

High-gain 28-GHz CP Patch Antenna with 6×6 FSS

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Abstract

The presented design offers a novel miniaturized single-feed circularly polarized (CP) microstrip patch antenna in conjunction with a 6×6 frequency selective surface (FSS) for gain improvement in Ka-band (28 GHz) applications. The proposed CP microstrip antenna uses the truncated corner microstrip patch design in order to obtain circular polarization and at the same time remains compact enough for future millimeter-wave wireless systems. In order to improve the radiation efficiency of the proposed design, the use of symmetric closed-ring 6×6 FSS is implemented above the radiating patch. Electromagnetic coupling between the antenna and FSS results in improvement of radiation characteristics of the antenna and increase in its gain. The reference CP antenna gives the gain of 7.28 dBi, impedance bandwidth of 2.72 GHz (9.74%) and 3-dB axial-ratio bandwidth of 1.97 GHz (7.12%). As a result of incorporation of the FSS layer, the gain is increased up to 11.01 dBi, which is equivalent to 3.73 dB of improvement in gain. Impedance and axial-ratio bandwidths become equal to 2.31 GHz and 1.74 GHz respectively. Results reveal that the developed FSS using single-layer configuration provides an efficient and low-complexity approach to enhance gain without affecting the impedance or polarization bandwidth performance. Considering its small size, high gain and circular polarization properties, the developed antenna is suitable for use in Ka-band satellite communications and 5G/6G millimeter-wave communication applications.

Keywords: Circularly Polarized Antenna, Frequency Selective Surface (FSS), Gain Enhancement, Ka-band Antenna, Microstrip Patch Antenna, Truncated-corner Patch.

Introduction

The demand for the high-data-rate wireless communication systems has made mmWaves for 5G, B5G and 6G develop faster than ever before. One of the most widely used mmWave frequency bands is 28 GHz of Ka-band because of its wide bandwidth, spectral efficiency and flexibility for space and terrestrial wireless communications. However, antenna design becomes harder due to increased propagation losses and strict requirements on the size, gain and polarization purity.

Various techniques such as arrays, parasitics, dielectric superstrates, metasurfaces and FSSs have been used to enhance microstrip antenna gain. Each approach varies in terms of realization, but FSS based structures could increase directivity and gain without complicating the system. The design and placement of the FSS unit cell could affect antenna performance through constructive interference of the transmitted and reflected waves.

This paper presents a circularly polarized microstrip patch antenna with a symmetric closed-ring 6x6 FSS structure for gain enhancement at 28 GHz. This proposed approach increases broadside radiation pattern, impedance match and axial ratio. Simulation results show considerable gain enhancement in comparison with reference antenna, which makes it suitable for satellite communication systems based on Ka-band and 5G/6G networks.

An analytical analysis was performed on advanced micro-scale structures with electromagnetic and energy transfer mechanisms (1). Gain improvement methods for a microstrip patch antenna operating at 28 GHz frequency for 5G networks were studied (2). The use of FSS layer led to gain and radiation performance improvement while preserving wide bandwidth (3). The design possessed enhanced impedance match and multi-band behaviour (4).

The FSS reflector resulted in enhanced radiation

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(Received 24th July 2026; Accepted 10th October 2026; Published 25th October 2026)

performance and antenna directivity (5). The usage of FSS layer led to gain, isolation and MIMO performance enhancement (6). The characteristic mode approach resulted in better comprehension of the mode behaviour, thus increasing the antenna performance (7). Designing of the compact size high-gain rectangular microstrip patch antenna operating at 28 GHz for future generation wireless systems was carried out (8). The introduced system made it possible to enhance the radiation properties (9). The introduced structure provided good directivity and electromagnetic wave manipulation performance (10). Designing of the FSS assisted microstrip antenna for WLAN and WiMAX application was proposed (11). The reflective surface enhanced the gain property in compact structure (12). The optimization helped in improving the radiation efficiency and directivity of the antenna (13). An enhanced gain with high radiation efficiency was achieved in the antenna design (14). FSS-loaded mmWave MIMO antenna for 28/38 GHz has been designed for future wireless applications (15). The FSS layer improved radiation performance while providing dual-band operation (16). The designed structure increased the directivity without making the antenna more complicated (17). The gain improvement techniques in MIMO antennas using FSS have been examined for IoT and vehicular communication system (18). Several ways to increase the gain of antennas, such as antenna arrays and metasurfaces, were mentioned (19). This study focused on the design of small-scale structures that will be able to increase the efficiency of the system (20). The findings showed the increasing role of advanced electromagnetic surfaces in the future wireless networks (21). Intelligent optimization and control techniques were used to enhance system performance in renewable energy applications (22). The study revealed the efficiency of optimization methods in improving the system performance (23). The study pointed out the ability of reconfigurable intelligent surfaces to manipulate electromagnetic waves and improve wireless communication performance (24). Intelligent optimization techniques were applied to enhance the performance in distribution networks (25).

Although gain enhancement has been achieved through FSSs, metasurfaces, reflectors and antenna arrays, there are some constraints. Firstly,

most Ka-band antennas with the assistance of FSSs are only interested in gain and bandwidth but ignore circular polarization. Secondly, many high-gain antennas use multi-layered metasurfaces, very large arrays and complex designs, hence increasing fabrication cost, structure height and manufacturing complexity. Thirdly, there are not many studies done to explore miniaturized single-fed antennas operating in circular polarization with a simple FSS structure at 28 GHz. Therefore, making a miniaturized and low-profile Ka-band circularly polarized antenna is yet to be explored. The Research Objectives of this paper are as follows:

- a) To design a small single feed circularly polarized microstrip patch antenna at 28 GHz for Ka-band applications.
- b) To design a symmetric closed ring 6×6 frequency selective surface (FSS) to improve the radiation properties of the antenna.
- c) To study the electromagnetic coupling behaviour between circularly polarized microstrip patch antenna and the proposed FSS structure.
- d) To improve the gain of the antenna while keeping the impedance bandwidth and axial ratio bandwidth acceptable.
- e) To obtain a low profiled and fabrication friendly antenna structure for 5G/6G, satellite communications and millimetre-wave wireless applications.

Methodology

The proposed antenna consists of a compact single-fed circularly polarized microstrip patch operating at 28 GHz. The design is developed in two stages: first, the CP patch is optimized and subsequently a 6×6 FSS layer is integrated above the antenna to enhance the broadside gain. The overall configuration is selected to retain the planar nature of the antenna while introducing a simple electromagnetic reflecting layer.

CP Patch Antenna

Circular polarization of the suggested antenna is obtained through symmetric corner truncations of the microstrip patch at the opposite corners. Corner modification leads to changes in current distribution across the patch, causing splitting of the fundamental resonant mode into two orthogonal modes. These modes are excited with almost equal amplitudes and with approximately

90-degree phase difference, creating circular polarization due to rotating currents distribution over the surface of the patch. The axial ratio plot shows that the antenna operates with circular polarization in the desired frequency range. Thus, the suggested configuration allows one to design a CP antenna using single feed line. The reference antenna employs a circular radiating patch excited by a microstrip feed line. A perturbation is introduced into the circular patch to excite two orthogonal modes with the required amplitude and phase relationship for circular polarization (CP). The feed position and patch perturbation are optimized to obtain the desired impedance matching and AR response around 28 GHz. The antenna is designed on a rectangular FR4 substrate with dimensions of $24 \times 24 \text{ mm}^2$ and a thickness of 1.2 mm. The optimized patch radius is 1.625 mm,

while the feed-line width and length are 0.641 mm and 9.186 mm, respectively. The notch radius and feed offset are 1.43 mm and 1.215 mm, respectively. The remaining geometrical parameters are defined by $W_n = 0.2 \text{ mm}$ and $L_n = 0.7 \text{ mm}$. The geometry and dimensions of CP antenna is shown in Figure 1 and Table 1 respectively. Figure 1 shows the geometrical configuration of the suggested single feed CP microstrip patch antenna, depicting both the top view and side view of the antenna. The proposed antenna comprises of a square patch with two of its corners truncated and printed on the top surface of a dielectric substrate, whereas the entire ground plane is placed on the other side. Circular polarization is generated through two orthogonally excited modes having the same amplitude but 90° phase difference.

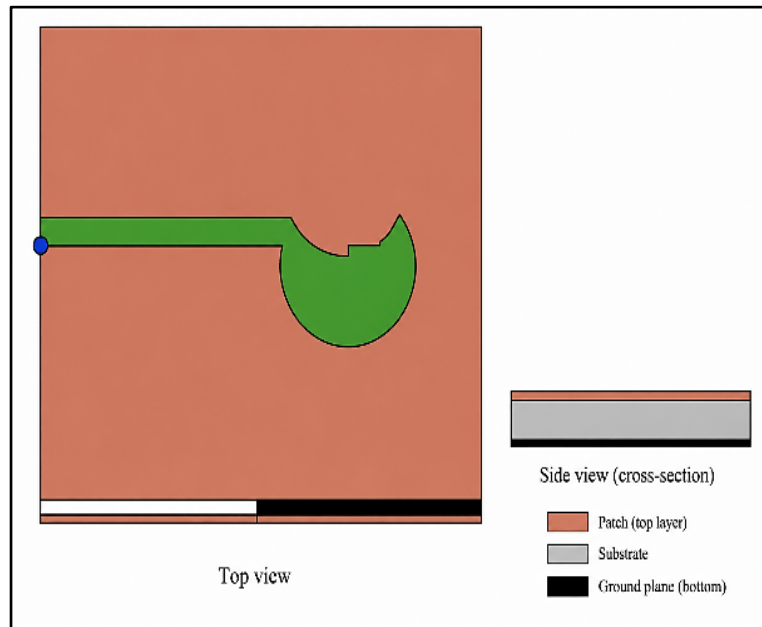


Figure 1: Geometry of CP Patch Antenna: Top View and Side View

Note: CP = Circular Polarization.

Table 1: Dimensions of the CP Antenna

Parameter	Symbol	Value (mm)
Substrate length	L	24
Substrate width	W	24
Substrate height	h	1.2
Patch radius	a	1.625
Feed-line width	W_f	0.641
Feed-line length	L_f	9.186
Notch radius	N_a	1.43
Feed offset	o	1.215
Slot/strip width	W_n	0.2
Slot/strip length	L_n	0.7

Note: CP = Circular Polarization.

Table 1 provides the optimized geometrical parameters of the designed CP patch antenna, including the size of the patch, the parameters of corner truncations, the parameters of the feed line, the size of the substrate and the thickness of the substrate. The above-mentioned parameters were carefully optimized for the resonant frequency of 28 GHz. The optimized reference antenna provides a gain of 7.28 dBi, an impedance bandwidth of 9.74% and an AR bandwidth of 7.12%. These characteristics are used as the baseline for evaluating the effect of the FSS layer.

6×6 FSS Configuration

A periodic FSS layer is introduced above patch to improve its directional radiation characteristics. The proposed FSS consists of 36 identical symmetric closed-ring elements arranged in a 6×6 array. A closed square-loop unit cell is selected because of its geometrical symmetry and relatively simple structure. The FSS unit cell has a periodicity of $P = 4\text{mm}$. The outer loop dimensions are $L_o = W_o = 3.2\text{mm}$, while the inner opening dimensions are $L_i = W_i = 2.4\text{mm}$. The metallic strip width is $w = 0.4\text{mm}$. Thus, the initial 6×6 array occupies approximately $24 \times 24\text{ mm}^2$.

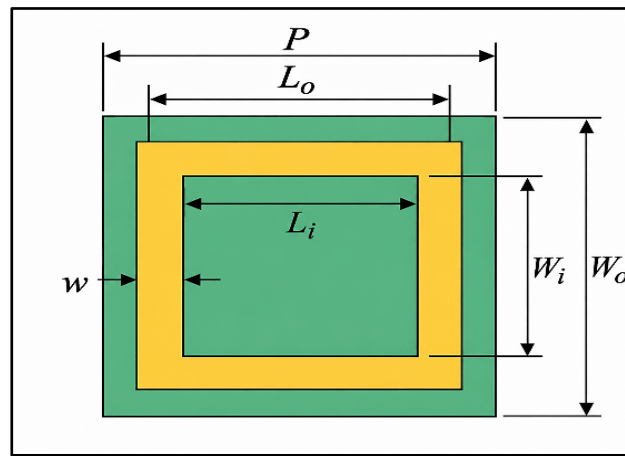


Figure 2: Geometry of the Symmetric Closed-ring FSS Unit Cell

Note: FSS = Frequency Selective Surface, P = Unit-cell Periodicity, L_o = Outer Ring length, L_i = Inner Ring Length, W_o = Outer Ring Width, W_i = Inner Ring Width, w = Ring Strip Width.

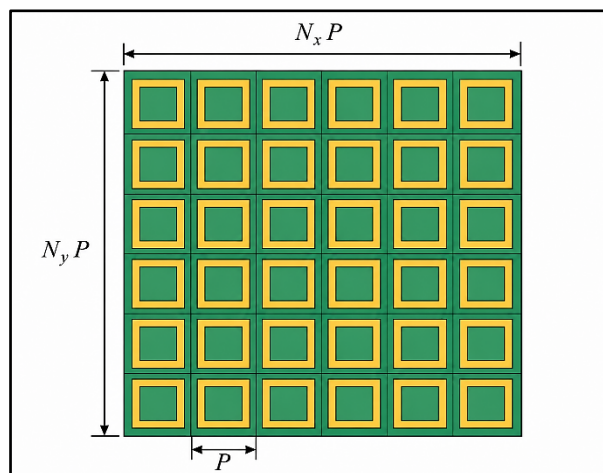


Figure 3: Geometry of the Symmetric Closed-ring 6×6 FSS Array

Note: FSS = Frequency Selective Surface, P = Unit-Cell Periodicity, N_x = Number of FSS Elements Along the x-direction, N_y = Number of FSS Elements along the y-direction.

Figure 2 shows the geometry of the proposed symmetric closed-ring FSS unit cell. The unit cell comprises a square closed-ring metallic cell whose outer dimensions, inner dimensions, ring width and periodicity are given by (L_o, W_o) , (L_i, W_i) , (w)

and (P) , respectively. It is designed to provide stable electromagnetic behaviour and good reflection properties at the required 28 GHz frequency. Figure 3 shows the geometrical shape of the suggested 6×6 symmetrical closed-ring FSS

array that is obtained through the repetition of the unit cells in the (x) and (y) directions. The dimension of the array depends on the number of the unit cells (N_x times N_y) and the periodicity (P). The FSS array is used as a reflective superstrate to increase the gain of the antenna using constructive interference of the emitted radiation from the patch antenna and the reflected waves from the FSS array. The initial antenna-to-FSS separation is selected as 4 mm. This parameter is subsequently optimized because the phase of the reflected field depends on the propagation distance between the patch and FSS. Previous investigations have shown

that FSS geometry, array configuration and antenna-to-FSS separation strongly influence the resulting gain and radiation characteristics (5, 9, 11, 13). Table 2 gives the design parameters of the proposed 6×6 symmetric closed-ring FSS, which include the dimension of unit cell, periodicity, width of the strip, substrate thickness and gap between the antenna and FSS. These design parameters were meticulously chosen in order to get the necessary reflection property at 28 GHz along with gain enhancement of the circularly polarized patch antenna.

Table 2: Parameters of the 6×6 FSS

Parameter	Symbol	Value
FSS periodicity	P	4.0 mm
Unit-cell length	P_x	4.0 mm
Unit-cell width	P_y	4.0 mm
Outer loop length	L_o	3.2 mm
Outer loop width	W_o	3.2 mm
Strip width	w	0.4 mm
Inner loop length	L_i	2.4 mm
Inner loop width	W_i	2.4 mm
FSS substrate thickness	h_f	0.508 mm
Antenna-FSS separation	g	4.0 mm
Array size	$N_x \times N_y$	6×6

Note: FSS = Frequency Selective Surface, P = Unit-Cell Periodicity, L_o = Outer Ring Length, L_i = Inner Ring Length, W_o = Outer Ring Width, W_i = Inner Ring Width, w = Ring Strip Width, N_x = Number of FSS Elements along the x-direction, N_y = Number of FSS Elements along the y-direction, h_f = FSS Substrate Thickness.

Antenna-FSS Integration

The optimized FSS array is positioned above patch with an air separation between the two structures. When the separation is appropriately selected, the reflected field can combine constructively with the direct radiation from the patch, thereby increasing the radiation intensity and realized gain. The antenna-FSS separation is therefore treated as a key optimization parameter. The FSS unit cell is initially analyzed using periodic boundary conditions, after which the optimized unit cell is replicated to form the 6×6 array. The complete antenna-FSS structure is then simulated to evaluate S_{11} , gain, radiation efficiency, radiation pattern and axial ratio.

Results

The proposed antenna is evaluated using full-wave EM simulation to investigate the effect of the 6×6 FSS layer on the performance of the 28 GHz CP patch. The comparison is based on the reflection coefficient, impedance bandwidth, axial ratio, gain and radiation characteristics. The reference and

FSS-loaded antennas are analyzed using the same operating conditions so that the effect of the FSS can be identified directly.

Reflection Coefficient and Impedance Bandwidth

The reflection coefficient, S_{11} , is used to evaluate the impedance matching of the antenna. The –10dB impedance bandwidth is determined from the frequency range over which S_{11} remains below –10dB. The reference antenna exhibits an impedance bandwidth of 2.72 GHz, corresponding to 9.74% around the 28 GHz operating region. After introducing the 6×6 FSS, the simulated bandwidth is 2.31 GHz. The change in bandwidth is attributed to the EM coupling between the patch and the reflecting FSS layer. Figure 4 shows the simulated S_{11} properties of the CP reference patch antenna and the FSS-loaded 6×6 antenna that is proposed. The impedance bandwidth of the CP antenna falls within the range of 26.566 to 29.294 GHz (2.728 GHz), while the impedance bandwidth for the FSS-loaded antenna falls within the range of

26.788 to 29.098 GHz (2.31 GHz). The findings suggest that the inclusion of the FSS slightly

narrows the impedance bandwidth but maintains impedance matching at 28 GHz.

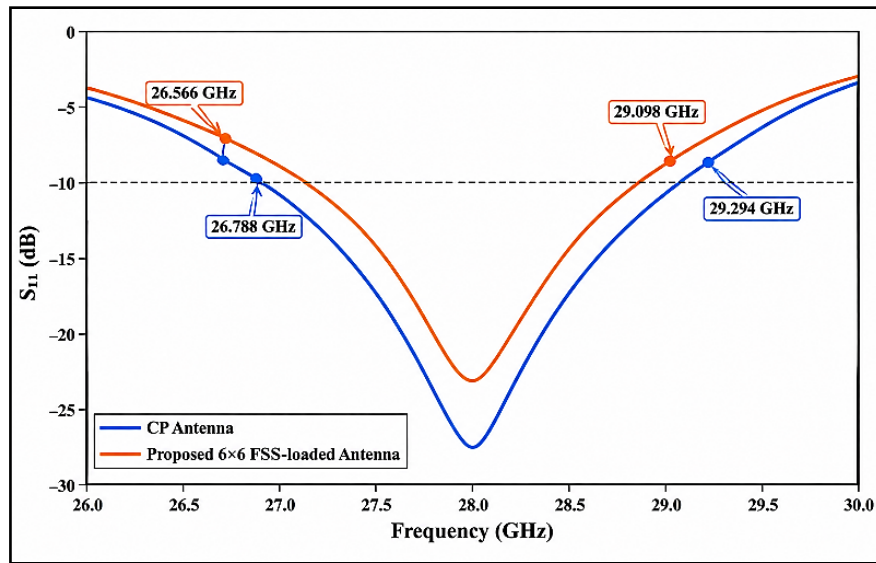


Figure 4: S₁₁ characteristics of the CP and proposed 6×6 FSS-loaded antennas

Note: S₁₁ = Reflection Coefficient, CP = Circular Polarization, FSS = Frequency Selective Surface, GHz = Gigahertz, dB = Decibel.

Table 3: Reflection Coefficient Impedance Bandwidth Comparison

Parameter	CP Antenna	6×6 FSS Antenna
Center frequency	28 GHz	28 GHz
Impedance Bandwidth	2.72 GHz	2.31 GHz
Fractional Impedance bandwidth	9.74%	8.26%
Reflection Coefficient	-27.12dB	-23.8dB

Note: FSS = Frequency Selective Surface, CP = Circular Polarization, GHz = Gigahertz, dB = Decibel.

Table 3 shows the comparison between the reflection coefficient and impedance bandwidth between the conventional CP antenna and the proposed 6x6 FSS-loaded antenna. It is clear from the table that the operating center frequency for both the antennas is equal, which is 28 GHz, while the impedance bandwidth and reflection coefficient for the FSS-loaded antenna are relatively smaller. However, the antenna still has good impedance matching and gain improvement through FSS structure. The FSS is primarily introduced for gain enhancement rather than for increasing impedance bandwidth. This behaviour agrees with previous FSS investigations, where considerable gain improvements were obtained with relatively small changes in impedance bandwidth [5, 13].

Axial-ratio Performance

The CP performance is evaluated using the axial ratio (AR). An AR value below 3 dB is generally used to identify the frequency region in which

circular polarization is maintained. The CP antenna provides an AR bandwidth of 1.97 GHz, corresponding to 7.12%. After integration of the 6×6 FSS, the AR bandwidth obtained from the current simulation is 1.74 GHz. The relatively small change indicates that the symmetric FSS configuration can be integrated with the CP patch while maintaining its circular-polarization response. Figure 5 shows the simulated axial ratio (AR) properties of the benchmark CP antenna and the newly designed 6×6 FSS embedded antenna. The reference antenna attains the 3-dB axial-ratio bandwidth ranging from 26.666 GHz to 28.558 GHz (1.892 GHz), whereas the bandwidth for the FSS loaded antenna ranges from 26.826 GHz to 28.649 GHz (1.823 GHz). For both designs, the minimum axial ratio is attained close to the operational frequency of 28 GHz. This demonstrates the preservation of the circular polarization property despite a small decrease in the axial-ratio bandwidth.

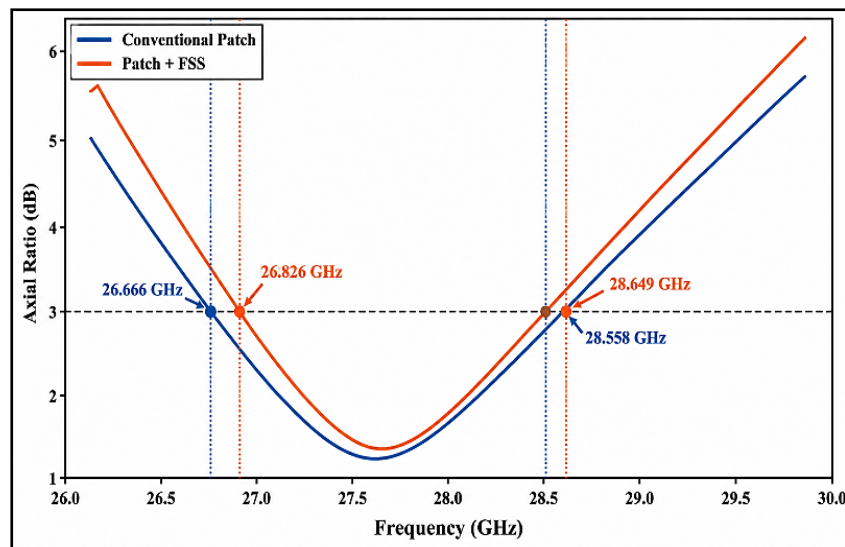


Figure 5: Simulated Axial Ratio Versus Frequency for the Reference and Proposed Antennas

Note: FSS = Frequency Selective Surface, AR = Axial-ratio, CP = Circular Polarization, GHz = Gigahertz, dB = Decibel.

Table 4: Axial-ratio Performance

Parameter	CP Antenna	6×6 FSS Antenna
AR bandwidth	1.97 GHz	1.74 GHz
AR bandwidth (%)	7.12%	6.26
AR (dB)	1.76	1.82

Note: AR = Axial-ratio, FSS = Frequency Selective Surface, CP = Circular Polarization, GHz = Gigahertz, dB = Decibel.

Table 4 indicates the comparison of the axial-ratio (AR) characteristics of the traditional CP antenna and the newly suggested 6×6 FSS loaded antenna has been presented. According to the table, the AR bandwidth for the CP antenna is found to be 1.97 GHz (7.12%) whereas the AR bandwidth for the FSS loaded antenna is measured as 1.74 GHz (6.26%). Despite a slight decrease in AR bandwidth due to FSS implementation, the antenna still manages to operate at axial ratio less than 3 dB. The preservation of the AR response is important because the FSS modifies the EM field surrounding the radiator. A polarization-symmetric enhancement surface is therefore advantageous for CP antennas. Similar considerations were reported for a polarization-independent Ka-band metasurface (10).

Gain Enhancement

The principal purpose of the proposed FSS is to increase the antenna gain. The CP patch provides a simulated gain of 7.28 dBi at 28 GHz. After incorporating the 6×6 FSS layer, the gain increases to 11.01 dBi. Therefore, the proposed FSS-loaded antenna provides a 3.73 dB gain enhancement compared with the CP antenna. Figure 6 shows the

simulation plots of realized gain of the reference CP antenna and the designed 6×6 FSS-based antenna at 28 GHz. It is observed that due to the use of FSS, there is a significant improvement in broadside radiation as the peak value of realized gain has increased from 7.28 dBi to 11.01 dBi, which represents gain enhancement of 3.73 dB.

The improvement is attributed to the reflecting behaviour of the FSS. With an appropriate antenna-to-FSS separation, the reflected field combines constructively with the direct field radiated by the patch, increasing the radiation intensity in the desired direction. This mechanism is consistent with the gain-enhancement behaviour reported for FSS-loaded antennas (5, 9, 11, 13). Table 5 describes the performance comparison between the traditional CP antenna and the newly proposed 6×6 FSS-loaded antenna is summarized. The gain improvement of the proposed antenna reaches from 7.28 dBi to 11.01 dBi, with a gain improvement of 3.73 dB, while it still operates at 28 GHz. Though some impairment in the impedance and axial-ratio bandwidth is noticed, the FSS-loaded antenna can provide good impedance matching and circular polarization performance.

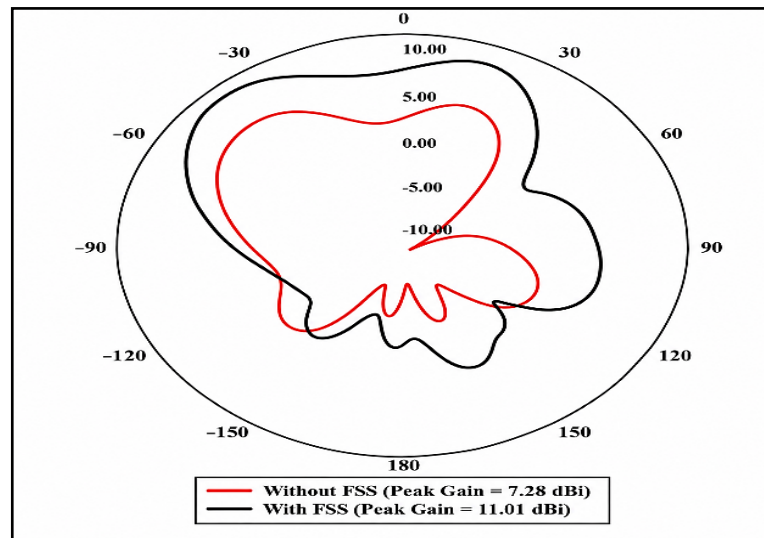


Figure 6: Simulated Realized Gain of the Proposed 6×6 FSS-loaded Antennas

Note: FSS = Frequency Selective Surface, PG =Peak Gain, dB = Decibel.

Table 5: Overall Performance Comparison

Parameter	CP	Proposed 6×6 FSS	Improvement
Operating frequency	28 GHz	28 GHz	-
Gain	7.28 dBi	11.01 dBi	+3.73 dB
Fractional Impedance bandwidth	9.74%	8.26%	-1.48%
AR bandwidth	7.12%	6.26%	-0.86%
Impedance BW	2.72 GHz	2.31 GHz	-0.41GHz
AR BW	1.97 GHz	1.74 GHz	-0.23GHz

Note: AR = Axial-ratio, BW = Bandwidth, FSS = Frequency Selective Surface, CP = Circular Polarization, GHz = Gigahertz, dB = Decibel.

Radiation Characteristics

The far-field radiation pattern is investigated at 28 GHz to determine the effect of the FSS on the directional characteristics of the antenna. The CP antenna radiates primarily through the circular patch, whereas the FSS-loaded configuration benefits from the additional reflected field. Figure 7 shows the comparison between the simulated E-plane and H-plane radiation patterns of the reference antenna and the proposed 6×6 FSS-loaded antenna at 28 GHz. The FSS-loaded design shows a more focused broadside radiation pattern,

implying higher directivity compared to the reference antenna. The observation is in agreement with the gain increase from 7.28 dBi to 11.01 dBi. Figure 8 shows the simulated 3D radiation pattern of the designed 6×6 FSS-loaded circularly polarized antenna at 28 GHz. In the simulated radiation pattern, it can be observed that a major broadside beam is generated along with high directivity, which indicates effective concentration of radiation power in a particular direction. Enhanced beam shape and radiation power illustrate the efficiency of the superstrate in terms of gain improvement.

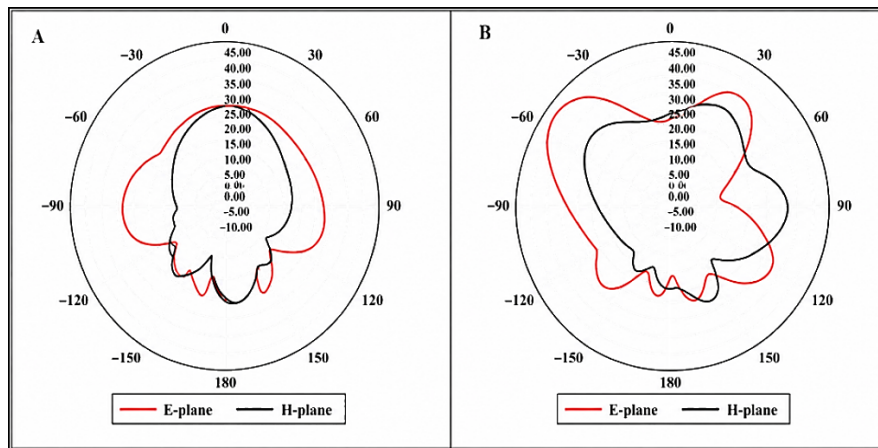


Figure 7: Simulated E-plane and H-plane Radiation Patterns at 28 GHz: (A) Reference Antenna, (B) Proposed 6×6 FSS-loaded Antenna

Note: FSS = Frequency Selective Surface.

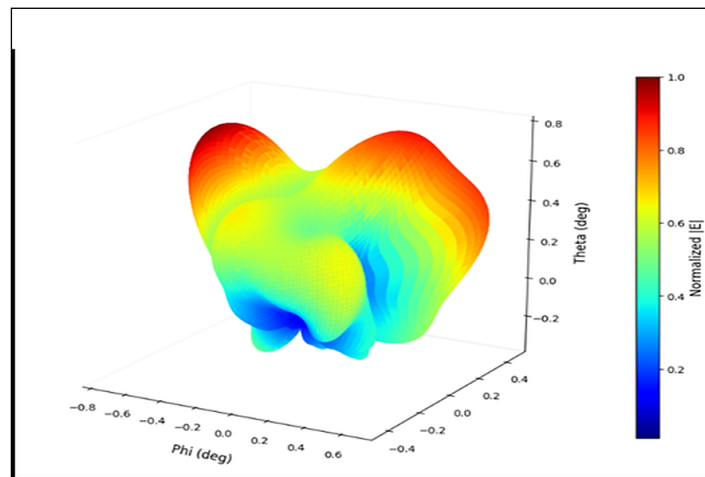


Figure 8: 3D Radiation Pattern of Proposed 6×6 FSS-loaded Antenna

Note: FSS = Frequency Selective Surface.

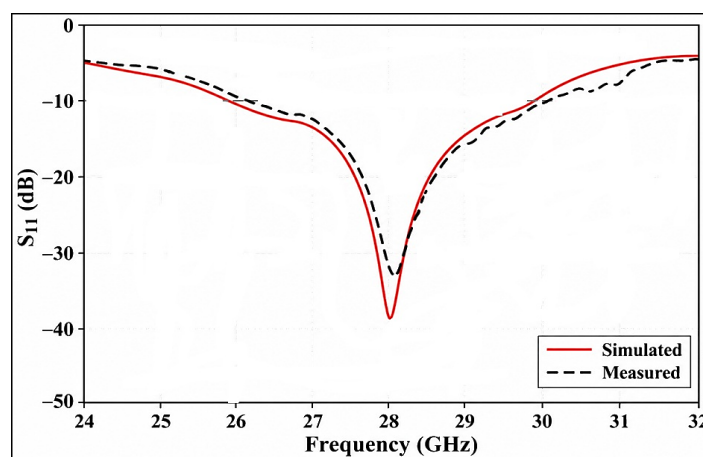


Figure 9: Simulated and Measured Input-impedance (S_{11}) of 6×6 FSS-loaded Antenna

Note: S_{11} = Reflection Coefficient, FSS = Frequency Selective Surface, GHz = Gigahertz, dB = Decibel.

Figure 9 represents the simulation and measurement results of the input reflection coefficient S_{11} for the proposed 6×6 FSS-loaded antenna

within its operational frequencies. From both the simulation and the measurement results, it is clear that they have a very good match and also share a

significant resonance point at around 28 GHz. The S11 plot gives positive feedback on the impedance matching of the proposed antenna. The FSS is expected to increase the broadside radiation intensity by redirecting part of the radiated energy toward the main beam. Consequently, the increase in realized gain is associated primarily with improved directivity rather than a fundamental

change in the radiating element. The suggested antenna radiates with right hand circular polarization (RHCP) in the broadside main radiation direction at 28 GHz. The polarity of the radiated wave has been identified from its far field polarized parameters, which indicate that the main radiated wave is RHCP.

Table 6: Comparison of Recent Gain-enhancement Techniques

Frequency	Enhancement Technique	Configuration	Gain Before (dBi)	Gain After (dBi)	Gain Improvement (dB)	References
2.9–9.3 GHz	U-slot FSS	5×6	3	8.12	+5.12	(11)
2.6–8.4 GHz	GA-optimized FSS	6×6	9	10.1	+7.8	(13)
28 GHz	Dielectric superstrate	0.5λspacing	6.04	8.31	+2.27	(2)
28–32 GHz	Phase-gradient metasurface	11×11, four-layer	8.12	≈10	≈+10	(10)
3.3–12 GHz	Complementary-loop FSS	6×6	3–5.3	8.1	+2.5–3	(5)
3–18 GHz	Ring/square FSS	5×5	6.5	10.5	+4–6	(9)
28 GHz	Inset feed with slit	-	-	>8	-	(8)
27.98 GHz	Inset feed with partial ground/DGS	-	-	-	-	(14)
28 GHz	Single-layer FSS	6×6	7.28	11.01	+3.73	Proposed

Note: GA = Genetic Algorithm, DGS = Defected Ground Structure, FSS = Frequency Selective Surface, GHz = Gigahertz, dB = Decibel.

Table 6 highlights the performance of the 6×6 FSS-loaded antenna compared to recent approaches for gain enhancement in different frequency ranges. From Table 6, it is clear that the gain enhancement is found to be 3.73 dB from 7.28 dBi to 11.01 dBi at 28 GHz. This gain enhancement is observed by using a single-layer FSS structure. As compared to other more complicated methods like multi-layered metasurface, dielectric superstrates and optimized FSS structure reported in the literature, the gain enhancement through the proposed FSS-loaded antenna has achieved an optimal balance among all.

Discussion

The above-mentioned results prove that implementation of the suggested 6 × 6 symmetric closed-ring FSS can significantly improve radiation properties of the circularly polarized patch antenna at the frequency of 28 GHz. In this case, the value of the realized gain changes from 7.28 dBi to 11.01 dBi with gain enhancement of 3.73 dB while maintaining adequate impedance matching and polarization performance. Such enhancement is provided mainly due to the constructive interaction of the direct radiation of the patch antenna and reflected waves generated by the FSS

superstrate. The FSS serves as the partially reflective surface that reflects the energy in the broadside direction and thus increases the directivity of the antenna.

The use of the FSS leads to the decrease in impedance bandwidth and axial-ratio bandwidth, but still the antenna provides the required performance for Ka-band applications. For example, the impedance bandwidth is reduced from 2.72 GHz (9.74%) to 2.31 GHz (8.26%) and the axial-ratio bandwidth is decreased from 1.97 GHz (7.12%) to 1.74 GHz (6.26%). It means that the influence of the FSS on the performance is mainly connected with radiation properties rather than the resonance phenomenon of the antenna (5, 11, 13).

A comparison with the gain enhancement methods described in the literature reveals even more the significance of the designed system. Although many researchers have obtained better gain enhancements by using multilayer metasurfaces, optimizing dielectric superstrates and FSS structures, these methods require complicated designs, bulky structures and tighter alignment. In this regard, the proposed antenna has an extremely simple design, as it uses only a single layer 6×6 FSS structure. Unlike the dielectric-

superstrate based antenna (2), where the authors obtained a gain enhancement of 2.27 dB at 28 GHz, the designed antenna demonstrates a better gain enhancement value of 3.73 dB. Moreover, as opposed to the multilayer phase gradient metasurface (10), our designed antenna is capable of significant gain enhancement with less complicated design.

Overall, the outcomes clearly indicate that the presented circularly polarized antenna, which employs the suggested FSS, is capable of providing a proper balance between improved gain, preserved bandwidth, low complexity of design and reasonable manufacturing cost. The antenna can be considered as a potential solution for 5G/6G communications, satellite communication, radars and other wireless applications operating at the Ka-band frequency range.

Conclusion

In this work, a miniaturized single-fed circularly polarized (CP) microstrip patch antenna with a 6×6 symmetric closed-ring frequency selective surface (FSS) for 28 GHz Ka-band applications has been suggested and studied. The FSS superstrate was used to improve the radiation performance of the antenna while keeping its small size and CP properties. According to simulation results, the proposed FSS-loaded antenna provides a realized gain of 11.01 dBi, which shows a 3.73 dB improvement as compared to the gain of 7.28 dBi of the reference CP antenna. The antenna exhibits satisfactory impedance matching and circular polarization properties with an impedance bandwidth of 2.31 GHz (8.26%) and an axial-ratio bandwidth of 1.74 GHz (6.26%). The gain improvement is mainly due to the constructive interference of the directly radiated electric field of the antenna and the reflected electromagnetic waves created by the FSS layer leading to the improved directivity in broadside direction. As opposed to previously presented multilayer metasurface and superstrate structures, the proposed structure provides an appropriate trade-off between gain improvement, complexity of the structure, low-profile design and manufacturing complexity.

Future work will revolve around the realization and experimentally testing of the new antenna design, as well as the optimization of FSS geometry for the improvement of both gain and bandwidth.

Also, exploring the possibility of designing the reconfigurable or tuneable FSS structure can be done. Moreover, application of the proposed idea to MIMO, beam-steering and 5G/6G millimeter wave antennas will increase its usability in next generation wireless communication platforms.

Although there is considerable improvement in the gain of the suggested antenna via the use of the 6×6 FSS superstrate, the current work is purely theoretical and requires further experimental verification. The fabrication and testing of the suggested antenna will be conducted in order to prove its performance parameters including impedance matching, axial ratio, radiation pattern and gain characteristics. For future research, efforts will be made to optimize the geometry of FSS unit cell as well as the antenna-FSS distance in order to increase gain and bandwidth. Additionally, the study will be extended for the development of reconfigurable FSS elements.

Abbreviations

AR: Axial Ratio, BW: Bandwidth, CP: Circular Polarization, dB: Decibel, FSS: Frequency Selective Surface, Ka-Band: Kurtz-above Band, mmWave: Millimeter Wave, RF: Radio Frequency.

Acknowledgement

The authors express their sincere gratitude to the Department of Electronics and Communication Engineering, Bharatiya Engineering Science and Technology Innovation University, for providing the necessary research facilities, technical support and academic guidance to carry out this research work successfully. The authors also thank the faculty members and laboratory staff for their valuable assistance and continuous encouragement during the research and manuscript preparation process.

Author Contributions

All authors contribute equally to the research, design the study, analyzed data and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Artificial Intelligence

(AI) Assistance

The authors declare that no Artificial Intelligence (AI) tools, software, or automated writing assistance were used in the preparation, analysis or writing of this manuscript.

Ethics Approval

This study does not involve human participants, animals, or any biological materials. Therefore, ethical approval was not required for conducting this research work.

Funding

The authors declare that no specific funding, grant, or financial support was received from any funding agency, commercial organization, or not-for-profit sector for the conduct of this research work.

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How to Cite: Kumar KP, Basha SM, Kumar MA. High-gain 28-GHz CP Patch Antenna with 6×6 FSS. Int Res J Multidiscip Scope. 2026;7(4):1722-1734. DOI: 10.47857/irjms.2026.v07i04.014520