Design of High Performance Circularly Polarized Radiating Element for Phased Array Antenna for Satcom on the Move

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Abstract. The paper describes the design, development, and characterization of a circularly polarized, wide beam radiating element for Electronically Steered Phased Array Antenna (ESPAA) for satellite communication (Satcom) on the move application at S-Band frequency. A corner truncated microstrip patch etched on Rogers TMM4 dielectric material placed on a rohacell filled the metallic cavity is proposed to achieve broader beam as well as wider bandwidth characteristics. The antenna has been simulated on finite element method-based ANSYS's high frequency structure simulator (HFSS) EM software using proper boundary conditions. Voltage standing wave ratio of 2.0:1 is achieved over the frequency band of 2.50-2.80 GHz. The measured axial ratio lies well below 3.2 over the frequency band (2.56-2.69 GHz). The measured 3-dB beam width of the antenna in E-plane and H-plane are 86.5 and 85.3 degrees respectively at 2.6 GHz.

Keywords: Cavity-backed, circular polarization, phased array, wide beam

1. Introduction

Satellite communication has been preferred for beyond line of sight communication. Satcom on the Move (SOTM) is specifically related to military ground vehicles. Satellite communication on the move system is a rapidly growing market where network capabilities are directly dependent on the performance of the antenna mounted on the vehicle. In SOTM system, a vehicle equipped with a satellite antenna can establish a communication link with a satellite and maintain the communication all time while the vehicle is moving. These types of systems are being used for voice, data and high-quality video transfer from one place to another. These are also being used for secure communication systems. To ensure continuous communication, it is necessary that the antenna beam should always be pointed accurately towards the satellite. Further, the antenna should be able to stabilize the radiation pattern during the movement of the platform [1].

The performance of SOTM system is mainly decided by the performance of the antenna used as the antenna faces the signals first. Satellite communication on the move has been using mechanically steerable antennas since many years. These systems have several limitations such as larger volume, low reliability, slow response, requires periodic maintenance and its maintenance cost is high. To overcome these limitations, an electronically steered phased array antenna is preferred for this application.

The amount of beam steering of S-Band SOTM depends on the location of the system being installed and location of the satellite (GSAT-6) being used. To communicate with the GSAT-6 satellite over the Indian geographical region, the required elevation angle ranges from 45 degrees to 85 degrees from the ground. Hence for beam steering ± 45 degrees from boresight would be sufficient enough to maintain communication all the time during movement of the vehicle.

ESPAA system mainly consists of an array of radiating elements, RF manifold network, transmit and receive module and beam controller unit. The radiation pattern of an array antenna is decided by the configuration of the array antenna, i.e., the inter-element spacing between radiating elements, amplitude and phase of the signal at the input of each radiating element, and also radiation pattern of the individual element. In phased array antenna, as the beam is steered from boresight, it becomes wider due to the reduction of the effective aperture area of the antenna and also beam scanning capability of a phased array antenna is decided by 3-dB beamwidth of its radiating elements [2-3].

Microstrip patch antennas (MPA) are most suitable radiating elements for phased array antenna due to their advantages of low profile, light weight, easy to manufacture and low manufacturing cost. However, the principal disadvantage of MPAs is their relatively narrow bandwidth which can be improved by increasing the thickness of the substrate. Unfortunately, surface waves generated with substrate thickness degrade the scan performance of phased array antenna [4-5].

The effect of surface wave can be improved up to the certain extent by using a cavity backed patch antenna. Cavity backed patch antenna gained significant importance over the last decade due to its compact shape, minimum surface wave loss, reduced backward radiation, higher radiation efficiency, minimize the coupling between radiating elements in the array environment, better impedance matching, and wide scan performance. The resonant fields in the cavity also help in reducing the size of the antenna without much affecting the antenna performance [6-12].

The present paper describes the realization of a low profile, light weight, wide beam, wide band, circularly polarized cavity backed patch antenna as a radiating element for S-band phased array antenna for SOTM application. This system will replace the bulky, mechanically steered antenna being used in present SOTM systems. The detailed design approach, simulation and optimization, results and discussion are discussed in the following section.

2. Design approach

Radiating elements play a critical role in deciding the performance of ESPAA. The Large impedance bandwidth, wide beamwidth, low RCS, high isolation and light weight are the prime requirements of any radiating element to be used for the realization of ESPAA. The inter-element spacing should be near to half of the operating wavelength to avoid the grating lobe. So, miniaturization of the size of the patch antenna is required. Miniaturization of the size of the patch is achieved by placing cavity beneath the patch which provides capacitive loading to the patch resulting in the reduction of its resonant frequency for a given physical length. In array environment, cavity backed patch antenna provides excellent isolation between adjacent antenna element by suppressing surface wave and radiation coupling. Also wide band and the wide beam can be achieved by using cavity structure without introducing the high dielectric constant material. Hence, a Cavity-backed antenna is the most suitable radiating element for wide angle scan performance of phased array antenna [13].

The design of cavity backed patch antenna depends on its operating frequency, beam width, gain, and polarization. Circularly polarized antenna is required for S-Band SOTM application to cater the multi-path effect and also to minimize polarization loss as S-band satellite transponder is circularly polarized. Truncation at the corner of the square patch is used to generate circularly polarized wave from patch antenna. Small isosceles right angle triangular areas of a patch are removed from the diagonally opposite corners of the square patch. Corner truncation is decided by the equation given below.

$$\frac{\Delta S}{S} = \frac{1}{2 * Q_0} \qquad (1)$$

Where ΔS is the area of perturbation, S is the area of the square patch and Q_0 is the unloaded quality factor of the patch. The value of Q_0 depends on the dimension of the patch and height, dielectric constant and loss tangent of a substrate material. The patch is coaxially fed along the central axis so that the orthogonal modes are generated. The primary advantage of single point feeding method is that it does not require any hybrid coupler.

For Phased array antenna, the radiating element should have as broad beamwidth as possible because it reduces the scan loss during the beam steering. To increase the beam width of the antenna a high dielectric constant substrate materialRogers TMM-4 (ε_r = 4.5) is used which reduces the size of microstrip patch and hence increases the beamwidth of the antenna. The increase in beamwidth of the designed antenna is sufficient enough for beam steering up to ± 45 degrees. Rohacell material having the dielectric constant ε_r of 1.0004 (close to the air ε_r) is used as a spacer which also provides rigidity to the antenna structure. The size of cavity depends on the resonant mode of the antenna structure. Being single layer configuration, this antenna provides very simple geometry in terms of fabrication.

3. Simulation and optimization

Finite element method based ANSYS's High Frequency Structure Simulator (HFSS) EM tool is used for simulation and optimization of designed antenna. 3D CAD model of the antenna element is shown in Figure1.

After modeling the antenna, its dimensions such as the size of truncation, the size of the patch, feed location and size of the cavity have is optimized for optimum radiation parameters over the frequency band.

In the present design, due to the resonant field inside the cavity reduction in patch size has been achieved as compared to conventional patch antenna at S-Band. The optimized cavity dimensions are $0.44\lambda_0$ (length) x $0.44\lambda_0$ (width) x $0.06\lambda_0$ (height) (λ_0 is the wavelength at the centre frequency, 2.60 GHz); with cavity wall thickness of 4mm. The size of 60 mil Rogers TMM4 dielectric substrate material is $0.49\lambda_0$ x $0.49\lambda_0$. The size of the patch is $0.30\lambda_0$ x $0.30\lambda_0$ with truncated corner of 0.095 λ_0. Antenna is fed at a distance of $0.076\lambda_0$ along the Y-axis from the center of the patch. The simulated E-plane and H-plane radiation patterns of the antenna are plotted in Figure 2 at 2.57GHz and 2.69GHz frequency. The variation of the peak gain over the frequency band is shown in Figure 3.

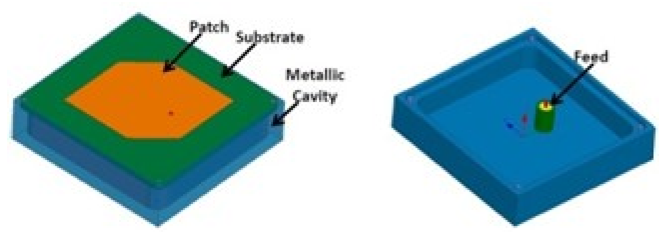
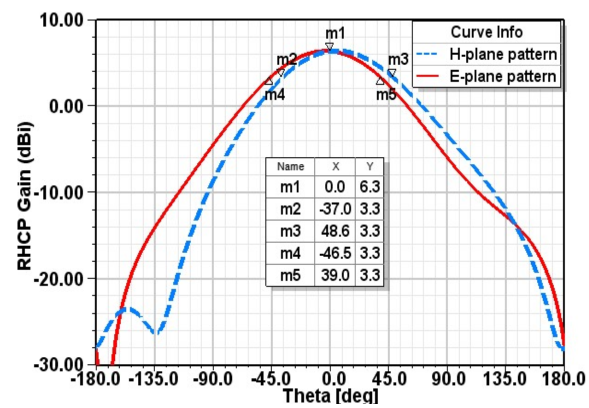
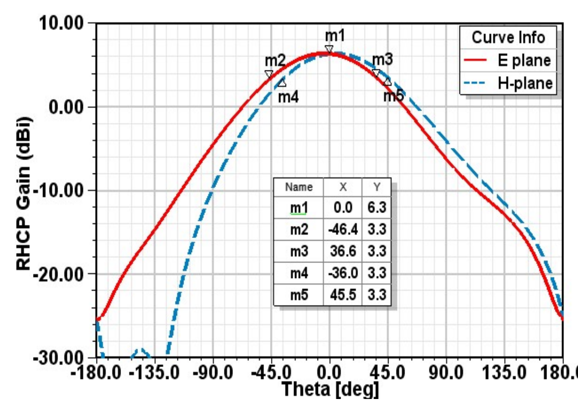


Fig. 1 (a). 3D CAD model of antenna (b) Inside view of cavity



(a) 2.57 GHz



(b) 2.69 GHz

Fig. 2. Simulated radiation pattern of proposed antenna

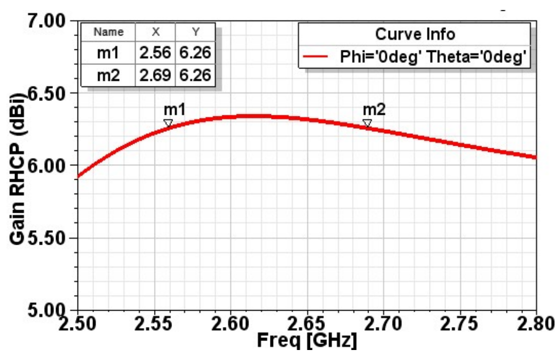


Fig. 3. Peak gain of antenna over the frequency band

For SOTM application, antenna impedance bandwidth, as well as axial ratio bandwidth, meets over the operating frequency band. The size of the cavity is optimized for desired impedance bandwidth as well as axial ratio bandwidth. The effect of cavity height, size on reflection coefficient and axial ratio of the antenna are shown in Figure 4 (a), 4 (b), and 4 (c), respectively. By increasing the height of cavity return loss degrades but at the same time axial ratio value improved. For 7 mm cavity height and 51 mm x 51 mm cavity size, antenna meets both impedance as well as axial ratio bandwidth. The size of truncation of the patch is also optimized for the desired band of frequency which is shown in Figure 4 (d). Truncation size of 11 mm gives better axial ratio over the desired frequency band.

Based on the performance of single cavity backed patch antenna, an 8x8 ESPAA is designed, modeled simulated, and optimized for SOTM application. CAD model of 8x8 ESPAA is shown in Figure 5. Each radiating element having its own transmit and receive module and connected through a coaxial feed. The transmit module would consist of a digital attenuator, phase shifter, and power amplifier network followed by diplexer while in receive mode, the signal would pass through diplexer then LNA, phase shifter, and digital attenuator. The inter-element spacing of the order of 0.50 λ_0 is considered to avoid the grating lobes in the visual scan region. Incremental phase shift with the value of 46.8, 93.6, 140.4 and 187.2 degrees is used to steer the beam at angle step of 15, 30 and 45 degrees respectively. Figure 6 shows the beam steering capability of the antenna. The simulated result indicates that antenna has the beam steering capability of ± 45 degrees from boresight. Scan loss of the order of 2.45 dB occurs at 45 degree considering mutual coupling effects of all radiating elements.

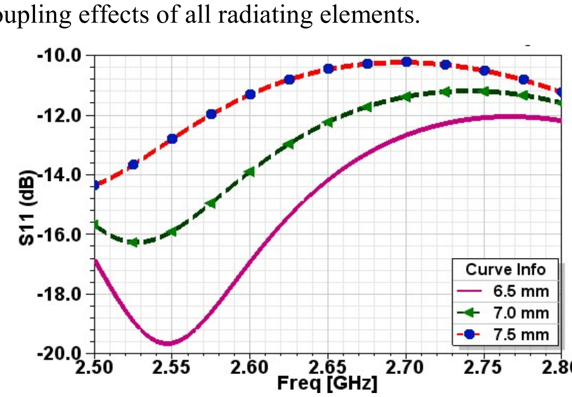


Fig. 4(a). Effect of cavity height on reflection coefficient

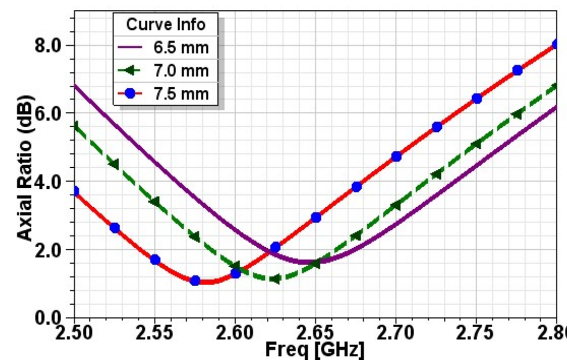


Fig. 4(b). Effect of cavity height on axial ratio

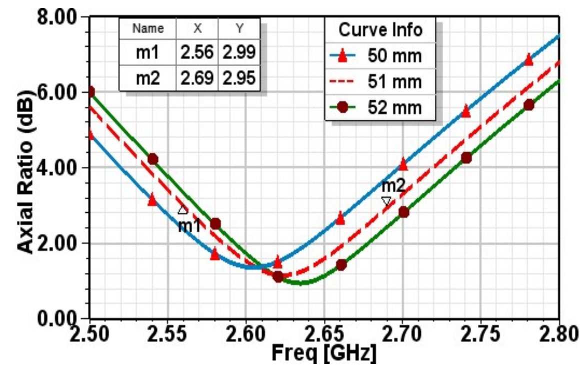


Fig. 4(c). Effect of cavity size on axial ratio

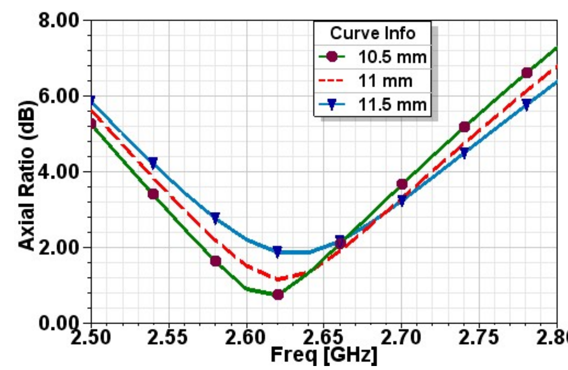


Fig. 4(d) Effect of the size of truncation on axial ratio

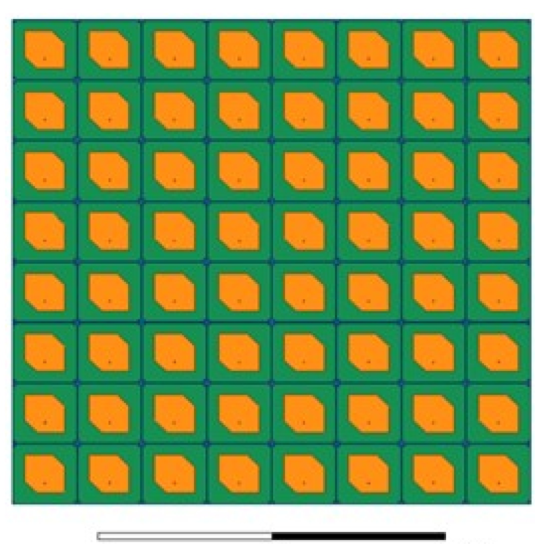


Fig. 5. HFSS model of 8x8 ESPAA

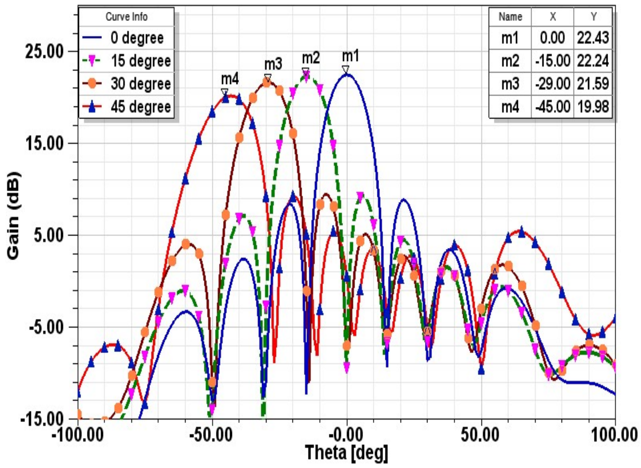


Fig. 6. Beam steering of 8x8 ESPAA

4. Results and discussion

The fabricated antenna consists of 60 mil Rogers TMM-4 substrate, rohacell spacer, metallic cavity and coaxial feed (SMA connector). Patch is printed on the top side of substrate and bottom layer is completely etched. A spacer is used to provide proper spacing and also provide extra mechanical strength to the antenna. Fabricated antenna is shown in Figure 7.

The VSWR of the antenna is measured using Rohde and Schwarz ZVK (10 MHz- 40 GHz) Vector Network Analyser. A comparison of simulated and measured value of VSWR and axial ratio are shown in Figure 8 (a) and 8 (b), respectively. It is clear that measured values follow the simulated results closely. Measured VSWR and axial ratio are well below 1.8 and 3.2 dB over the desired frequency band (i.e. 2.56GHz–2.69 GHz). The measured radiation patterns of the antenna at 2.57 GHz and 2.69 GHz are plotted in Figure 9 (a) and 9 (b), respectively. Measured 3 dB-beamwidth of the antenna is 86.3 degree in E-plane and 85.3 degrees in H-plane compared to the simulated value of 85.6 degree in E-plane and 85.5 degree in H-plane at 2.57 GHz. Measured gain of the antenna is 6.0 dBi at 2.57 GHz and 6.08 dBi at 2.69 GHz compared to simulated value of 6.26 dBi.There is some variation in the measured data which may be accorded due to fabrication tolerances and measurement inaccuracy.

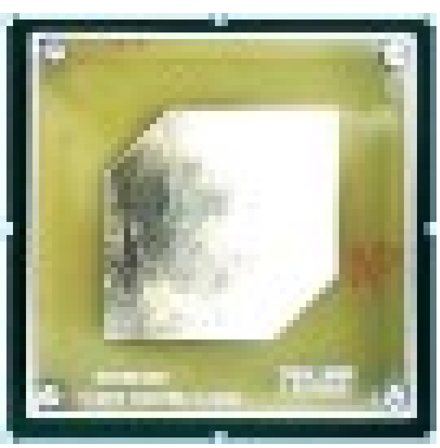


Fig. 7. photograph of developed antenna

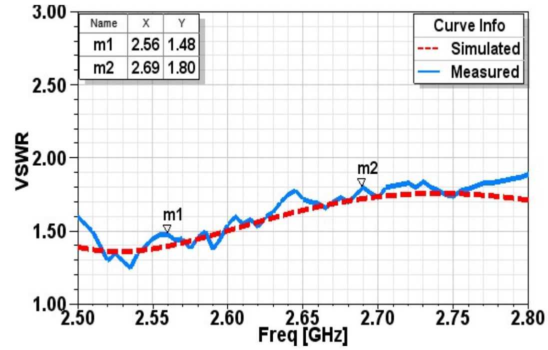


Fig. 8 (a). Simulated and measured VSWR plot

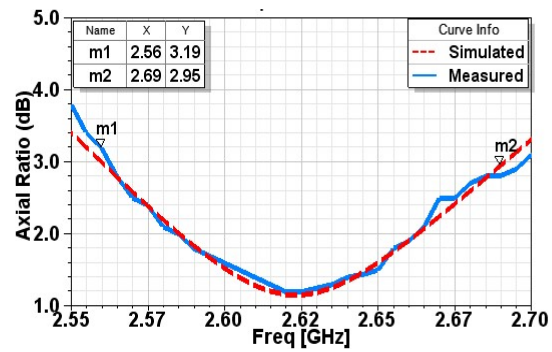


Fig. 8 (b). Simulated and measured axial ratio plot

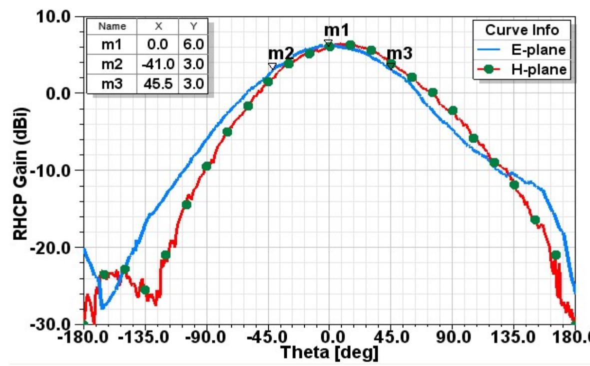


Fig. 9 (a). Measured radiation pattern at 2.57 GHz

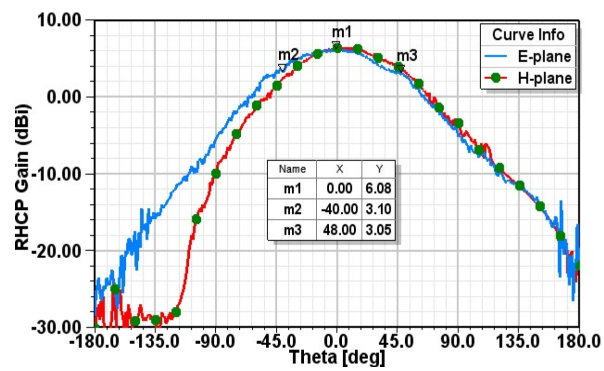


Fig. 9 (b). Measured radiation pattern at 2.69 GHz

5. Conclusion

A circularly polarized cavity-backed microstrip patch antenna has been designed, simulated, optimized and developed at S-Band. The measured radiation patterns of the antenna show excellent resemblance to the simulated results. The designed antenna has a wide impedance as well as axial ratio bandwidth. The 3-dB beamwidth of the antenna is better than 86 degrees and RHCP gain of the antenna is better than 6.0 dBi over the frequency band. Being a cavity on the back side of patch antenna, this antenna provides better isolation and less mutual coupling between radiating elements in the array environment. The simple structure of the antenna, as well as the robust and simple manufacturing process, it is most suitable for radiating element for phased array antenna for satellite communication.

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