta + 4\frac{\mu_a^2}{\mu^2}\cos^2\theta}}{2\left(\frac{\sin^2\theta}{\mu_\parallel}+\frac{\cos^2\theta}{\mu}\right)}, \quad (1)$$

where $\mu_\perp = \mu - (\mu_a^2/\mu)$. The terms μ_a and μ represent the off-diagonal and the diagonal terms of the permeability tensor respectively. For the wave propagation vector of the incident electromagnetic wave is parallel to the applied external dc magnetic bias ($\theta = 0^o$), the wave propagation constant can be resolved into two parts, given by $k' = \omega\sqrt{\varepsilon\mu^R}$ and $k'' = \omega\sqrt{\varepsilon\mu^L}$.

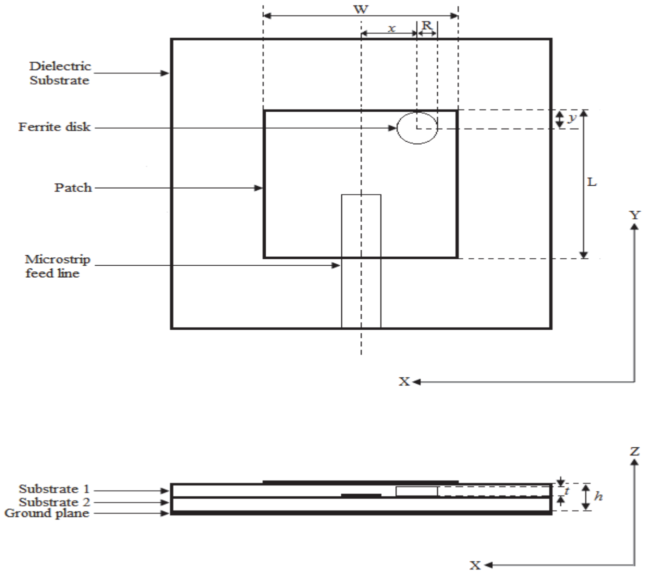


Fig. 1. Geometry of rectangular patch antenna with ferrite disk showing top view and side view

The wave in the ferrite will consist of two circularly polarized waves with k' and k'' representing the propagation constants of the right hand and the left hand circularly polarized waves respectively. Here μ^R and μ^L are roots of Eqn. 1 representing the permeability of the RHCP and LHCP wave respectively.

B. Cavity Region Model of Patch Antenna

The cavity region of a rectangular microstrip antenna can be modelled as an equivalent rectangular waveguide with the side walls approximated as magnetic conductor while top and bottom walls approximated as electric conductors. For such a configuration i.e. L > W > h, TM_{010} is the dominant mode with the electric field given as [30]:

$$E_z = E_0 \cdot \cos\left(\frac{\pi}{L}y'\right). \quad (2)$$

III. NUMERICAL AND EXPERIMENTAL TECHNIQUE

In the rectangular patch antenna was designed and simulated to study the effect of self biased ferrite disks on the radiation characteristics of the antenna. Fig. 1 shows the design of the rectangular patch antenna. A proximity coupled feed technique was employed for improved impedance matching. The initial dimensions of antenna were obtained using Transmission Line Model equations [30].

The width (*W*) of the patch is given as:

$$W = \frac{1}{2f_r\sqrt{\mu_o\varepsilon_o}} \cdot \sqrt{\frac{2}{\varepsilon_r+1}} = \frac{\vartheta_o}{2f_r} \cdot \sqrt{\frac{2}{\varepsilon_r+1}}, \quad (3)$$

where f_r is the resonant frequency, ϑ_o is the speed of light in free space and ε_r is the permittivity of the dielectric substrate.

The effective permittivity (ε_{reff}) of the dielectric substrate is given as [31]:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} - \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-\frac{1}{2}}, \qquad \left(\frac{W}{h}>1\right) \quad (4)$$

The extended length (ΔL) due to fringing field effects is given as [32]:

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff}+0.3)\cdot\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\cdot\left(\frac{W}{h}+0.8\right)} \quad (5)$$

The effective length (L_{eff}) of the patch is given as:

$$L_{eff} = L + 2\cdot\Delta L. \quad (6)$$

where the actual length (*L*) of the patch is given by the equation:

$$f_r = \frac{1}{2L\cdot\sqrt{\varepsilon_{reff}}\cdot\sqrt{\mu_o\varepsilon_o}} = \frac{\vartheta_o}{2L\cdot\sqrt{\varepsilon_{reff}}}. \quad (7)$$

The design parameters are calculated considering a total height of the substrate as 3.2 mm and proximity coupled microstrip feed. The actual fabrication is done on two different substrates which are then combined. Since the height of each substrate (1.6 mm) is greater than the height of the ferrite disk (1.5 mm), there is no effect on the combined height of the substrate and the disk. Then simulation is carried out using combined disk and substrate and the shift in frequency is adjusted by changing the position of the disks (Fig. 2 and Fig. 4).

These dimensions were then optimized for a centre frequency of 2.435 GHz. The optimized dimensions of radiating patch is 27.07 x 27.07 mm^2 which is placed on a 55 x 55 mm^2 FR4 substrate with ε_r of 4.4 and tan δ of 0.012. The height of the substrate (h) was 3.2 mm and the feed line was placed at the height of 1.6 mm from the ground plane.

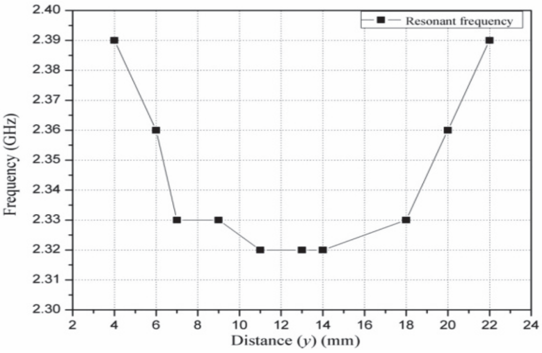


Fig. 2. Variation of resonant frequency along length of patch

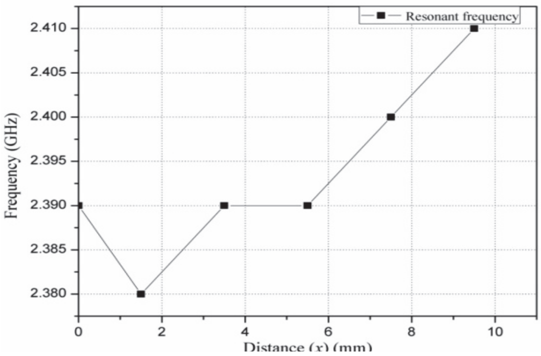


Fig. 4. Variation of resonant frequency along width of patch

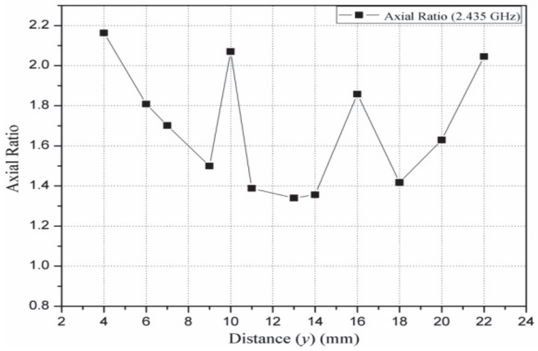


Fig. 3. Variation of axial ratio along length of patch

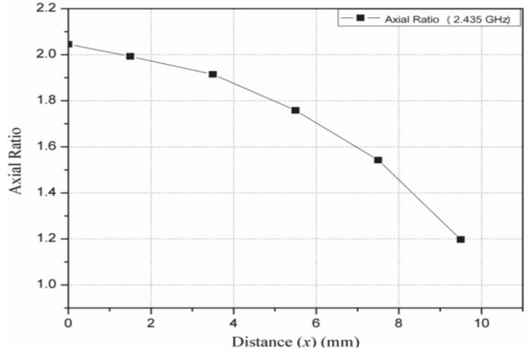


Fig. 5. Variation of axial ratio along width of patch

This conventional microstrip patch antenna was simulated using HFSS software. The simulated characteristics of antenna in terms of return loss, gain and axial ratio are shown in Table I. The antenna shows a gain of 4.66 dB at frequency of 2.435 GHz while the axial ratio is 363.91 at the resonant frequency. High value of axial ratio shows that the designed antenna is linearly polarized.

Next the ferrite material was used to improve the antenna characteristics in terms of return loss, directive gain and axial ratio. A ferrite disks of the radius R = 4.0 mm and thickness t = 1.50 mm with $\varepsilon_r = 5.20$, $\tan \delta = 0.25$, $4\pi M_S = 3392$ G were inserted at the height 1.6 mm from the ground plane. Depending on the M-H curve of a magnet, ferrites with high anisotropy and hence coercivity have high demagnetization field. In absence of external demagnetization field and factors such as heat, mechanical shocks, ferrites such as YIG (Yittrium Iron Garnet) can retain magnetization for a very long duration. The effects of insertion of ferrite disk with respect to the position X and Y of were studied shown in Figs. 2 to 5. An external magnetic bias field of 0.001 A/m was applied in the z-direction to the ferrite disk. The entire geometry was simulated using Ansoft High Frequency Structure Simulator (HFSS) 13.0.

Fig. 2 shows the variation in the resonant frequency with respect to the Y position (x = 0 mm) of the ferrite disk. It is observed that the deviation of the resonant frequency of the ferrite based antenna with respect to the resonant frequency of a simple patch antenna is minimal at the edges of the patch and increases as one moves to the centre of the patch. Fig. 3 shows the variation in the axial ratio of the ferrite based antenna. The axial ratio shows a non-uniform decrease with values close to 1 near the centre of the patch.

Next, the position of the ferrite disk was varied along the edge X position (y = 4 mm) of the patch (along the width) perpendicular to the feed. The variation was made in one direction considering the symmetry of the patch along the width. Fig. 4 shows the variation in the resonant frequency with respect that of the normal patch antennas decreases as the disk is moved towards the end of the patch. The axial ratio shows a marked decrease with increasing distance of the disk from the centre of the edge of the patch as shown in Fig. 5.

Thus, it can be inferred that the shift in the resonant frequency is minimum when the ferrite disk is placed at the edges along the length of the patch while the axial ratio attains a minimum value with the disk placed at the edges along the width of the patch.

To further improve the radiation characteristics, two ferrite disks were inserted at the corners of the patch orthogonal to the microstrip feed line. The antenna showed resonant frequency at 2.435 GHz corresponding to left hand circular polarization. The axial ratio at the resonant frequency was found to be 1.12 which confirmed the circular polarization of the antenna (Fig. 6). For the frequency bandwidth from 2.375 GHz to 2.495 GHz the axial ratio was found to be less than 1.30.

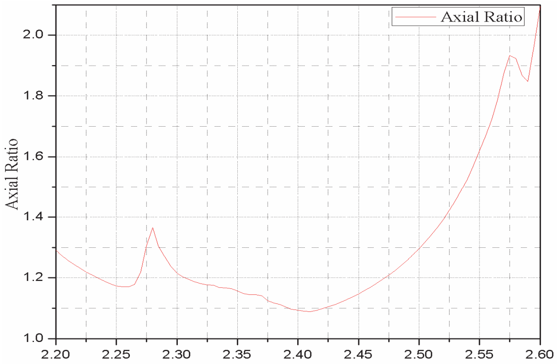


Fig. 6. Axial ratio of antenna with two ferrite disks

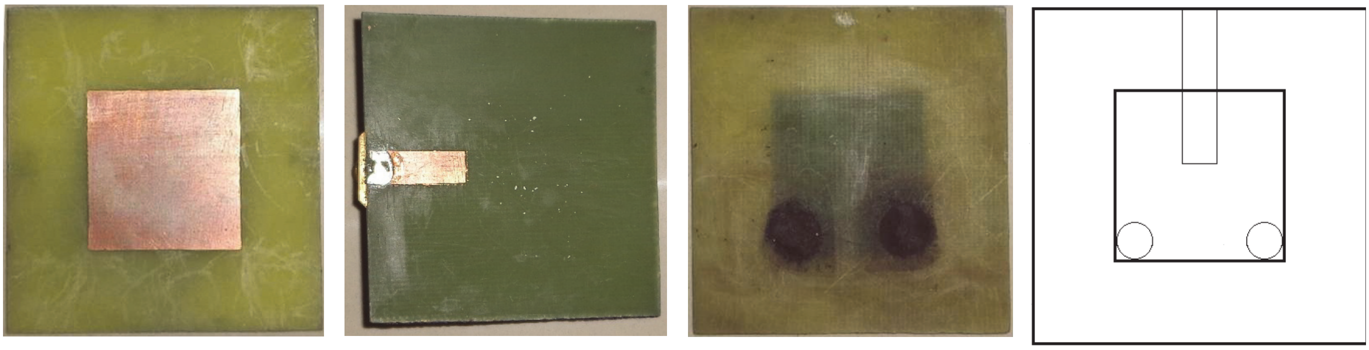

(a) (b) (c) (d)

Fig. 7. (a) Patch on substrate 1; (b) Microstrip feed line on substrate 2; (c) Patch with two ferrite disks; and (d) Image of ferrite disks

Based on the above simulation results, a patch antenna was fabricated with the dimensions 27.07 x 27.07 mm^2 on a 55 x 55 mm^2 FR4 substrate (Fig. 7). The feed line was etched onto the top of the substrate 2 (FR4). Comparison between the experimental and the simulated results of the normal patch antenna and ferrite based patch antenna is shown in Fig. 8. The radiation characteristics were measured with the help of Vector Network Analyzer (Agilent N5171) and a signal generator. The antenna showed a return loss of 43.73 dB at a resonant frequency of 2.47 GHz with an impedance bandwidth of 97.7 MHz.

For measurement of gain, two identical antennas were fabricated and their gain was calculated using Friis transmission equation. Then, using one of these antennas the gain of ferrite loaded antenna was similarly calculated with the aid of Friis transmission equation. The gain was found to be 4.86 dB and the axial ratio was 10.23 at 2.47 GHz. Next two ferrite disks were inserted in the bottom of substrate 1 (FR4) and the measurements were taken. The resonant frequency showed a shift to 2.455 GHz with a return loss of 39.72 dB. The antenna showed an improved bandwidth and gain of 140 MHz and 6.16 dB respectively. The value axial ratio obtained was 1.02. Figs. 9 and 10 show the radiation pattern of the normal and the ferrite based antenna respectively. The value of axial ratio obtained was 1.02. The experimental results are in agreement with the simulation results. The values of the radiation parameters are shown in Table I.

Initially, a single disk was placed at one corner of the radiating edge opposite to the microstrip line. The normal patch antenna which resonated at 2.45 GHz showed a shift to 2.39 GHz (Fig. 2. y = 4 mm). The position of the disks was gradually shifted to the opposite radiating edge along the non-radiating edge. The resonance frequency shows a further decline as the disk was brought to the centre of the non-radiating edge (Fig. 2). On bringing the disk to the corner of the second radiating edge, the resonant frequency once again became equal to 2.39 GHz.

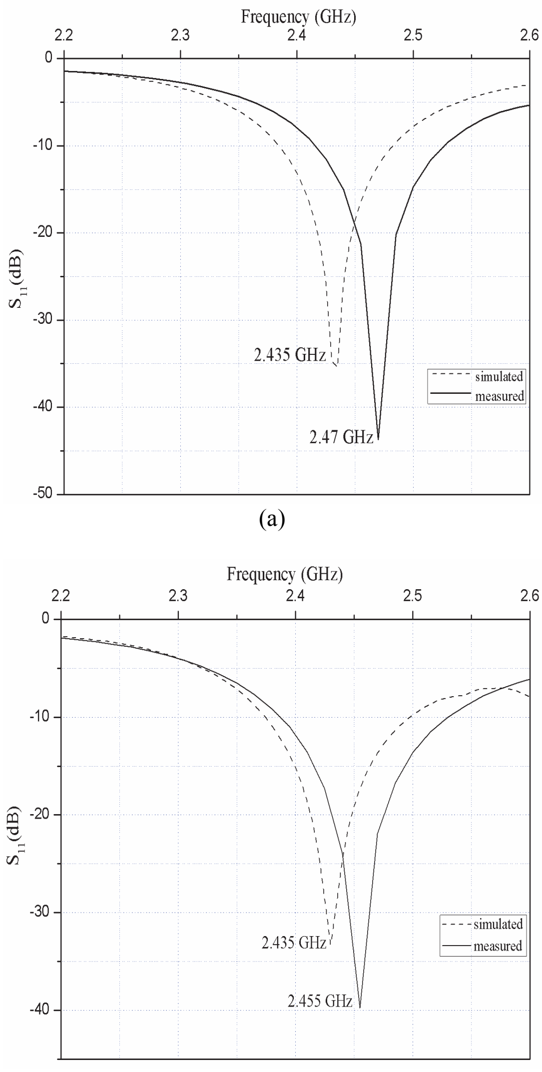
TABLE 1

COMPARATIVE STUDY OF DIFFERENT ANTENNA PARAMETERS

Antenna Parameters	Simple Patch		Patch +1 disk	Patch + 2 disks	
	Sim.	Meas.	Sim.	Sim.	Meas.
f_r (GHz)	2.435	2.47	2.39	2.435	2.455
S_{11} (dB)	-35.42	-43.73	-15.50	-33.26	-39.72
Gain (dB)	4.66	4.86	4.80	4.59	6.16
BW (MHz)	97.7	120	79	122.7	140
Axial Ratio	363.91	10.24	2.11	1.12	1.02

Next the disk was placed at the centre of the radiating edge opposite to the microstrip line and slowly moved along it (radiating edge) (Fig. 4). The resonant frequency starts to increase from 2.30 GHz to 2.41 GHz as we move to the corner. Secondly, the axial ratio is found to decrease similarly as on moves to the corner of the radiating edge (Fig. 5). Thus the corner of radiating edge (either 1 or 2) was found to be suitable position for ferrite disks. However, one disk was not sufficient for satisfactory results (axial ratio = 1), we used two disks instead.

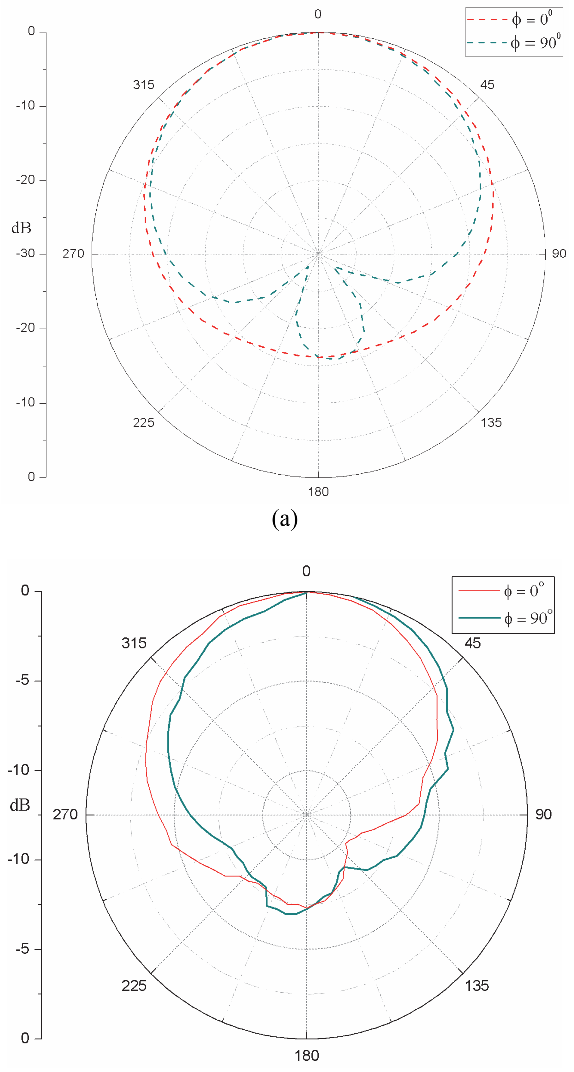
The slight discrepancy in the experimental and the simulated results can be explained on the basis of the deviation of the value of permittivity of the FR substrate used from the ideal value of 4.4 [33]. The second reason may be presence of an air gap between substrate 1 and substrate 2 due to the unevenness of the surfaces. The air gap can act as a dielectric layer between the two substrates thereby changing the value of effective dielectric constant of the substrate [30]. The ground plane dimension is 55 x 55 mm^2. In our design, we have used two different substrates for the feed and the patch. Further, there might be a misalignment between the two substrates when they are brought together. This may be the reason for the appreciable radiation in the lower hemisphere. For the simulation finite ground plane was used. The results conform to the frequency standard for nanosatellites [34-36].



(a)

(b)

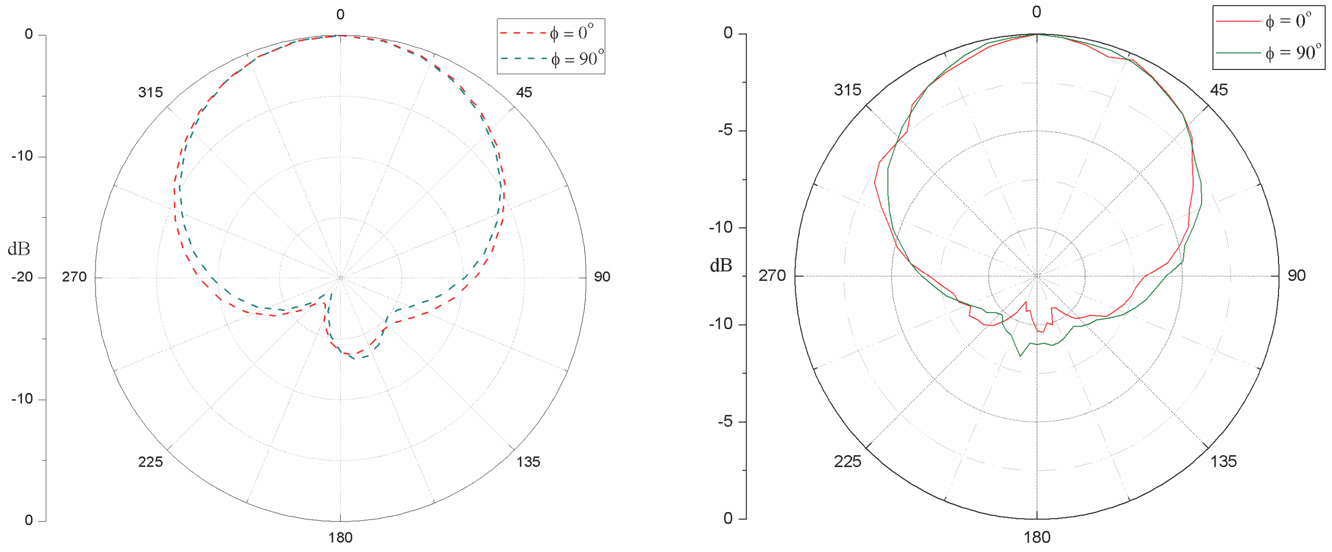
Fig. 8. Comparison between simulated and experimental resonant frequency of: (a) Normal patch antenna and (b) Ferrite based antenna



(a)

(b)

Fig. 9. Radiation pattern of a normal patch antenna: (a) simulated; and (b) fabricated



(a)

(b)

Fig. 10. Radiation pattern of ferrite based antenna: (a) simulated; and (b) fabricated

IV. CONCLUSION

The use of self biased ferrite disks for obtaining circular polarization is reported. The ferrite based antenna showed a resonant frequency of 2.455 GHz with a return loss of 39.72 dB and a bandwidth of 140 MHz. The antenna showed an improved gain of 6.16 dB and circular polarization. The antenna works in the S band and an array of antennas based on the above prototype can be used in the nano-satellites. The presence of self biased ferrite eliminates the use of external magnets for providing magnetic bias thereby makes the antenna light and compact.

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