Progress In Electromagnetics Research M, Vol. 97, 97–106, 2020

Flexible Frequency Selective Surface in Convoluted Square Form with Microstrip Patch for X-Band Application

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Abstract—This article reports a very efficient Frequency Selective Surface (FSS) with Convoluted Square Loop (CSL) shape is designed for applications in the X-band. They are designed on the surfaces of an FR-4 substrate. Frequency selective surface (FSS) is a combination of a periodic structure designed to selectively absorb, reflect, and transmit electromagnetic (EM) waves. FR-4 material provides durability and flexibility. A convoluted square loop structure reduces the size of the unit cell, and it also has a better stability with good gain. So, a CSL patch with a CSL FSS array with a slot on dual FR4 substrates is introduced for the improvement in overall gain and bandwidth. As per the design parameters, a structure is designed at 10 GHz. This structure is designed with ANSYS HFSS. The proposed antenna structure has a return loss of −36.424 dB, and VSWR value is 1.0307. The measurement results show a gain improvement of 6.266 dB and bandwidth of 5.882 dB.

1. INTRODUCTION

Frequency selective surface is any thin, repetitive surface designed to reflect, transmit, or absorb electromagnetic fields based on the frequency of the field in [1] by Munk. These surfaces can be referred to as a spatial filter, and they can also respond to a particular frequency in the whole EM spectrum. FSS found in numerous applications in wideband communication, microwave, millimetre wave, and radar systems such as spatial filters, radar absorbing materials (RAM), artificial magnetic conductors (AMC), planar lenses, radomes, sub-reflector, polarizer, and reflect arrays antenna is stated in [2] and [3]. The most important advantage of FSS is easy fabrication due to its simple geometry and low cost. The structure contains an array of slots which are patches with different shapes designed on different substrates which will act as a band pass, band stop, low pass, or high pass spatial filters [4, 5]. Nowadays, FSS array alone is used as an antenna which is for having good return loss but provides low gain in X-band application. To eliminate low gain in X-band, a patch is added in substrate 2 which is mentioned [6, 7]. It consists of a flat rectangular sheet or "patch" of metal, mounted over a larger sheet of metal called a ground plane. It can be used to make high gain array antennas. There are different structures of patch antenna, in which a square patch is used in [8, 9], and it can be easily fabricated and simplicity impedance matching, but itself has a low stability, narrow bandwidth, and surface wave excitation that reduce radiation efficiency. Convoluted square loop has better stability, used to reduce the size of the unit cell, having high gain and high bandwidth. For the proposed design, a convoluted square loop (CSL) element is chosen, as it offers good stability and gain value. The proposed structure consists of an FSS CSL array with a CSL patch, printed on double FR-4 laminates with operating frequency 10 GHz.

Received 20 August 2020, Accepted 15 September 2020, Scheduled 10 October 2020
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2. ANTENNA DESIGN

Microstrip or patch antennas are becoming increasingly useful because they have low cost, a low profile and are easily fabricated. The shapes of microstrip patch antenna are circular, rectangular, triangular, and square. In present day, communication square shape is mostly used to design an antenna for good impedance matching. FSS array antenna is used to provide good performance in X-band. But looking into array, size is problematic. To eliminate that problem, a convoluted square patch is taken as FSS because convoluted square loop structure reduces the size of unit cell, and it also has a better stability with good gain value. An FSS CSL array structure shown in the Figure 1 is used to increase gain and stability for X-band application. FSS provides effective shielding in X-band. A frequency-selective surface (FSS) is a structure most typically consisting of two-dimensional periodic elements, and it is designed and proposed for both square and CSL array structure, which is mentioned in Figures 2 and 3. It has the operating frequency in X-band (8–12 GHz). All the parameters mentioned in Table 1 is derived using formulas.

The thickness (h) of the FR-4 substrate is derived from the formula mentioned below

$$h = \frac{0.0606\lambda}{\sqrt{\varepsilon_r}} \tag{1}$$

where ε_r = relative permittivity, $\lambda = \frac{c}{f}$ in which c = velocity of light $(3 * 10^8)$, f = operating frequency.

The length of the element is derived from the formula mentioned below,

$$L = \frac{c}{4 * \sqrt{\varepsilon_{eff}} * f} \tag{2}$$

where c = velocity of light $(3 * 10^8)$, f = operating frequency and ε_{eff} = dielectric constant.

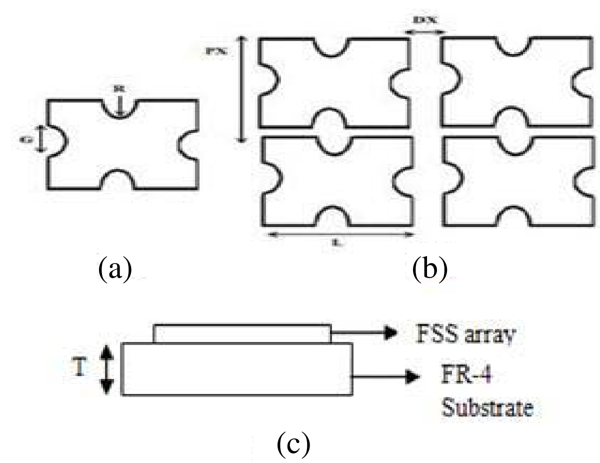

Figure 1. (a) CSL. (b) Elements array (unit cell). (c) Side view of CSL as FSS.

Table 1. Parameters of FSS array.

Parameters	Dimensions (mm)
L	4.6
PX	5.1
DX	0.5
R	0.5
$G = 2R$	1

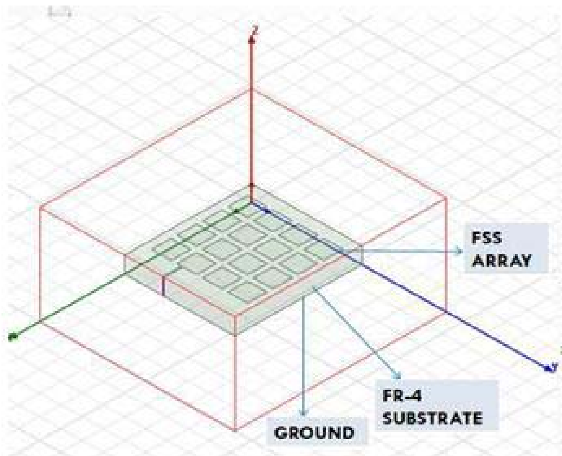

Figure 2. FSS structure of square array.

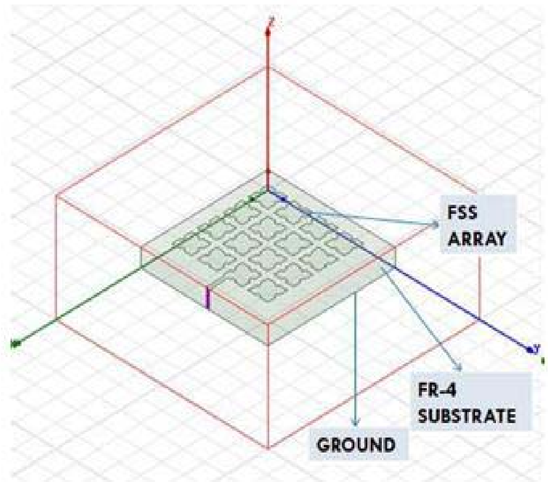

Figure 3. FSS structure of CSL array.

The radius of the convoluted square loop is derived by using the formula,

$$R = \frac{c}{2 * \pi * f * \sqrt{\varepsilon_{eff}}} \tag{3}$$

FR4 material ($\varepsilon_r = 4.4$) is used to analyze the dielectric constant of the material

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \tag{4}$$

where $1 < \varepsilon_{eff} < \varepsilon_r$.

The length of the convolution in each patch is derived from the formula,

$$G = 2R \tag{5}$$

The bandwidth is calculated by using the formula mentioned below,

$$\text{Bandwidth} = \frac{F2 - F1}{F_c} \tag{6}$$

where F_1 = lower frequency, F_1 = upper frequency, F_c = centre frequency.

The inter-element spacing between two antenna structures is derived by using the formula

$$DX = \frac{\lambda}{2} \tag{7}$$

The necessary parameter to drive the antenna structure is mentioned in Table 1. FSS structure using square and CSL is designed, and a microstrip feed is used as an input for these structures.

In Figure 2, FSS structure in square shape is designed, and it is the simplest structure to design, but itself has the drawbacks of low stability, and the size of the unit cell is large, so convoluted square structures is introduced at each centre of the square element to eliminate these two drawbacks.

CSL structure has better stability, low profile; the enhanced fractional bandwidth because of reduced unit cell structure is mentioned in Figure 3. Initially, a single FSS with CSL structure is designed. Then, an FSS array in CSL shape is designed, and parameters are noted down. Again FSS array with CSL structure is designed and the parameters are noted down.

In order to identify and verify the improvement of gain and bandwidth in antenna, a patch is introduced, and an FSS structure is designed and proposed for both square patch and CSL patch. The proposed FSS design is stimulated on an FR-4 substrate, and it is depicted in Figures 4 and 5.

In order to increase the antenna parameters, a slot is introduced in the ground in Figures 4 and 5.

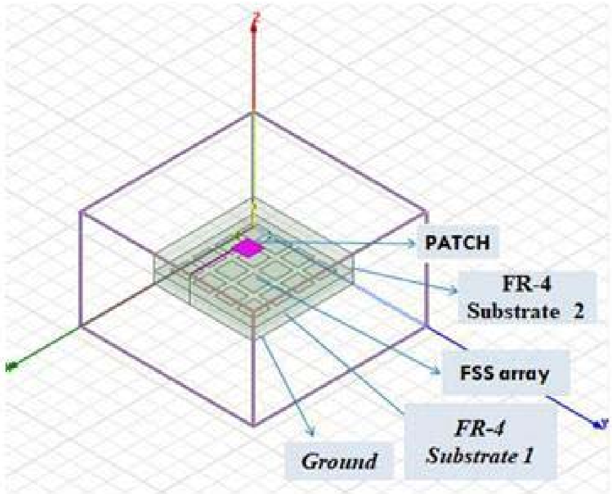

Figure 4. FSS structure of square array with patch.

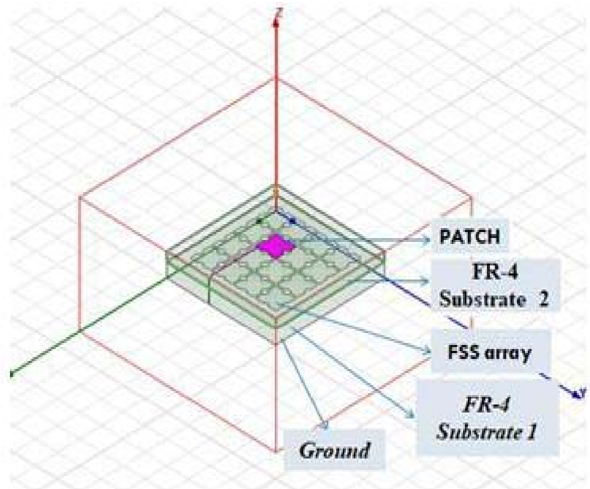

Figure 5. FSS structure of CSL array with patch.

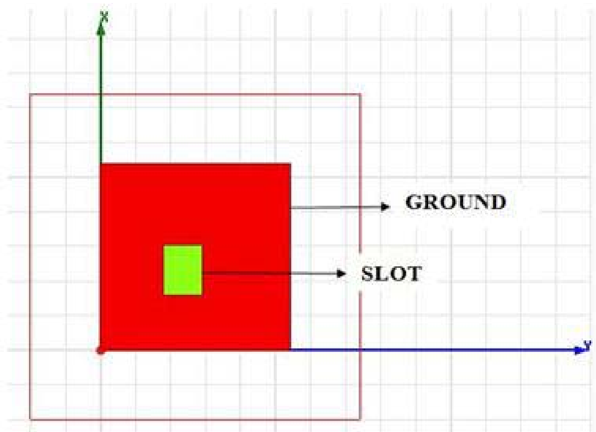

Figure 6. CSL patch with slot on ground.

3. RESULTS AND DISCUSSION

3.1. FSS Array in Square Shape

The FSS array in square shape is designed, and its return loss has the value of −14.8262 dB at 10.9 GHz. It also has the bandwidth value of 5.705 dB seen at −10 dB shown in Figure 7.

The FSS array in square shape is designed and its VSWR shown in Figure 8, and it has the VSWR value of 1.443 dB at 10.9 GHz.

In Figure 9, the gain of FSS array in square shape is shown, and it has the gain value of 3.070 dB.

3.2. FSS Array in CSL Shape

The FSS array using CSL is designed, and its return loss has the value of −22.507 dB at 10.8 GHz shown in Figure 10. Compared with Figure 7, it has high return loss, low distortion, high efficiency, and bandwidth value of 5.313 dB.

In Figure 11, the VSWR of FSS array in CSL shape is shown, and it has the value of 1.162 dB at 10.8 GHz. Comparing this to Figure 8, it has high VSWR value.

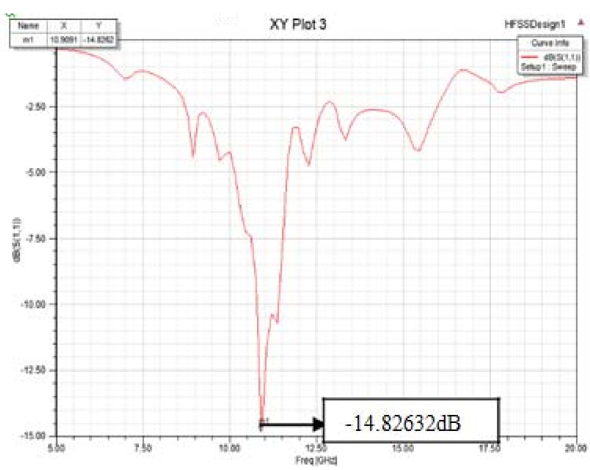

Figure 7. Return loss of FSS array in square shape.

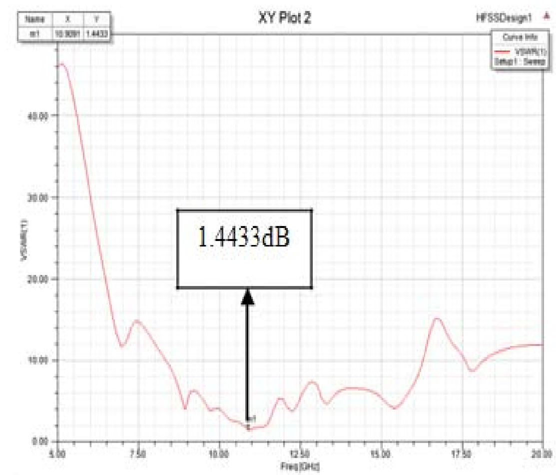

Figure 8. VSWR of FSS array in square shape.

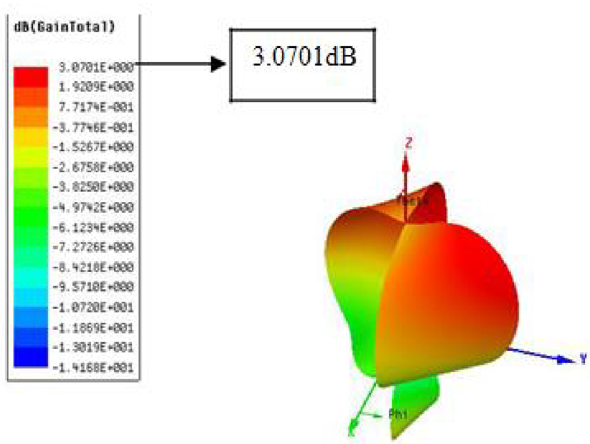

Figure 9. Gain of FSS array in square shape.

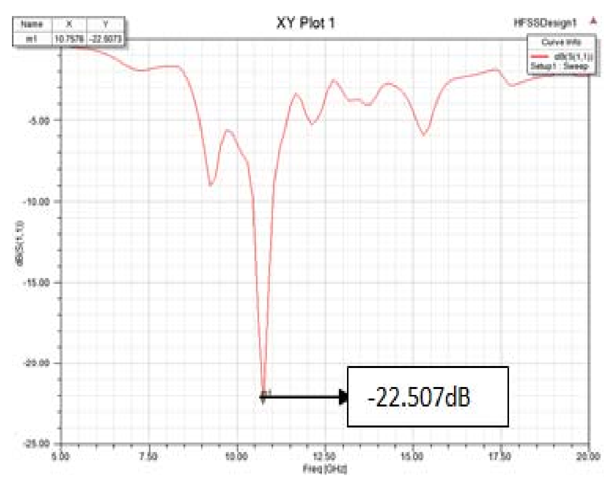

Figure 10. Return loss of FSS array in CSL shape.

In Figure 12, the gain of FSS array in CSL shape is shown, and it has the value of 3.8479 dB. Comparing this to Figure 9, it has high gain.

3.3. Square FSS Array in One Layer with Square Patch in Another Layer

The FSS array using a square patch is designed, and its return loss has the value of −11.484 dB at 8 GHz shown in Figure 13. Compared with Figure 7, it has increased return loss value, low distortion, high efficiency and bandwidth of 5.953 dB.

In Figure 14, the VSWR of FSS array using square patch element is shown, and it has the value of 1.789 dB at 8 GHz.

In Figure 15, the gain of FSS array using square patch element is shown, and it has the value of 3.619 dB. Comparing this to Figure 8, it has high gain.

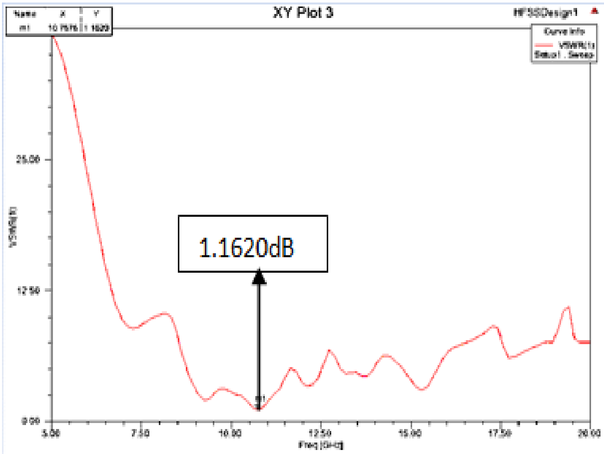

Figure 11. VSWR of FSS array in CSL shape.

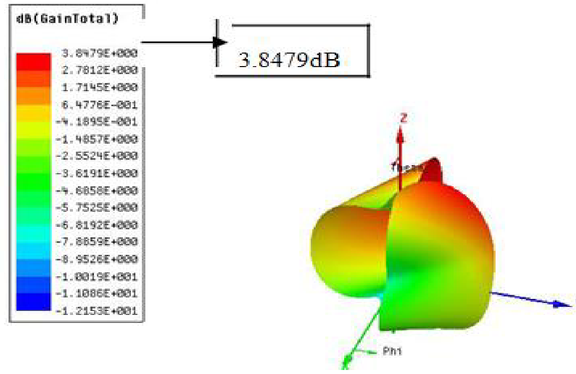

Figure 12. Gain of FSS array in CSL shape.

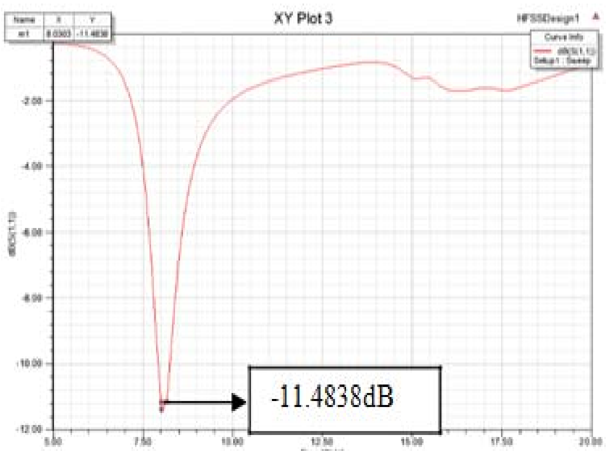

Figure 13. Return loss of FSS array in square patch element.

Figure 14. VSWR of FSS array in square patch element.

3.4. CSL FSS Array in One Layer with CSL Patch in Another Layer

The FSS array using a CSL patch is designed, and its return loss has the value of -25.077 dB at 8.6 GHz shown in Figure 16. Compared with Figures 7, 10, 13, it has a high return loss, low distortion, high efficiency, and high bandwidth value of 7.236 dB.

In Figure 17, the VSWR of FSS array using CSL patch element is shown, and it has the value of 1.118 dB at 8.6 GHz.

In Figure 18, the gain of FSS array using a CSL patch has the value of 5.257 dB. Compared to Figures 9, 12, 15, Figure 18 has better improvement in gain in the case without slot.

3.5. Square FSS Array in One Layer with Square Patch in Another Layer with Slot on Ground

The FSS array using square patch with slot is designed, and its return loss has the value of -19.8442 dB at 10.151 GHz shown in Figure 19. Compared with Figures 7, 10, 13, 16, it has a high return loss, low distortion, and high efficiency.

In Figure 20, the VSWR of FSS array using square patch element is shown, and it has the value of 1.2267 dB at 10.151 GHz.

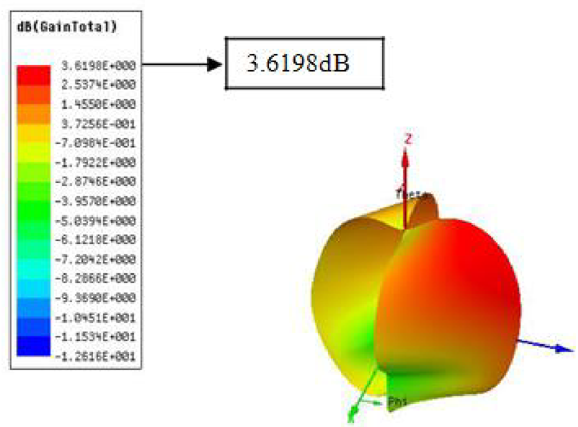

Figure 15. Gain of FSS array in square patch element.

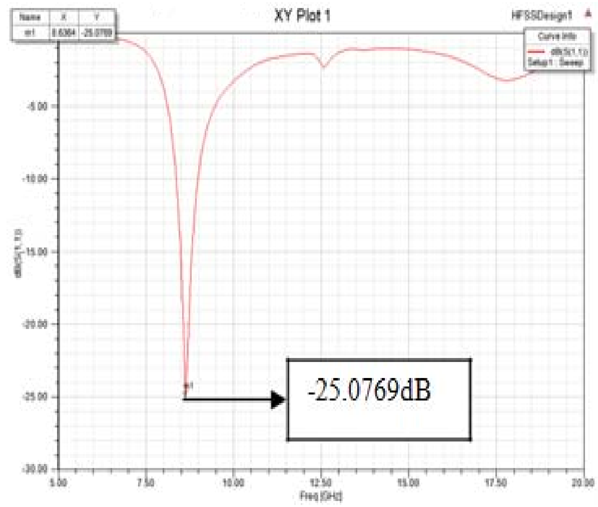

Figure 16. Return loss of FSS array in CSL patch element.

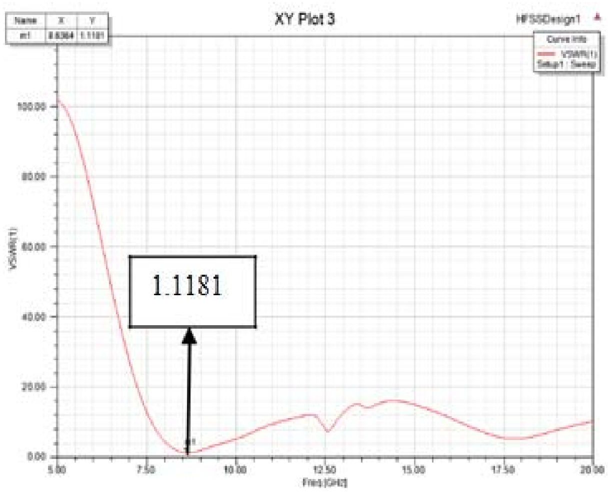

Figure 17. VSWR of FSS array in CSL patch element.

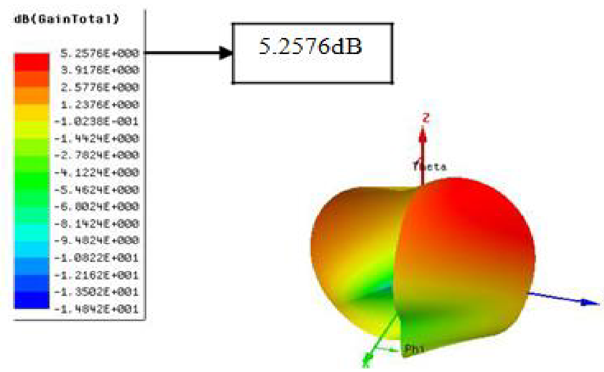

Figure 18. Gain of FSS array in CSL patch element.

Compared to Figure 18, Figure 21 has a minimum gain of FSS array using square patch element, and it has the value of 4.6882 dB. Comparing all antenna designs it is has comparatively good gain.

In Figure 22, the bandwidth of FSS array with square patch element with a slot is shown, and it has the bandwidth value of 5.2 dB.

3.6. CSL FSS Array in One Layer with CSL Patch in Another Layer with Slot on Ground (Proposed Design)

The FSS array using CSL patch with a slot is designed, and its return loss has the value of -36.4241 dB at 10.151 GHz shown in Figure 23. Compared with Figures 7, 10, 13, 16, and 19, it has a high return loss, low distortion, and high efficiency.

In Figure 24, the VSWR of FSS array using CSL patch element with a slot on ground is shown, and it has the value of 1.0307 dB at 10.151 GHz.

In Figure 25, the gain of FSS array using CSL patch element is shown, and it has the value of 6.2666 dB.

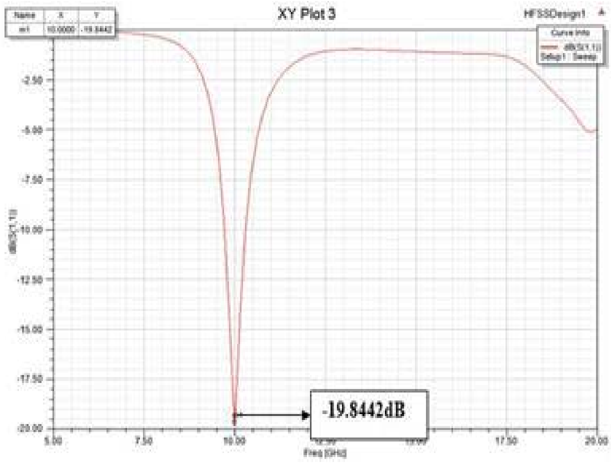

Figure 19. Return loss of FSS array in square patch element with slot on ground.

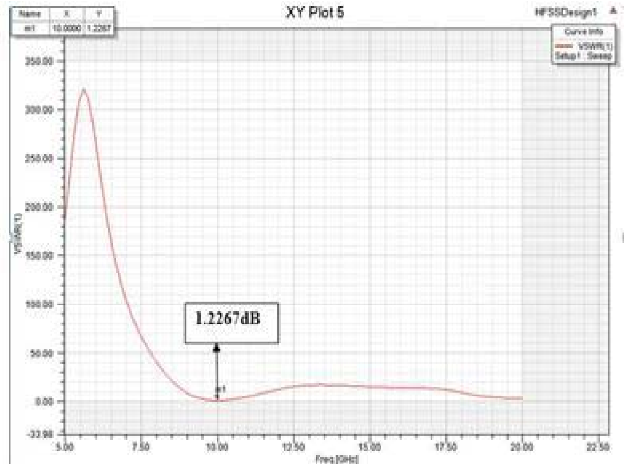

Figure 20. VSWR of FSS array in square patch element with slot on ground.

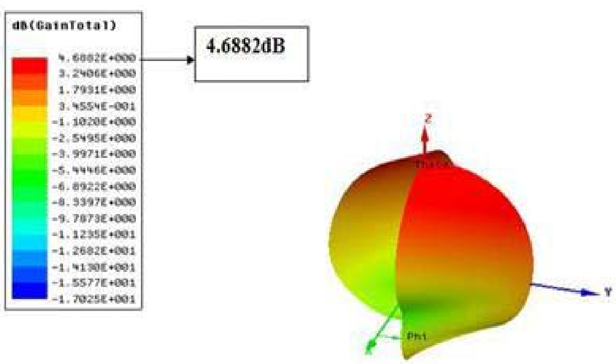

Figure 21. Gain of FSS array in square patch element with slot on ground.

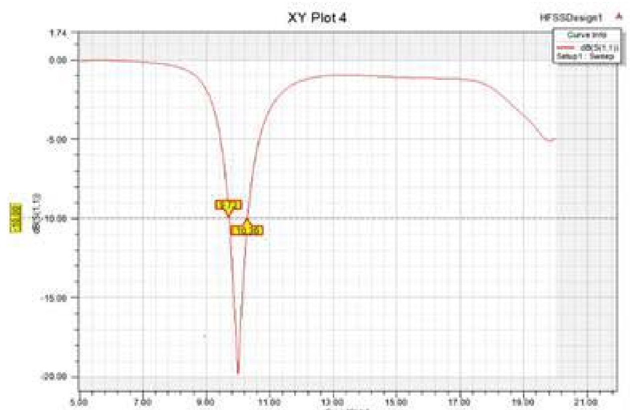

Figure 22. Bandwidth of FSS array in square patch element with slot on ground.

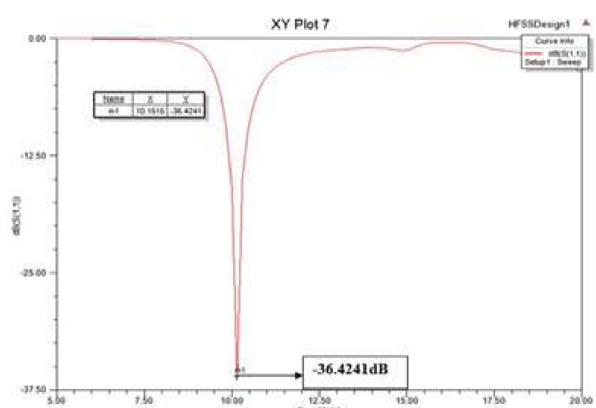

Figure 23. Return loss of FSS array in CSL patch element with slot on ground.

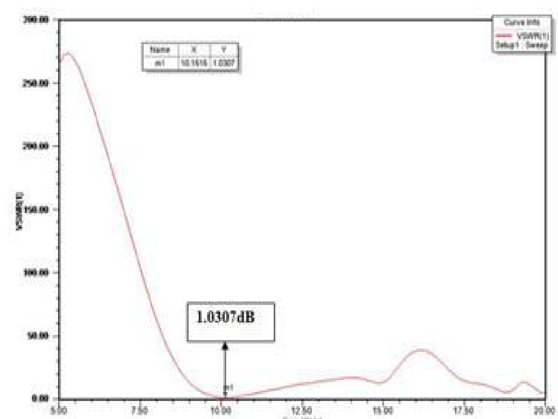

Figure 24. VSWR of FSS array in CSL patch element with slot on ground.

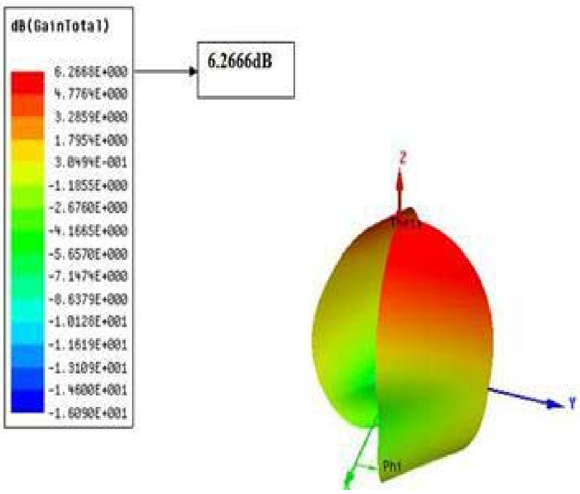

Figure 25. Gain of FSS array in square patch element with slot on ground.

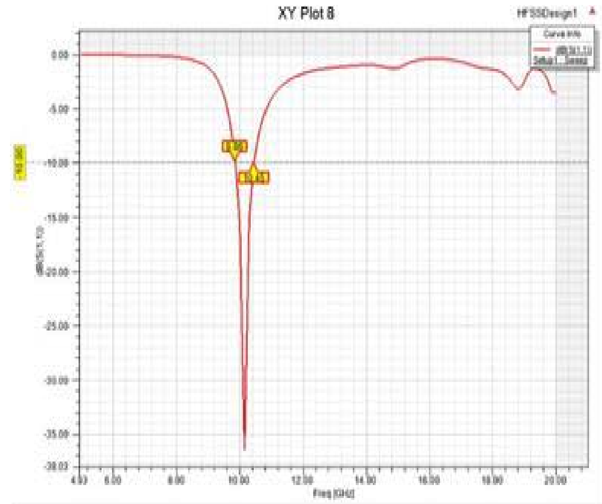

Figure 26. Bandwidth of FSS array in CSL patch element with slot on ground.

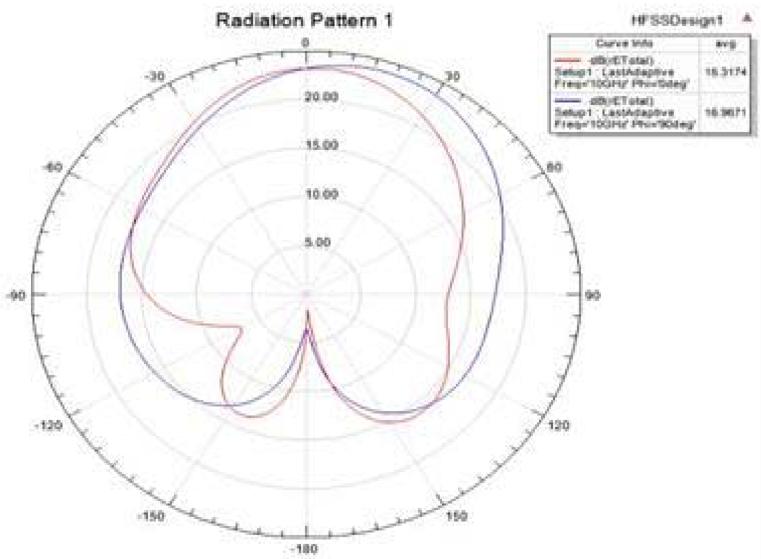

Figure 27. Radiation pattern of FSS array in CSL patch element with slot on ground.

Table 2. Comparison of all parameters without slot.

Parameters Structure	Return loss (dB)	VSWR (dB)	Gain (dB)	Band Width (dB) (−10 dB)
FSS in Square shape	−14.826	1.443	3.070	5.705
Square FSS array with Square patch	−11.484	1.789	3.619	5.953
FSS in CSL shape	−22.507	1.162	3.548	5.313
CSL FSS array with CSL patch	−25.077	1.118	5.258	7.236

In Figure 26, the bandwidth of FSS array with CSL patch element with a slot is shown, and it has the bandwidth value of 5.8 dB.

In Figure 27, the radiation pattern of FSS array in CSL shape with a slot on ground is shown, and the radiation has omnidirectional pattern.

Table 2 compares the performance of all designed antennas without slot in that CSL FSS array in one layer with CSL patch on another layer, and it shows better improvement in gain and bandwidth than all the antenna designs. Figure 25 has a good gain value in the case of using a slot (proposed design gain value) which is mentioned in Table 3.

Table 3. Comparison of all parameters with slot.

Parameters Structure	Return loss (dB)	VSWR (dB)	Gain (dB)	Band Width (dB) (−10 dB)
Square FSS array with Square patch with slot on ground	−19.882	1.2267	4.688	5.246
CSL FSS array with CSL patch with slot on ground (proposed design)	−36.424	1.0307	6.266	5.882

4. CONCLUSION

The CSL patch is a miniaturized unit cell which takes the advantage of decreasing the size of the structure. The design has a good return loss of −36.424 dB, good gain of 6.266 dB, and bandwidth of 5.882 dB in X-band applications. The proposed structure is used for many conformal applications in the X-band such as spatial filters, radar absorbing materials (RAM), artificial magnetic conductors (AMC), planar lenses, radomes, sub-reflector, polarizer, and reflect arrays antennas.

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