Design and Analysis of Square and Torus ring Shaped Material - Unit cells for X-Band Reflectarray

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Abstract. A Reflectarray antenna is considered a hybrid antenna fed with microstrip, and elements of the antenna are designed to comprise features of both reflector and phased array antennas. Elements of the antennas are made such that the materials are comprised of micro strip patch elements and are printed on Roger 5880, a lossy material with a dielectric of 2.2. Comparative analysis of the unit cell geometry of the Reflectarray antenna is demonstrated for both square patch and Torus ring material-based configurations. Torus ring and square patch material-based configurations are proposed and designed to operate within the X-band frequency range of 8-12 GHz. Simulation results are provided for these configurations, demonstrating the return loss, bandwidth, and phase reflection curve, also known as the 'S' curve. Among these configurations, the Torus patch material-based configuration showed favorable results for phase linearity. These configurations are considered to develop reflectarray antennas with superior performance characteristics.

1. INTRODUCTION

A reflectarray, as the name reflects, is a flat surface and acts as a reflector made up of resonant elements. The advantages of using a reflectarray antenna are as follows: Low cost, low weight, and small stowed volumes make it very suitable for satellite communication systems to minimize launch costs. Previously, applications involving high gain antennas make use of parabolic reflectors and phased arrays [1]. The problem in using a parabolic reflector is its manufacturing difficulty owing to the curved surface profile, mainly for higher microwave frequencies. In addition, its geometric configuration leads to large size and weight. Furthermore, it is also difficult for a parabolic reflector to scan electronically in a wide angle. On the flip side, phased array antennas can scan beams electronically by large angles in space using controllable phase shifters. However, the biggest disadvantage of the phased array antenna technology stems from the high hardware size requirements of each array element or sub-array, which has to be connected to a dedicated transceiver module. The transceiver

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module is generally bulky and expensive in nature, thereby making the use of phased array technology very expensive for high-gain applications[2]. However, Reflectarray Antennas-Reflectarray antennas present an innovative technology alternative to existing reflector and phased array antenna technology. A "micro strip reflectarray" comprises a flat surface having a planar array of micro strip patches that remain illuminated by a 'feed' element [3].

The biggest disadvantage of reflectarray antennas is their narrow bandwidth. This disadvantage can be overcome by tuning the dimensions of new unit cell geometries, adding stub lines, and using angular rotation to the patches [4] [5]. Phase characteristics of the reflectarray elements can be appropriately optimized by changing the dimensions of patch materials [6] [7], starting from a minimum value with fixed incremental steps, say 0.5 mm. In this paper, Roger 5880 substrate material of thickness 1.6 mm and dielectric constant 2.2 is used to analyze the phase reflection characteristics [8] [9] of both square and torus ring unit cell geometries. Every radiating element material is designed to re-radiate the incident electromagnetic field [10] [11] with a phase shift that is appropriate for the formation of a phase coherent beam in the desired direction [12] [13]. The entire performances of reflectarray depend upon the phase response [14] [15] of these compact micro strip unit cells [16] [17]. In this paper, we present a comparison study [18][19] between the conventional square patch material with a novel geometry patch such as torus [20], highlighting their impact on the phase performance [21][22][23] and potential for improved bandwidth [24][25].

2. CONCEPT OF REFLECTARRAY

The reflectarray antenna can be viewed as an antenna that results from combining the principle of compensation of phase in a parabolic reflector antenna and that of discrete phase control in a planar phased array. For an ordinary reflector antenna, it is the property of the parabolic reflector ideally to equalize the phase of all waves arriving from the reflector and summing up in-phase towards a desired direction. However, if such a reflector were flattened, there will be no more equalization of phase, and hence, the reflectarray replaces an ordinary reflector with a flat surface supporting numerous resonant elements, such as square patches, rings, or torus ring structures, which are supposed to provoke a specified reflecting phase. Indeed, it should be noted that the required element phase can be directly obtained from a classical reflector condition, in which it is required that the phase of waves traveling from the element to a desired direction is constant over the reflector aperture. Therefore, each element is compensated in its geometry to provide a reflection phase that compensates for the phase error of the feed path and synthesizes a linear phase distribution over the surface. As such, a flat reflectarray can attain properties of focusing and beamforming, similar to a parabolic reflector, with the advantages of low profile, weight, and easiness of fabrication of printed Micro Strip Technology. A reflectarray is a class of high-gain antenna with a flat shape that makes use of a feeder source and its surface provided with a phase-controlled reflective element. This arrangement allows it to form a beam, similar to that of a parabolic reflector, but with minimized weight, thickness, and cost of fabrication. Additionally, reflectarray is used in satellite communication, radar, and remote sensing, including 5G and 6G technologies.

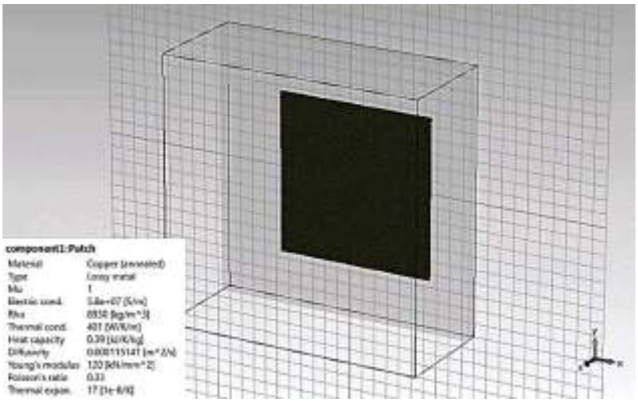
3. DESIGN PROCEDURE

In this study, we use a commercial software package for EM simulation, CST Microwave Studio, which is based on the Finite Integration Technique (FIT) and utilizes the Floquet mode method (infinite periodic boundary conditions) for periodic structure analysis. The unit cell is separately simulated and analysed, and appropriate boundary conditions are applied to exhibit return loss and phase reflection characteristics. In this study, electric boundary walls and magnetic boundary walls are set for the unit cell, and a plane wave is applied using the Floquet mode. The specific value of the angle of incidence of the plane wave is determined by a specific value of a spherical coordinate parameter, denoted as ϕ. In this study, we have explicitly determined this value for simulation analysis. In this analysis, two Floquet modes are excited for the structure. Some factors have been considered to determine the result of the unit cell performance. outer radius is set to 5 mm, and inner radius is 3 mm. All the unit cells in this paper have been designed to operate in the frequency band between 8 GHz and 12 GHz, covering the X-band frequency range. The patches in this paper were fabricated using the Roger 5880 lossy substrate material; the properties of this substrate material include permittivity (Ɛr) = 2.2, substrate thickness = 1.6 mm, and the backing ground plane is made of annealed copper, having a thickness of 0.035 mm. The return loss, bandwidth, and phase reflection curves were achieved using the simulation, while the performance is evaluated using the Figure of Merit (FOM).

$$FOM = \Delta\phi \,/\, \text{Return loss in (dB)} \qquad (1)$$

Δϕ is the variation in the reflection phase in degrees and Δf is the variation in the reflectarray antenna resonant frequency in MHz, thus FOM is calculated here in °/MHz.

4. DESIGN OF X-BAND SQUARE UNIT CELL



component1:Patch

Material	Copper (annealed)
Type	Lossy metal
Mu	1
Electric cond.	5.8e+07 [S/m]
Rho	8930 [kg/m^3]
Thermal cond.	401 [W/K/m]
Heat capacity	0.39 [kJ/K/kg]
Diffusivity	0.000115141 [m^2/s]
Young's modulus	120 [kN/mm^2]
Poisson's ratio	0.33
Thermal expan.	17 [1e-6/K]

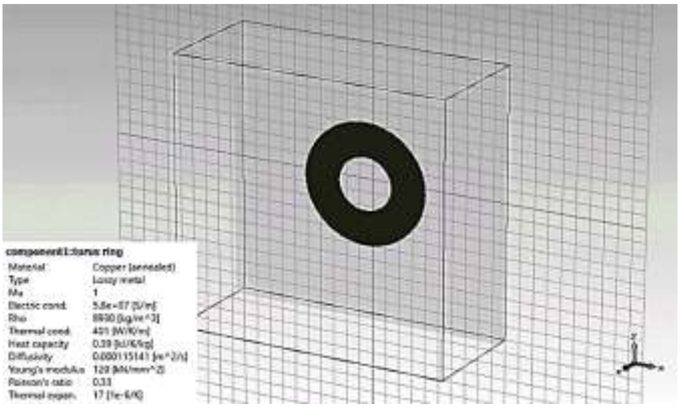
Figure. 1 Square patch

The X-band square microstrip unit cell is designed to function as a resonant reflective element, which has the capability to provide a controllable phase of reflection. The reflective array concept involves providing a specified phase shift by each element, accounting for the different path lengths from the source, and the design of the square patch acts as a viable method for achieving this. The unit cell is designed to work as a grounded dielectric cavity, where the patch size mainly influences the fundamental TM10 mode of resonance. The change in the length of the sides ‘a’ of the square patch, within the appropriate range, results in the variation of the input reactance from capacitive to inductive, covering a range of 300-360°.

In the present design, a square patch is printed on Rogers 5880 substrate material, characterized by the permeability ε_r = 2.2 and the substrate height \(h = 1.6 mm \), backed by the conducting ground plane. Floquet boundary conditions are applied to model the periodic structure employing CST Microwave Studio simulation software. A normally incident TE/TM plane wave excites the periodic array. Under the given range of 8-12 GHz, the reflection coefficient \(\Gamma = |\Gamma| e^{j\phi} \) is computed, and the resulting phase-dimension plot is utilized to determine the range of the achievable phase compensation. Furthermore, the signal reflection magnitude is affected by the conductor and dielectric losses, while the bandwidth is related to the resonant characteristics of the structure. It is necessary to select the element size to satisfy the condition \(a < 0.5 \lambda_0 \); the element size needs to satisfy this inequality to achieve adequate phase resolution and exhibit low mutual coupling. The Fig. 3 also depicts the achievable static linear phase range on the structure’s linear section, and the structure’s results are quantified using the FOM, i.e., the achievable phase and the operating bandwidth.

Therefore, the X-band square unit cell represents a low-profile resonant scatterer whose dimensions are optimized to offer extensive phase coverage, moderate bandwidths, and acceptable levels of reflection loss.

5. DESIGN OF X-BAND TORUS RING UNIT CELL



component1:torus ring

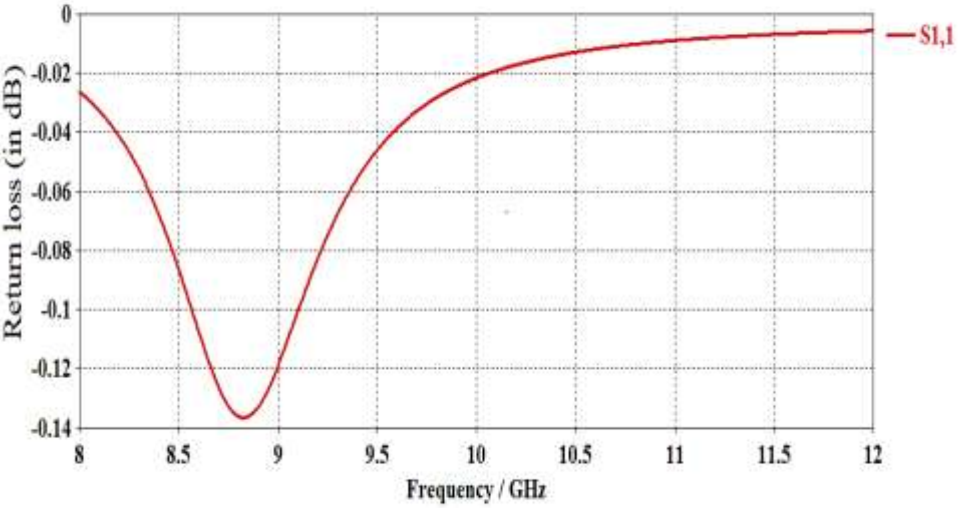
Material	Copper (annealed)
Type	Lossy metal
Mu	1
Electric cond.	5.8e+07 [S/m]
Rho	8930 [kg/m^3]
Thermal cond.	401 [W/K/m]
Heat capacity	0.39 [kJ/K/kg]
Diffusivity	0.000115141 [m^2/s]
Young's modulus	120 [kN/mm^2]
Poisson's ratio	0.33
Thermal expan.	17 [1e-6/K]

Figure. 2 Torus Ring Patch

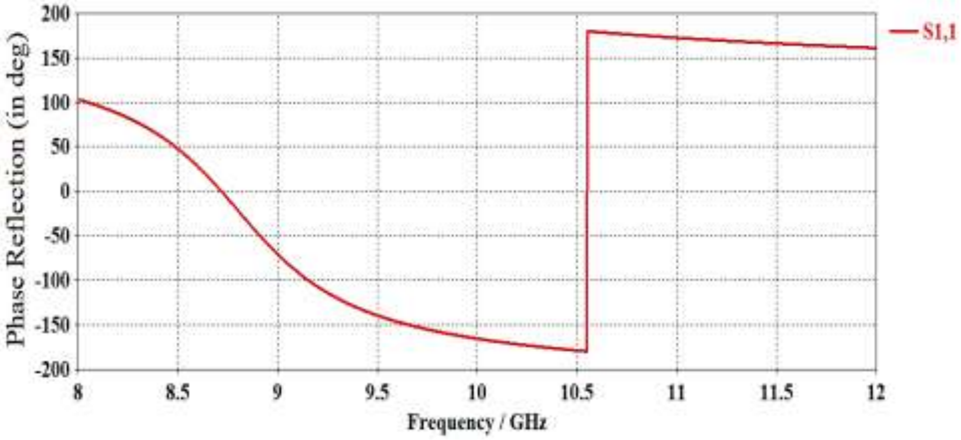
The torus ring unit cell is a resonant micro strip structure designed to give enhanced phase agility and better bandwidth characteristics for reflectarray applications. Unlike the conventionally used square patch, the torus ring consists of a circular patch with an inner circular aperture that forms a ring-shaped resonator whose electromagnetic response is determined by both the outer radius Ro and the inner radius Ri. The proposed geometry characterized with two radii introduces an additional degree of freedom that enables fine control of the surface reactance and resonance behavior. Consequently, multiple resonant paths can often be supported by the torus ring structure, yielding broader phase variation and improved linearity in the phase response over the X-band frequency range of 8-12 GHz. In this case, the torus ring element is printed on Rogers 5880 material with εr = 2.2, and its thickness is indicated by h=1.6 mm. Furthermore, a copper ground plane is used for this design. The unit element is then simulated under periodic conditions; Floquet mode excitation is applied, which represents an infinite array excited by a normally incident plane wave. This ensures that the ring element boundaries are subjected to circulating currents, while there is a reflection coefficient of $\Gamma=|\Gamma|ej\phi$. The phase is then varied, which is associated with the torus ring element based on characteristic operating conditions. The ring element is then mainly subject to resonant frequency conditions based on variations in its width, indicated by W=Ro-Ri. This ensures an impedance transition from capacitive to inductive. The structure is then designed to realize a smooth phase shift, which is typically larger than what is covered by a solid patch of a single layer. This geometry also reduces the effective electrical size of the unit cell, which may minimize the reflection loss and/or the phase stability for obliquely incident waves. The static linear phase range is considerably broadened due to the distributed current path.

6. RESULTS AND ANALYSIS

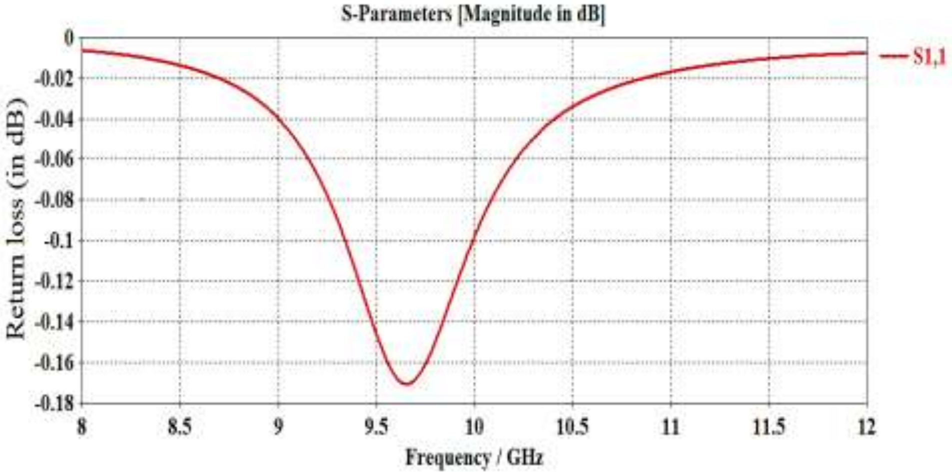
The square patch is simulated over the frequency range of 8 to 12 GHz. Graph 1 shows the S parameter magnitude in dB versus frequency. The maximum resonance occurs at 8.8 GHz close to the centre frequency. The reflection loss is -0.135 dB. Bandwidth is 1150 MHz. From graph 2, the phase reflection curve is swinging between 100° to 200° contributing overall total phase shift to 300°. The torus ring patch is simulated in the frequency range of 8 to 12 GHz. The graph 3 shows the S parameter magnitude in dB versus frequency. The maximum resonance occurs at 9.7 GHz near to centre frequency. The reflection loss is -0.17 dB. Bandwidth is 1600 MHz . From graph 4, the phase reflection curve is swinging between 140° to 200° contributing overall total phase shift to 340°.



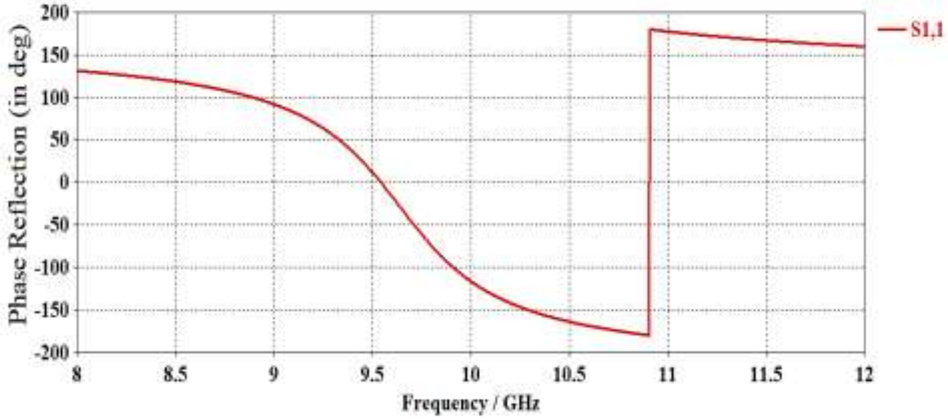
Graph.1 Square patch - Return Loss



Graph 2. Square patch - Phase Reflection



Graph. 3 Torus Ring Patch – Return Loss



Graph. 4 Torus Ring Patch – Phase Reflection

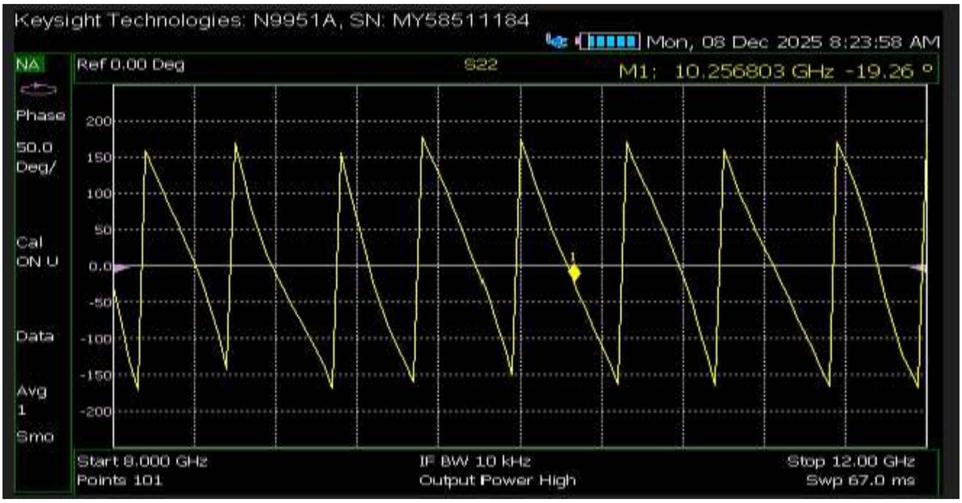
7. FABRICATED PATCHES

Figure. 3 Square patch

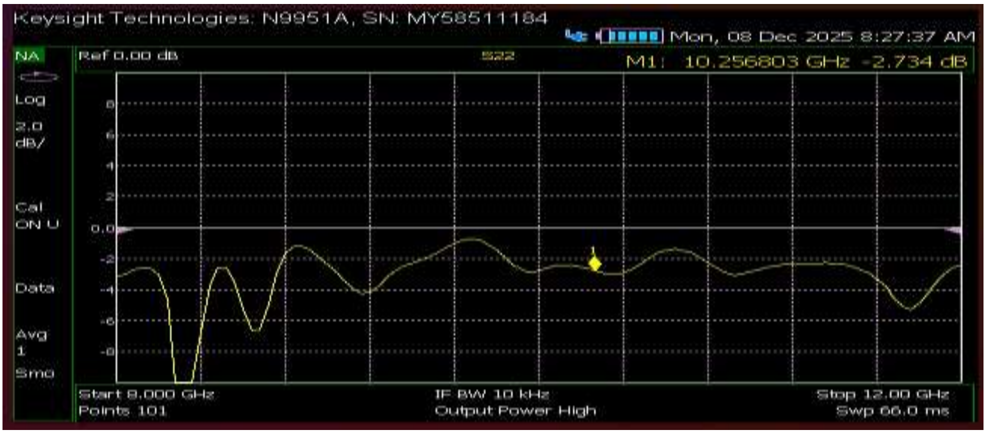
Figure. 4 Square patch

8. RESULTS OF MEASUREMENTS

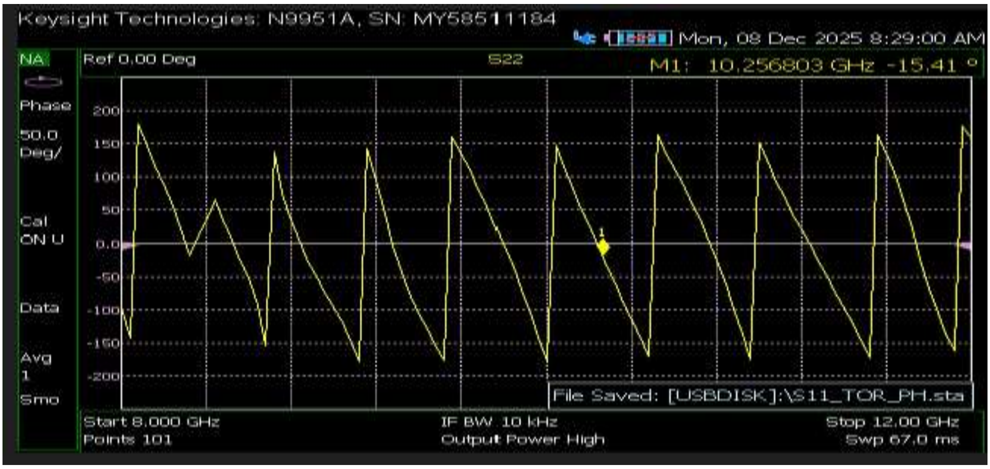
Graph 5. Square patch – Return Loss



Graph 6. Square patch – Phase Reflection



Graph 7. Torus ring – Return Loss



Graph 8. Torus ring – Phase Reflection

The experimental results show that reflection loss for square patch is -4.2 db and Torus ring patch is -4 db. The phase reflection achieved is 320 degrees .Figure of merits got improvement compared to simulation results. Comparing simulation and measurement reading, bandwidth is covering broad range for various applications. Torus ring patch produces good bandwidth in simulation and measurement. The results are tabulated as below.

TABLE I COMPARISONS OF RESULTS OBTAINED

Parameters	**Square Patch by Simulation**	**Torus Ring Patch by Simulation**	**Square patch Measurement**	**Torus-ring patch Measurement**
Reflection loss (in dB)	-0.135	-0.17	-4.2	-4
Bandwidth (MHz)	1150	1600	550	1000
phase Reflection Range (in degree)	300	340	320	320
Figure of Merit	0.26	0.20	0.58	0.32

A typical Figure of Merit (FOM) quantifies how well it covers 360-degree phase range and how flat the reflection magnitude over the frequency of interest

9. CONCLUSION

The reflection characteristics and phase behavior were directly taken from the CST-generated S-parameter graphs for the Square Patch and Torus Ring Patch. The Square Patch reflects stronger, with lower loss and a more favorable Figure of Merit, meaning it yields higher phase efficiency per MHz of operating bandwidth. Torus ring shows broad bandwidth compared to square patch. While the Torus Ring Patch achieves the largest static linear phase range (330°), it also has higher reflection loss that drops its overall efficiency. The Square Patch thus gives better phase performance relative to bandwidth, while the Torus Ring Patch offers improved phase agility and may be beneficial in reflectarray designs which require larger phase coverage. Because of large phase coverage, we will be able to design torus ring array for satellite applications as a future scope of work. The key challenge in fabricating torus ring patch with square patch is proper choice of substrate material like Rogers 5880 as simulation results produces are smooth reflection phase.So, the substrate thickness and dielectric constant also plays major role in getting results smoothly.

The authors proclaim that they have no conflict of interest. There are no financial, personal, or professional relationships that could have influenced the work reported in this paper

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