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Wideband Frequency Selective Surface Based Transmitarray Antenna at X-Band

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ABSTRACT

In this paper, a wideband multilayer transmitarray antenna is designed for Ku frequency band. The unit cell is designed at 12GHz using frequency selective surface structure. A new double square ring with center patch based multilayer unit cell has been designed and simulated. Then, the effect of substrate thickness variation on transmission coefficient magnitude and phase range is discussed. In the final design, the horn antenna designed at X-band is used as a feed source for transmitarray antenna. The simulation results show a wide impedance bandwidth from 10 to 13GHz. Besides, a wider gain bandwidth of 1.975GHz with a peak gain of 19dB is also achieved. All simulation results have been verified by the measurement. The proposed transmitarray design will find applications in high gain, directional and low profile antennas for X-band communication systems.

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1. INTRODUCTION

The popularity of transmitarray (TA) antennas in the high gain antenna family have increased in recent years [1-6]. The parabolic lens type, reflectarray and phased array antennas have been used due to their high gain and directivity. However, conventional parabolic type antennas were bulky and had huge sizes. Although the reflectarrays antennas are compact and have high gain [7-15], reflectarrays face the problem of main beam hindrance due to the source placement in the main beam direction. Phased array antennas provide compact planar array configuration and beam reconfigurability [16-23].

Nevertheless, the power loss and complexity due to complex feeding network are significant concerns. Therefore, the transmitarray antenna is an attractive solution because it can provide a low profile structure with high gain and directivity. Transmitarray antennas also provide a solution to the problem of feed blockage by placing the source antenna on the backside of multilayer space fed arrays.

Transmitarray antennas can be categorized into three major types depending upon their configuration. These correspond to the receiver-transmitter type, metamaterial and frequency selective surface. The mostly used TA configuration is comprised of receiver-transmitter type structure [24-31]. In this configuration, the bottom layer acts like a receiving space fed array. The center layer provides a desired delay or phase shift required for each unit cell. Active devices can also be integrated with the bias layer for amplification and beam switching. The top layer, which is mostly the replica of the bottom layer, re-transmits the received signal with the required phase shift. In terms of simulations, the configuration is easy to be implemented. However, due to the complexity in assembling, the required results are usually not obtained.

This is due to the involvement of multiple vias between these three layers, active devices in the biasing layer and alignment issues.

On the other hand, the frequency selective surfaces (FSS) can be used as spatial bandpass filters. FSS-based transmitarray unit cells are low profile, have wider bandwidth and wider phase range. By parametric adjustment, required transmission coefficient phase shift can be obtained. The FSS-based transmitarray unit cells have more straightforward implementation as vias for layer interconnection are not used. In transmitarray antennas, FSS multiple layers are used to enhance the phase range, bandpass filtering and increasing the gain [3, 32-35]. In FSS configuration, the phase range of a unit cell can be increased by increasing the number of layers. However, increasing the number of layers will also reduce the transmission coefficient magnitude. Due to this reason, a compromise between phase range and transmission coefficient magnitude has to be made. These two parameters are also dependent upon the type of substrate being used.

Furthermore, transmitarray antennas suffer from narrow bandwidth [5, 26, 27, 30] due to small bandwidths covered by radiating elements used in transmitarrays. This is due to the limitations using biasing and interconnection circuits which limit the overall bandwidth of the transmitarray. Therefore, in this paper, we have designed a wideband transmitarray using a new FSS-based double square ring with center patch unit cell at 12GHz. The unit cell and complete transmitarray antenna simulations are performed in CST studio software. Initially, we will discuss the design for the unit cell and complete transmitarray antenna. Then, the parameters used in the structure will be described. The result section comprise of unit cell and complete TA antenna analysis. Finally, the results obtained from parametric simulations is been discussed.

2. Transmitarray Antena Design

The basic transmitarray antenna structure using multilayer frequency selective surface (M-FSS) can be seen in Figure 1 [36]. In this configuration, the feed horn acts as a source. The TA elements perform desired phase compensation and retransmit the collimated wave. The phase compensation depends upon the phase delay produced due to incident wave travelling from feed source to the specific antenna element. The vector from the feed source phase center to *i*th element is denoted as R_i and the position vector as r_i from transmitarray center.

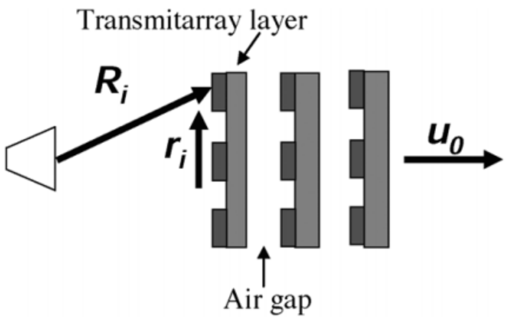
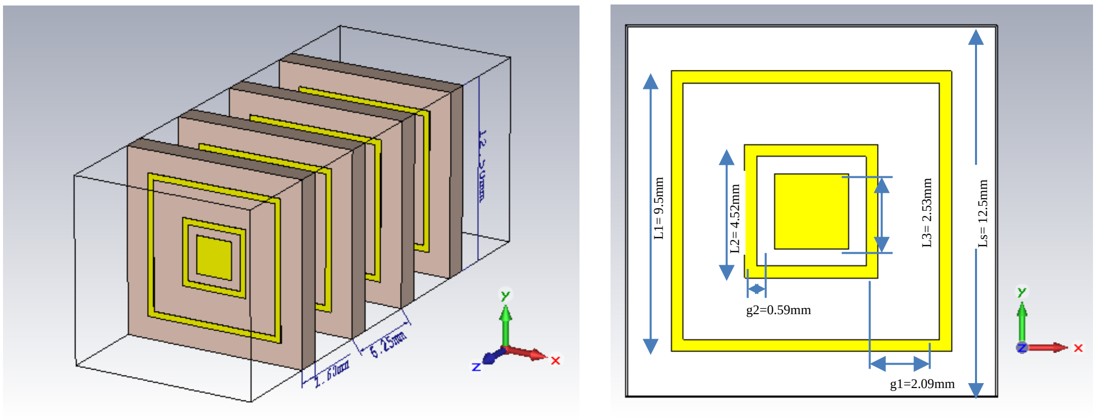


Figure 1. The geometry of M-FSS Transmitarray Antenna [36]

The phase adjustment value Φ_i can be calculated using the position vectors R_i and r_i by using equation 1 below. It can be seen that phase value also depends upon the propagation constant k and main transmitted beam direction u_0. The spacing between the FSS layers is normally kept to be quarter of a wavelength at the design frequency. However, optimizations can be performed by varying the distance between FSS layers.

$$\Phi_i + k[R_i + r_i . u_0] = 2\pi n, n = 0,1,2, ... \quad (1)$$

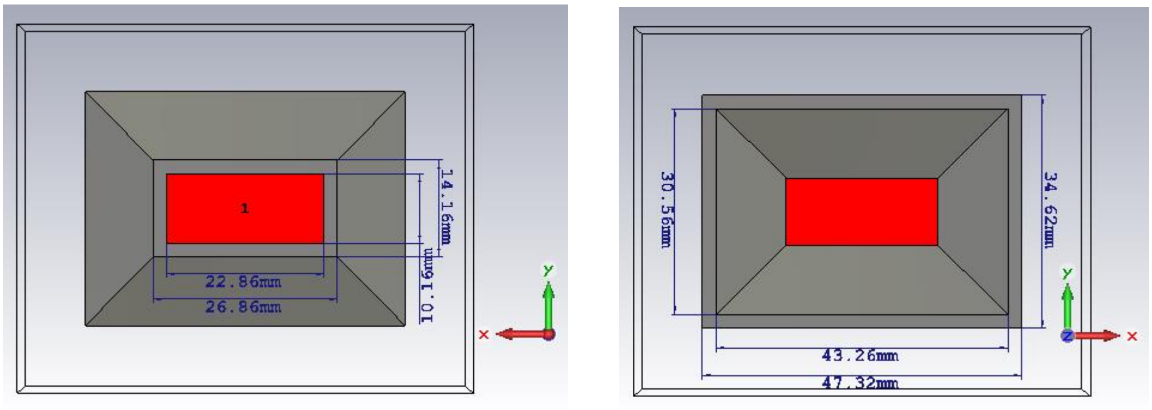
The isotropic and top views of multilayer FSS structure are shown in Figure 2(a) and 2(b), respectively. The unit cell is designed and simulated at 12GHz using FR4 substrate with thickness of 1.6mm using CST studio. The proposed design is wideband due to multi-resonant structure comprised of a double square ring with center patch. The interlayer spacing is kept to be a quarter of wavelength which in this case is 6.25mm. The parametric simulations for M-FSS structure are performed by varying the length of the outer square ring "L1". The side lengths of the inner square ring "L2" and the center patch "L3" are varied accordingly. The gap between the two rings g1, g2 is optimized and varies simultaneously as 0.22 x L1 [37] and 0.22 x L2, respectively. The exact dimensions of a unit cell can be seen in Figure 2(b). The copper strip width has to be kept small, having the value of 0.4mm. The dimensions can be rounded to first decimal places without significant change in transmission coefficient magnitude and phase.



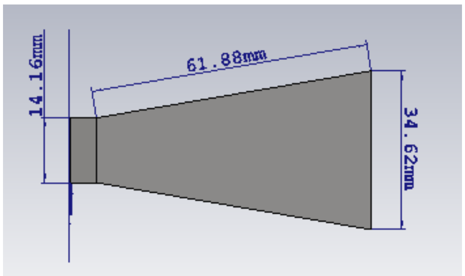
(a) (b)

Figure 2. Isotropic and top views of Multi-layer FSS unit cell

The transmitarray structure requires a high gain source to illuminate the space fed frequency-selective surface-based arrays. The horn antenna is most suitable for such applications due to its wide impedance and gains bandwidth. The top, bottom and side views of X-band Horn antenna with a rectangular waveguide section are shown in Figure 3(a), 3(b) and 3(c). The rectangular waveguide section is matched with WR90 standard having dimensions of 22.86mm x 10.16mm. The phase delay is obtained by calculating the distance travelled by the incident wave from the feed source center to each specific element.



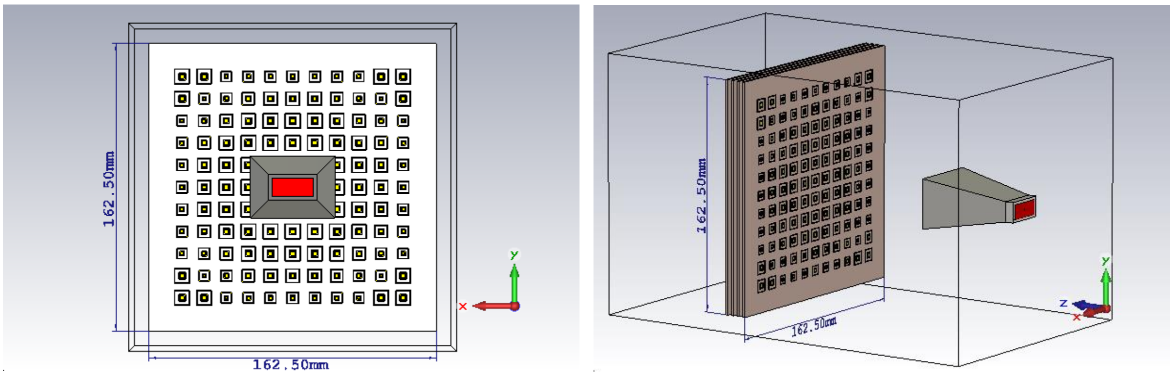
(a) (b)



(c)

Figure 3. X-band horn antenna with rectangular waveguide section (a) Bottom (b) Top (c) Side view

The complete transmitarray antenna designed at 12GHz with four FSS layers is shown in Figure 4. The distance between consecutive frequency selective surface layers is 6.25mm which is equal to the quarter wavelength. The copper strip used to design transmitarray has a thickness of 0.4mm. The transmitarray is made up of 11 x 11 elements having the unit cell spacing of 12.5mm, which is half of the wavelength. The thickness of the substrate is 1.6mm. The overall side length for 11 x 11 transmitarray is 162.5mm. The M-FSS based TA layers are placed at a distance of 103.91mm from the phase center of horn antenna. The focal distance to the aperture diameter ratio is kept to be 0.8 for maximum aperture efficiency.



(a) (b)

Figure 4. M-FSS type transmitarray antenna design (a) Top (b) Isotropic views

The fabricated frequency selective surface transmitarray antenna can be seen in Figure 5. The prototype has been fabricated using FR4 substrate, and four FSS layers have been used to develop the overall structure. In order to hold the FSS layers and the horn antenna, we have designed a base layer using FR4 substrate strips with 1.6mm thickness and eight columns using plastic spacers. The overall structure shows good mechanical strength to hold the FSS layers along with the Horn antenna.

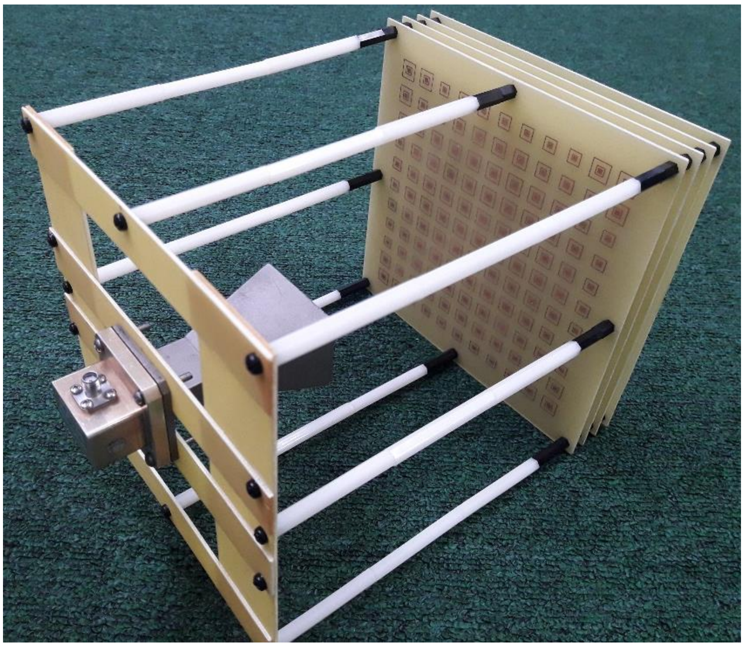


Figure 5. Prototype of FSS Transmitarray antenna

3. RESULTS AND ANALYSIS

The transmission magnitude and phase plots for 4-layer FSS unit cell on FR4 using different substrate thickness of 1.6mm are shown in Figures 6. It can be seen that the maximum transmission coefficient (S21) phase range for 1.6mm substrate thickness is 185 degrees. Nevertheless, the phase range has been increased to 273 degrees when 0.5mm thickness substrate is used as depicted in Figure 7. This shows that the phase range can be increased by using thinner substrates.

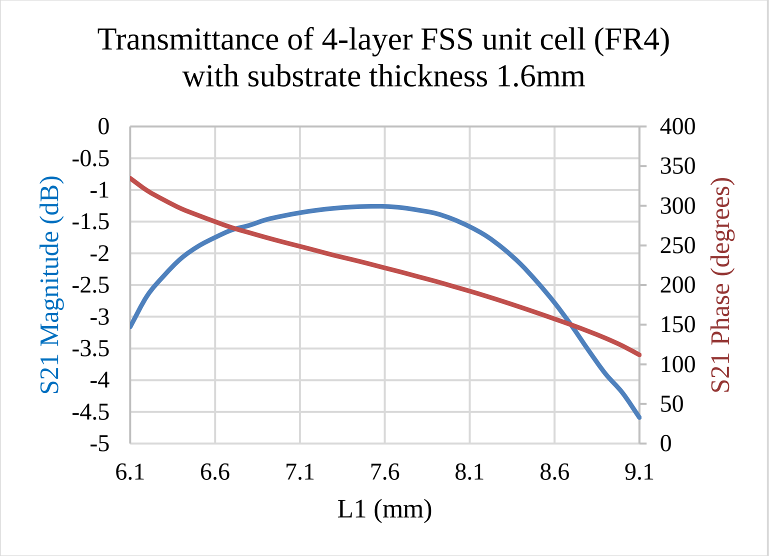


Figure 6. S21 magnitude and phase plots for unit cell design on FR4 substrate with thickness = 1.6mm

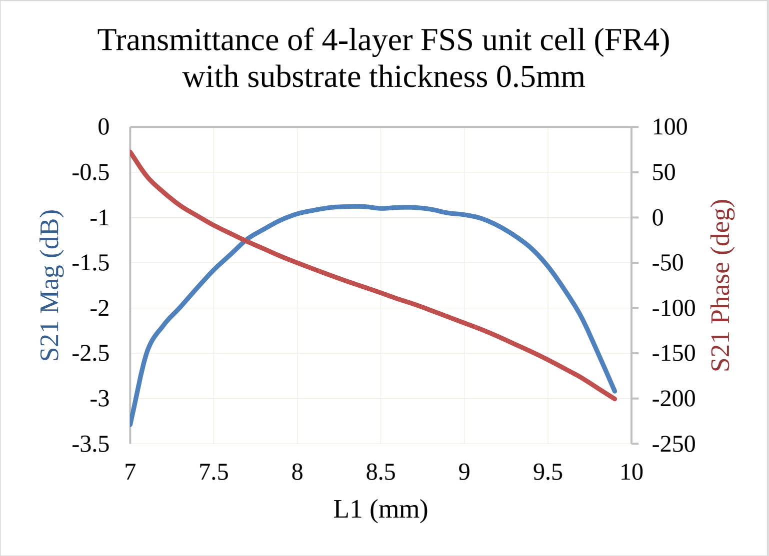


Figure 7. S21 magnitude and phase plots for unit cell design on substrate thickness = 0.5mm

In addition, the transmission coefficient magnitude and phase range can be further improved using Rogers RT/Duroid 5880 substrate with lower permittivity of 2.2. The plots shown in Figure 8 show that the transmission coefficient phase has been increased to 395.6 degrees.

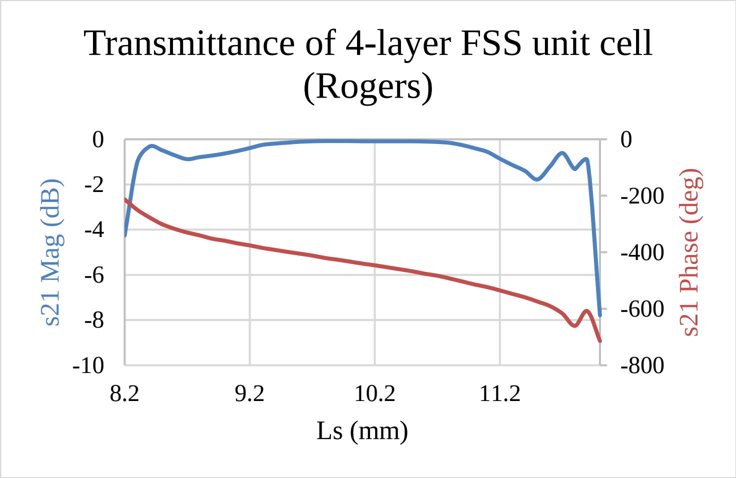


Figure 8. S21 magnitude and phase plots for unit cell design using Rogers RT/Duroid 5880 substrate with thickness 1.6mm

The horn antenna (feed source) has wide impedance matching with S11 below -10dB starting from the initial frequency of 6.65GHz. These results are shown in Figure 9.

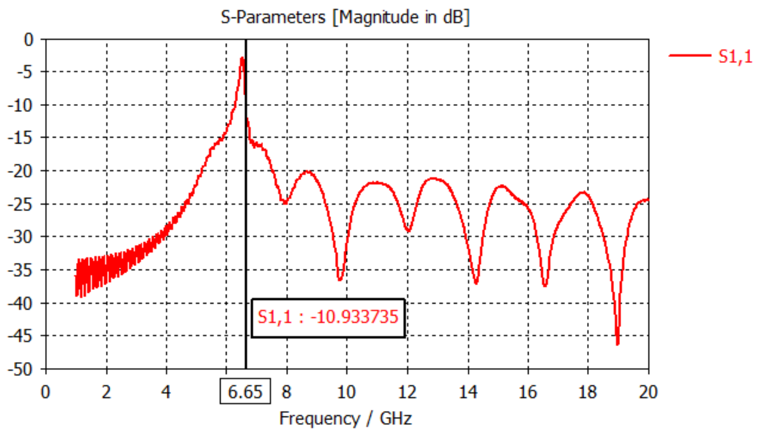


Figure 9. S11 magnitude (dB) plot for Horn antenna design

The radiation pattern for horn antenna is shown in Figure 10(a) and 10(b), in terms of E and H-plane plots. The radiation pattern shows the peak gain of 14.05dB at 12GHz frequency. The detailed gain versus frequency plot can be seen in Figure 11.

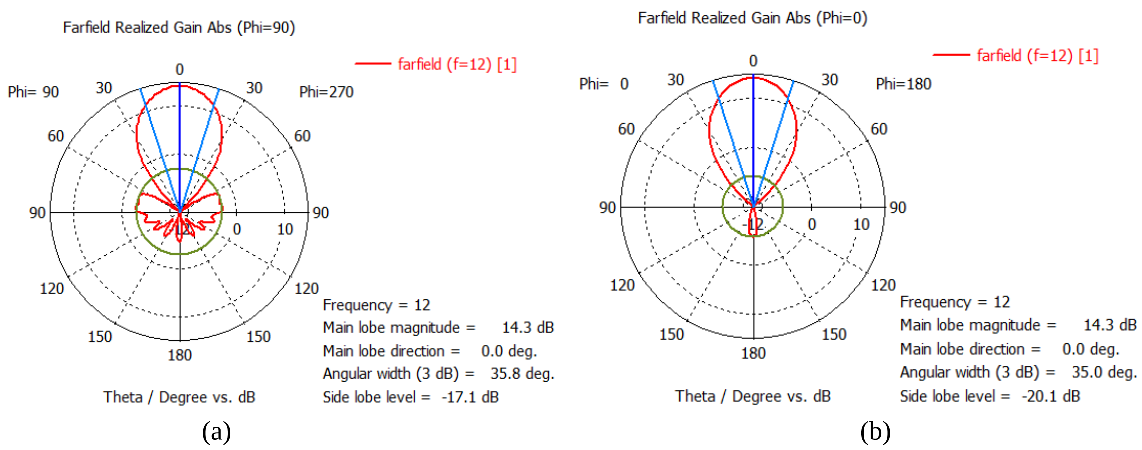


Figure 10. The radiation pattern for Horn antenna at 12GHz (a) E-plane (b) H-plane

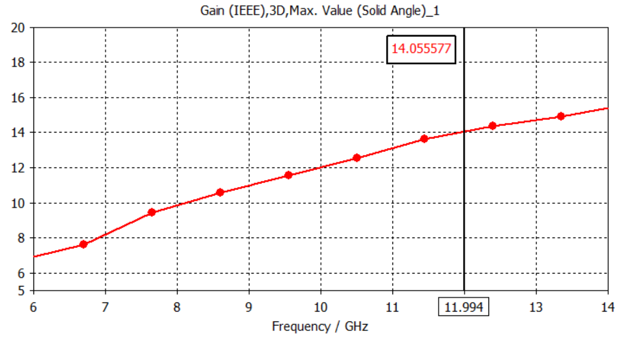


Figure 11. Gain versus frequency plot for Horn antenna design

The complete transmitarray design using FSS unit cell, the S11 simulated and measured results can be seen in Figure 12. The S11 plots shows the wider impedance matching.

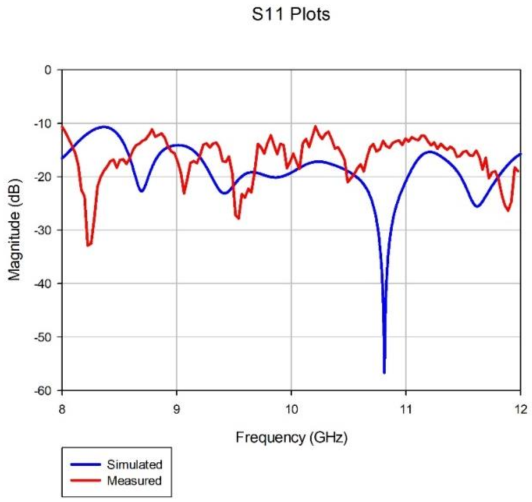


Figure 12. Simulated and measured S11 magnitude (dB) plots for proposed transmitarray antenna

The maximum gain versus frequency plot is shown in Figure 13. It can be seen that the maximum gain of 18.96 dBi has been achieved in the simulation. The 1-dB gain bandwidth is calculated from Figure 13 below, having a value of 2 GHz and an aperture efficiency of 60.2%. However, the measurement results show that peak antenna frequency has been slightly shifting to the lower frequency. The measured gain bandwidth is obtained as 1 GHz. This is mainly due to the fabrication error, especially in terms of the precession of the unit cell sizes, multilayer structure alignment and the distance between horn antenna and FSS layer.

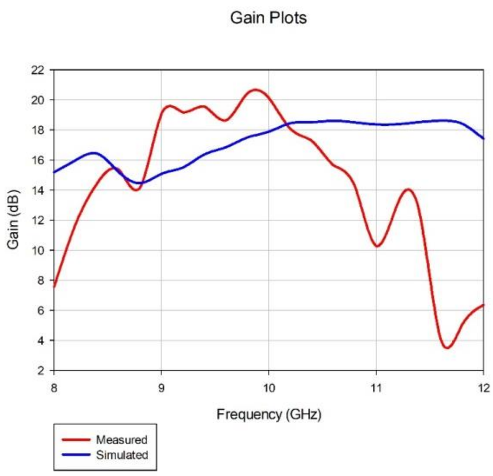


Figure 13. Simulated and measured gain versus frequency plot for proposed transmitarray antenna

The radiation pattern plots (polar plots) for full transmitarray antenna are shown in Figure 14, showing the comparison of simulated and measured results at the peak antenna gain.

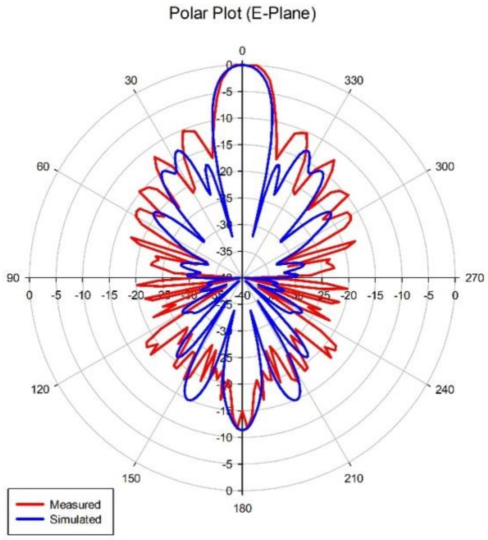
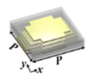
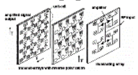
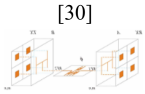
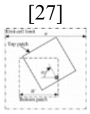
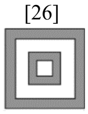
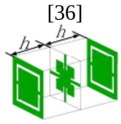


Figure 14. Comparison of simulated and measured radiation pattern (Polar Plot) for the double square ring with center patch transmitarray antenna at peak gain

Finally, the comparison of the proposed frequency selective surface transmitarray antenna with other works is carried out in Table 1. From these results, we can see that we have successfully designed a wideband transmitarrray antenna by using a new double square ring with center patch unit cell. The simulation results show 16.7 % 1 dB gain bandwidth has been obtained.

Table 1. Comparison of Transmitarray antennas with the proposed wideband Transmitarray design

Antenna Type	Unit Cell	Freq (GHz)	Peak Gain (dBi)	Gain BW (%)	Aperture Efficiency (%)
Metasurface Antenna	 [5]	10	21.4	9.14	36.3
Transmitarray of transistor amplifiers	 [30]	12.5	23.5	2.5	-
Electronically reconfigurable transmitarray	 [27]	12	16	5.8	30
Wideband circular polarized transmitarray	 [26]	60	23.9	6.5	17
Transmitarray using double square rings	 [36]	30	28.6	7.5	47
AMC based low profile transmitarray	 [38]	27.8	25.7	5	46
Proposed Wideband FSS transmitarray		12	18.96	16.7	60.2

4. CONCLUSION

In this research, a wideband transmitarray antenna is designed using a four-layer frequency selective surface unit cell. A new double square ring with center patch unit cell is designed at 12GHz using low-cost FR4 substrate. The complete transmitarray design shows a maximum gain of 19dB. Besides, wider impedance matching is achieved over the X-band frequency range of 10 to 12GHz. The simulated 1-dB gain bandwidth calculated from the gain frequency plot is 2GHz with 60.2% aperture effieciency. The proposed transmitarray design can be used for high gain satellite communication systems.

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BIOGRAPHY OF AUTHORS

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