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DUAL CIRCULARLY POLARIZED BROADBAND MICROSTRIP ANTENNA ARRAY FOR SPACE RE-ENTRY VEHICLE APPLICATIONS IN S BAND

S. Femina Beegum[1], Manoj Joseph[2], Saji Joyas[3], M. Jayakumar[4] and J. Girija[5]
[1]Department of Electronics, Cochin University of Science and Technology, India
[2,3,4,5]Vikram Sarabhai Space Centre, Indian Space Research Organization, Thiruvananthapuram, India

Abstract

This paper presents the design details of an integrated 4x4 element dual feed dual circularly polarized microstrip antenna array in the S-band. The dual circular polarization is achieved by the use of quadrature hybrids. Power division for the dual input array is achieved through two 1x16 equal split equal phase corporate feed networks. The quadrature hybrids and corporate feeds for the proposed array are designed in multilayer printed circuit boards (PCB) in stripline configuration. This antenna can be used to transmit or receive both right-handed circularly polarized (RHCP) waves or left-handed circularly polarized (LHCP) waves simultaneously or one at a time by terminating the other port with 50Ω resistance. The proposed antenna has 700MHz of 10 dB impedance bandwidth (27%), 400MHz of 3dB axial ratio bandwidth and 300MHz of 3dB gain bandwidth centred at 2.5GHz with a peak gain of 15.5dB in both polarizations. It has a 3dB beam width of 26° and cross-polarization levels below 20dB in both the polarizations. Design and simulation of patch array, quadrature hybrids and 1x16 corporate feeds in multilayer configuration, PCB stack-ups, fabrication, integration and testing processes are discussed in detail. The effect of thermal protection system (TPS) of the re-entry vehicle on antenna performance parameters was studied and presented.

Keywords:

Antenna Array, Corporate Feed, Dual Circular Polarization, LHCP, Multilayer, Quadrature Hybrid, Reentry Vehicles, RHCP, S-band, Stripline

1. INTRODUCTION

Circularly polarized microstrip antenna arrays form an integral part of communication systems of satellites, reusable launch vehicles and satellite ground stations. The low-profile planar design of such arrays makes them the perfect choice for aerospace applications where projecting elements are not desirable. Dual polarized arrays provide polarization diversity or polarization configurability along with high gain. In signal reception chains, polarization diversity offers additional scope for diversity combining of orthogonally polarized signals for added gain and improved signal-to-noise ratio performance [1].

Most common feeding methods for microstrip antennas, such as probe feed, microstrip line feed, aperture coupling and proximity coupling, have their own advantages and disadvantages. When microstrip lines are easy to fabricate and simple to do impedance matching, they suffer from surface waves and spurious feed radiations, limiting the impedance bandwidth [1]. Probe feeding also has similar advantages along with low spurious radiations but has narrow impedance bandwidth [1], [2]. Aperture coupling is used in designs as a non-contact feeding method which reduces the excitation of higher-order modes [1] but causes the excitation of parallel plate modes leading to a reduction in polarization purity [3]. Out of the four feeding methods, proximity coupling provides the highest bandwidth, but it is difficult to fabricate [1]. Generally, in the case of microstrip patch arrays, the antenna elements are fed through probe feed [5], [6] or microstrip line feed [7], [8] or aperture coupling [9], [10].

Broadband characteristics in microstrip antennas are achieved through different techniques such as the use of stacked patches [11], [12] slots [13], [14] parasitic elements [15] meta-surface [16] etc. All these designs are based on the use of air [13]-[16], foam [12] or thick substrates [11] as dielectrics for added thickness to achieve the required gain and bandwidth specifications.

Standard techniques used to achieve circular polarization include sequential feed with progressive phase shift [16], [17] slotted patches [11], [12] power divider with phase shifter [13] delay lines [18] delay rings [15] ground slots [19] and quadrature hybrids [14]. While all the above techniques are widely applied for the single sense of polarization, i.e. either right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP), dual circular polarization relay mostly on quadrature hybrids [1], [20] and at times on delay lines [21].

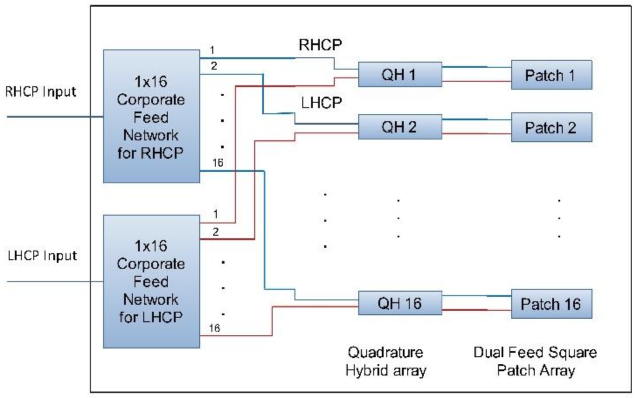
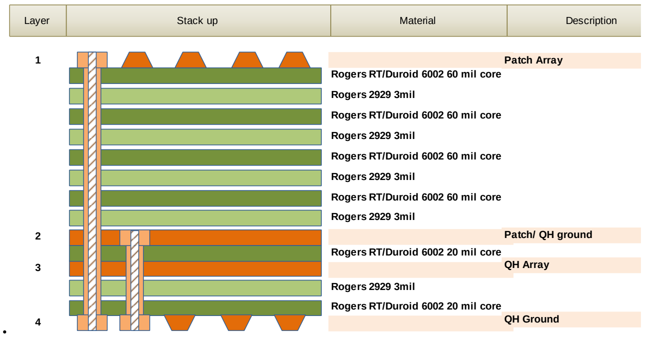


Fig.1. Configuration of antenna array

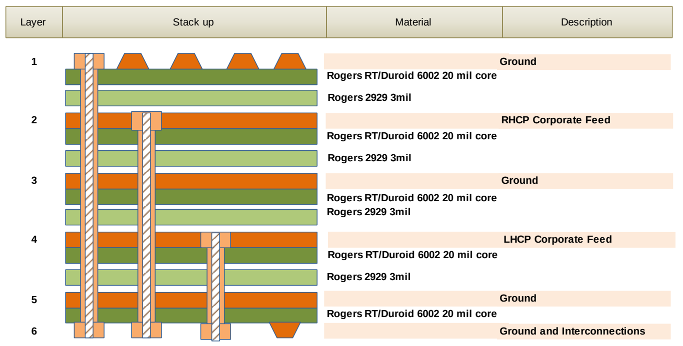
Feed networks and couplers are designed as microstrip lines whenever the design topology is not based on multilayer printed circuit boards (PCBs) [21]-[22]. But when the antenna design demands multilayer configuration either for its integration with electronics as in phased array antennas or for mounting on metal surfaces as in launch vehicles or reentry vehicles, stripline design needs to be implemented for feed networks and couplers[20], [22].

[20], which is the basic reference for the proposed array design, uses a thick substrate to acquire ruggedness, uniformity and required bandwidth in both polarizations. Here the dual circular polarization is achieved with a quadrature hybrid coupler that provides a 90° phase difference between its two output ports. The outputs from the stripline quadrature hybrid are fed to the two

dimensionally orthogonal feed points in the patch through coaxial probes.



(a)



(b)

Fig.2. PCB stack-ups (a) PCB1 and (b) PCB2

The effect of thermal protection systems (TPS) on different types of antennas for space shuttle and re-entry vehicles are studied and presented in [24]-[26]. The presence of TPS affects the antenna parameters depending on the type of antenna, number of layers and electrical properties of TPS and the placement of TPS on and around the antenna. The proposed dual circularly polarized broadband microstrip antenna array in S-band is intended for the onboard communication systems of reentry launch vehicles. The proposed antenna array consists of a 4x4 dual feed square patch array, a 4x4 quadrature hybrid array and two 1x16 corporate feed networks corresponding to RHCP and LHCP inputs. Quadrature hybrid array and corporate feed networks are designed with multilayer PCBs in stripline configuration. As it is meant for space applications, the proposed antenna array is designed and realized using space-qualified substrates. The required polarization, i.e. LHCP or RHCP for transmission, can be selected by feeding the corresponding port. Unused ports, if any, can be terminated with 50Ω resistor termination.

Two types of TPS, namely silica tile (ST) and flexible external insulation (FEI) blanket are used for simulation studies and testing. ST and FEI are used on the re-entry vehicle depending on the location and thermal load [26]. Design, simulation and analysis were carried out in Ansys HFSS EM simulation software. The design details of the antenna array, along with simulated and measured results, are presented in the following sections.

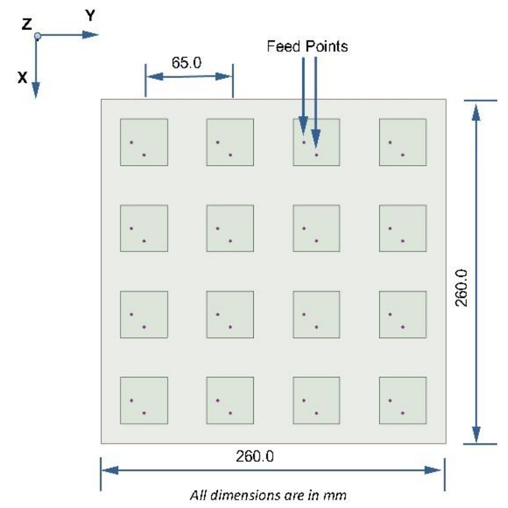
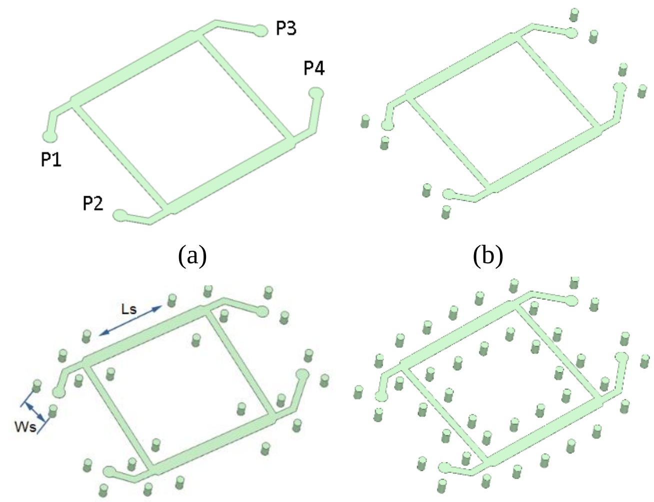


Fig.3. Patch Array



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

Fig.4. Quadrature hybrid design with different via configurations (a) C1, (b) C2, (c) C3 and (d) C4.

2. DESIGN DETAILS

The block schematic diagram of the proposed antenna array is shown in Fig.1. The proposed array has two inputs, one for RHCP and one for LHCP. These inputs are connected to two 1x16 equal split equal phase corporate feed networks, one for RHCP and one for LHCP. These feed networks are realized in separate layers of multilayer printed circuit boards (PCB) in stripline configuration. Next comes an array of 16 quadrature hybrids arranged in a 4x4 configuration. This quadrature hybrid array is also designed in stripline configuration on another layer of the multilayer PCB as a 4x4 array. The sixteen outputs from RHCP corporate feed network feed the sixteen RHCP inputs of the quadrature hybrids, while the outputs from LHCP corporate feed network feed the LHCP inputs of the quadrature hybrids. On the top layer of the multilayer PCB, sixteen dual-feed square microstrip patches are organized as a 4x4 array. The outputs from each quadrature hybrid are fed to the two orthogonal feed points of the corresponding microstrip patches through plated vias.

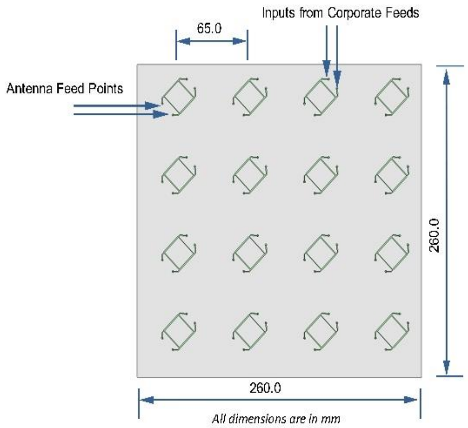


Fig.5. Quadrature hybrid array

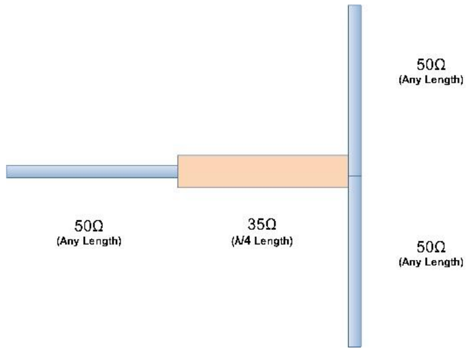


Fig.6. Basic building block for corporate feed network

Due to the limitations in maximum achievable thickness for PCBs from the side of fabrication facilities, the entire array is designed and realized as two multilayer PCBs. The first one, namely PCB1, is a four-layer PCB that houses the antenna array and the quadrature hybrid array.

The two corporate feed networks are realized in the second PCB, i.e. PCB2, which consists of six layers. Subsequently, the PCBs are stacked one over the other using mounting screws, and the interconnections are completed by soldering corresponding feed pins. The stack-up for both the PCBs is shown in Fig.2. All the components of the antenna are designed using Rogers RT/Duroid 6002 laminates with dielectric constant 2.94 and loss tangent 0.0012. The total substrate thickness for the patch array is 6mm, while the substrate thickness for the quadrature hybrid array and the corporate feed networks is 0.5mm. Hydrocarbon-based 2929 bond ply from Rogers is used to bond the laminates during multilayer PCB fabrication. The dielectric constant of 2929 is 2.94, and its dissipation factor is 0.003 at 10GHz. The overall dimension of the array is 260mm x 260mm x 10mm without connectors.

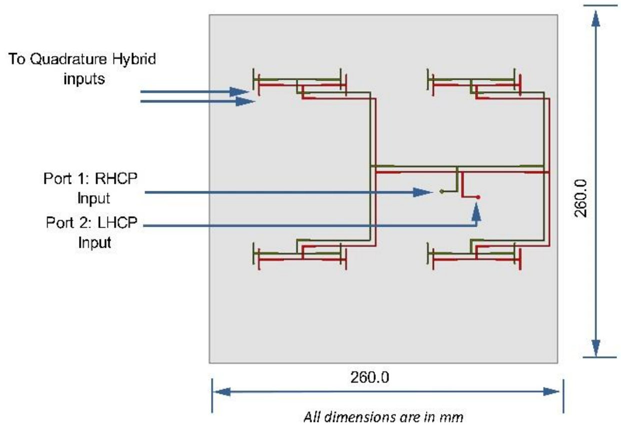


Fig.7. RHCP and LHCP corporate feed networks

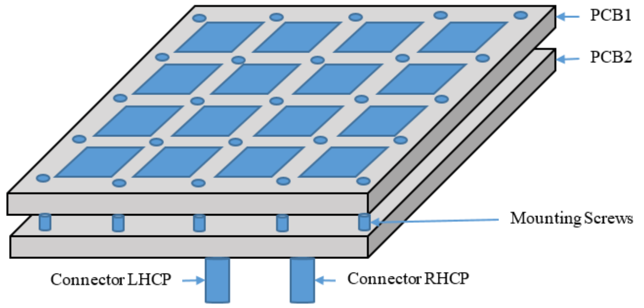


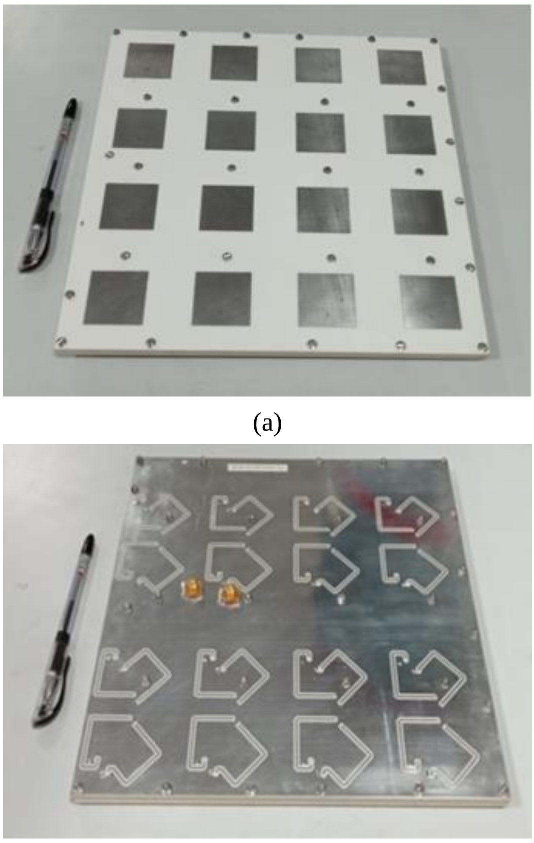
Fig.8. Schematic of mechanical stacking

2.1 PATCH ARRAY

The dual feed square patch elements with orthogonal feed points [28] and 35.25mm x 35.25mm dimensions are placed 65mm apart from each element in a 4x4 array configuration. The inter-element spacing is about 0.5λ of the design frequency. The thickness of the patch antenna substrate is 6mm. The configuration of the 4x4 element patch array is shown in Fig.3.

2.2 QUADRATURE HYBRID AND QUADRATURE HYBRID ARRAY

The quadrature hybrids are intended to provide a 90˚ phase shift between the signals at the orthogonal feed points of the dual feed square patch to achieve circular polarization. The quadrature hybrid is designed with 50Ω and 35.4Ω branches as per the theory [29]. The optimized widths for these impedances for the stripline design are 0.65mm and 1.12mm, respectively. Optimized lengths for the 50Ω and 35.4Ω branches are 19.23 and 18mm, respectively. The placement and orientation of the quadrature hybrids are done in such a way that the outputs of the quadrature hybrid come just under the feed points of the antenna.



(a)

(b)

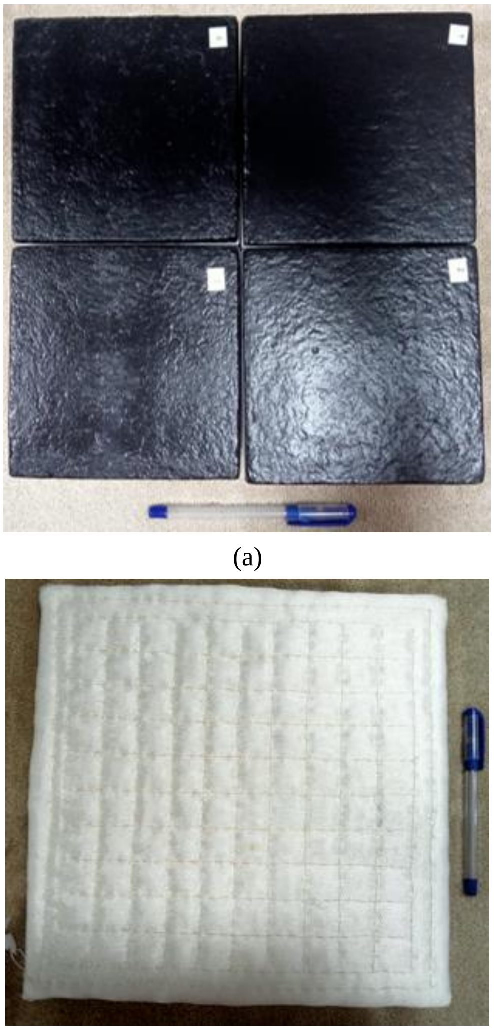
Fig.9. Photograph of the fabricated antenna array. (a) Top view and (b) Bottom view

As the quadrature hybrid is designed in a stripline configuration, metal vias need to be placed near the stripline to connect upper and lower ground planes. This is required to maintain the uniformity of the ground potentials and also to suppress the excitation of parallel plate modes [30]. Four different configurations of via arrangements were simulated to get acceptable performance in terms of S parameters. These configurations, namely C1, C2, C3 and C4, are shown in Fig.4. Based on the simulated results of S parameters, configuration C3 is selected for further designs. In this configuration the length wise spacing 'Ls' of the vias is less than λ/8 and width wise spacing 'Ws' is 4-5 times of stripline width.

The quadrature hybrids are arranged in a 4x4 array configuration corresponding to the patch array, and the configuration of the quadrature hybrid array is shown in Fig.5. The patch array and quadrature hybrid array are incorporated in PCB1.

2.3 CORPORATE FEED NETWORK

Two 1x16 equal split equal phase corporate feed networks are designed to feed the RHCP and LHCP inputs of the quadrature hybrid array. The feed networks are designed using 50Ω and 35.4Ω striplines [31]. The basic 1x2 feed element, which is the building block for 1x16 feed, is shown in Fig.6. This basic feed element is replicated to achieve the required 1x16 feed. Corporate feed networks for RHCP and LHCP are designed in separate layers of PCB2. Overlaid diagram of the two corporate feed networks is shown in Fig.7. The optimized stripline widths for 50Ω and 35.4Ω impedances are 0.65mm and 1.12mm, respectively. The optimized length of the 35.4Ω quarter-wave transformer is 18mm. A required number of vias similar to quadrature hybrid are provided for these corporate feed networks also.



(a)

(b)

Fig.10. Photograph of the antenna array with (a) ST and (b) FEI

Outputs from the corporate feed networks are brought to the bottommost layer and then fed to quadrature hybrid inputs. The transmission lines that are used for the above interconnections are designed as microstrip lines. This particular way of routing is selected with the intention that in the future, these microstrip lines can be replaced by phase shifters and attenuators to convert this proposed static array into an electronically controlled phased array without much changes in antenna array design. The schematics for mechanical stacking and the photographs of the integrated antenna array are shown in Fig.8 and Fig.9 respectively. RHCP and LHCP signals are fed to or received from the antenna array through standard SMA connectors.

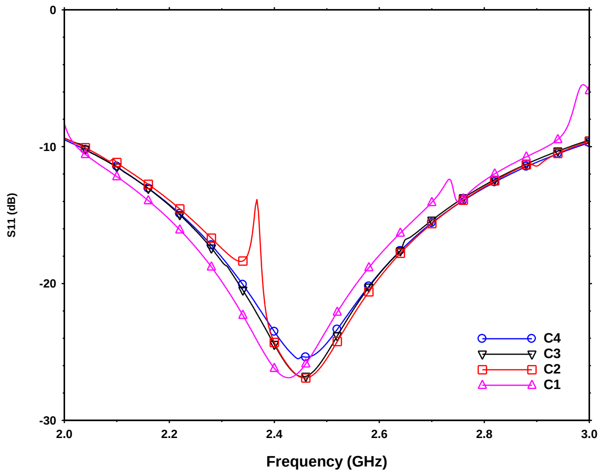


Fig.11. Simulated S11 values of the quadrature hybrid in different via configuration

The thickness of ST and FEI are 55mm and 22mm respectively. The dielectric constant and dissipation factor for the ST are 1.17 and 0.00025 at 5GHz while that of FEI are 1.77 and 0.0362 at 1MHz. The antenna array with ST and FEI mounted on it are shown in Fig.10.

3. RESULTS AND DISCUSSION

The S11 values of the quadrature hybrid for all four different configurations are shown in Fig.11. The result shows that proper vias are required along with all branches of the quadrature hybrid in addition to the signal launching points to get a smooth S11 curve. Based on the results, configuration C3 is adopted for further design build-up.

Patch array, quadrature hybrid array, RHCP and LHCP corporate feed networks are simulated and analyzed independently. Then each section is integrated and simulated with successive sections and analyzed. Fine-tuning was required for the design values of each section after integration to achieve the required performance. All the dimensions specified in this paper are those values after final tuning. The results of the final antenna array are presented here.

The measured S Parameters of the antenna in its original configuration (without TPS), with FEI and with ST are shown in Fig.12. The proposed antenna array has 700MHz bandwidth from 2.2GHz to 2.9GHz (27%). The measured gain values with respect to frequency for both LHCP and RHCP polarizations are shown in Fig.13. The proposed antenna array has a maximum gain of 15.5dB with a side lobe level of -13dB for both the polarizations at 2.4GHz and its 3dB gain bandwidth extends from 2.35GHz to 2.65GHz. The measured axial ratio values with respect to frequency are shown in Fig.14. It shows the 3dB axial ratio bandwidth for this antenna is 400MHz from 2.25GHz to 2.65GHz. In the presence of SI and FEI, the maximum gain becomes 15.7dB and 15.4dB respectively.

The simulated radiation patterns of the antenna array for RHCP and LHCP inputs at 2.4GHz in XZ and YZ planes are shown in Fig.15. The proposed antenna array has a 3dB beam width of 26° and cross-polarization levels below 20dB for both the polarizations.

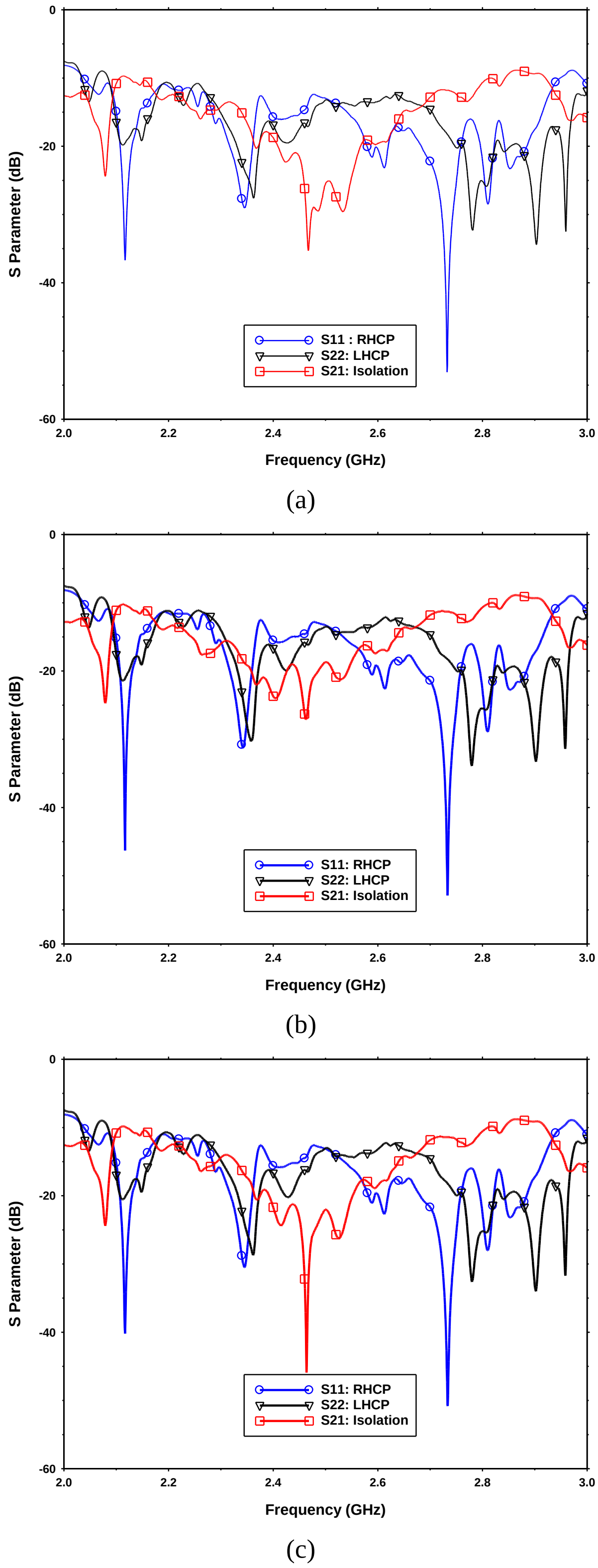


Fig.12. Measured S Parameters of the antenna array (a) without TPS (b) with FEI and (c) with ST

The results show that both ST and FEI do not have any significant effect on S parameter values and gain. This can be attributed to the low dielectric constant values of both the materials and wideband performance of the antenna.

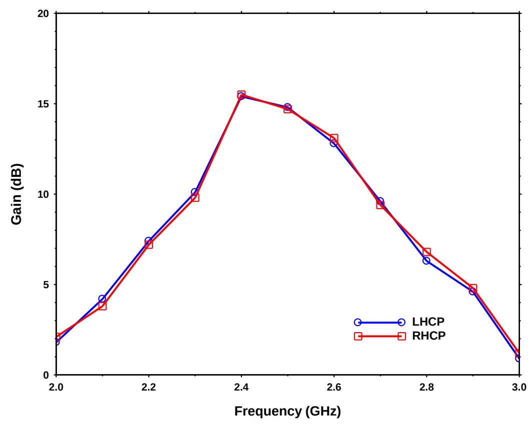


Fig.13. Measured Gain vs. frequency

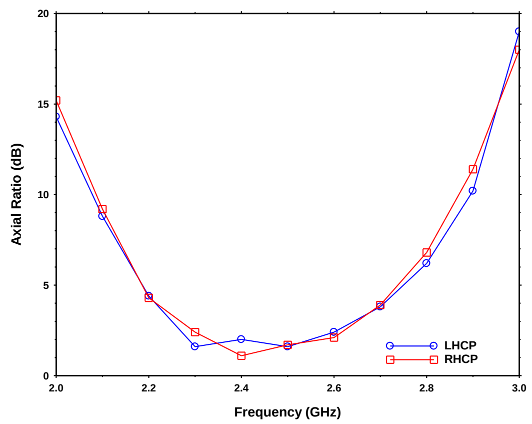
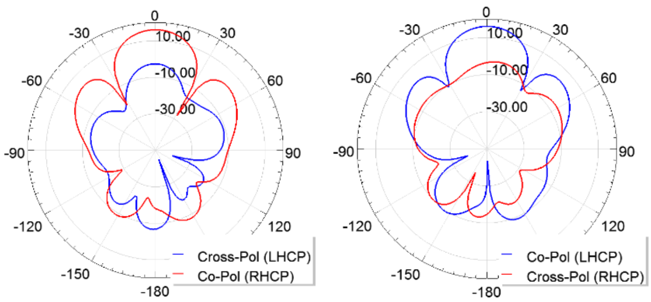
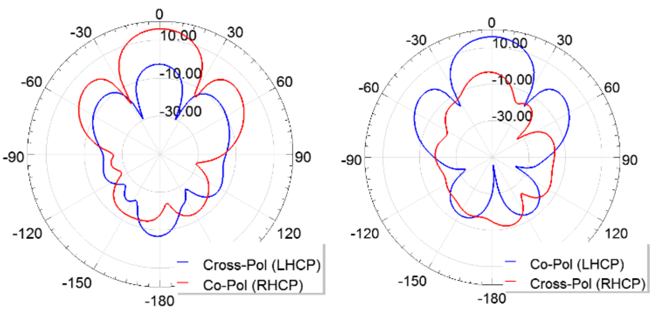


Fig.14. Measured Axial ratio vs. frequency



RHCP LHCP

(a)



RHCP LHCP

(b)

Fig.15. Simulated Radiation patterns at 2.4GHz at (a) XZ Plane and (b) YZ plane

4. CONCLUSION

A 16-element broadband dual feed dual circularly polarized microstrip antenna array is designed and realized using state-of-the-art multilayer PCB fabrication techniques using space-qualified substrate materials. The proposed S-band antenna array with stripline quadrature hybrids and corporate feeds are well integrated and fabricated as two multilayer PCBs. The antenna provides 700MHz impedance bandwidth at 10dB return loss and maximum gain of 15.5dB in both polarizations with cross-polarization levels of more than 20dB at bore sight. 400MHz axial ratio bandwidth and 300MHz of 3dB gain bandwidth make this antenna a suitable choice for space communication systems, including satellites and reentry launch vehicles. The effect of Thermal Protection Systems of the re-entry vehicle on the antenna performance parameters were studied and no significant variations are observed.

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