



Metasurface-Integrated Compact Circular Patch Antenna for 33 GHz Flexible 5G Applications

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Abstract

In this paper, a compact circular microstrip patch antenna integrated with a metasurface superstrate is designed and analyzed for flexible 5G applications at 33 GHz. The proposed antenna is implemented on a thin FR-4 board with overall dimensions of $9 \times 9 \times 1.7 \text{ mm}^3$. The antenna is excited by an inset-fed microstrip line, and a metasurface superstrate composed of 49 circular-ring elements arranged in a 7×7 array is employed to enhance the electromagnetic performance. The antenna was designed and simulated using CST Studio Suite, and its performance was evaluated in terms of reflection coefficient, -10 dB impedance bandwidth, directivity, realized gain, radiation pattern, and surface current distribution. The results show that the metasurface superstrate improves impedance matching, bandwidth, radiation characteristics, and gain compared with the conventional circular patch antenna. The conventional antenna achieves a -10 dB impedance bandwidth of 1.5 GHz , whereas the metasurface-integrated antenna achieves 3.7 GHz . The simulated metasurface-integrated antenna exhibits an S_{11} of -47 dB , directivity of 8.7 dBi , and realized gain of 8.2 dBi . The fabricated prototype achieves a measured -10 dB impedance bandwidth of 2.9 GHz , S_{11} of -40 dB , directivity of 8.1 dBi , and realized gain of 7.3 dBi . These results confirm the suitability of the proposed antenna for compact Ka-band 5G and IoT wireless communication applications.

Keywords: circular patch antenna; circular-ring metasurface; FR-4 substrate; 33 GHz; Ka-band; flexible 5G; realized gain.

1. Introduction

The rapid development of fifth-generation (5G), beyond-5G, and emerging IoT systems has spurred the demand for small antennas that can support high-data rates, low-latency, wide bandwidth, and reliable wireless connectivity [1], [2]. In order to fulfill these requirements, modern wireless systems are increasingly moving to the millimeter-wave spectrum where wide spectral resources are available for high-capacity communication links [1], [2]. More specifically, the Ka-band region around 33 GHz is attractive for short-range and high-speed wireless communication because it allows for miniaturization of antennas while providing enough bandwidth for compact 5G and IoT systems [1], [2]. Microstrip patch antennas find wide applications in millimeter-wave systems due to their low-profile planar structure, low-cost fabrication, and compatibility with integrated RF circuits. However, conventional microstrip antennas suffer from limited gain and narrow bandwidth at millimeter-wave frequencies. FR-4 has a higher dielectric loss at high frequencies compared to low-loss microwave substrates. However, it is attractive for compact and flexible antenna design because it is cheap, easily available, mechanically flexible in thin layers, and compatible with standard printed circuit board fabrication. Flexible, wearable, and conformal communication systems impose stringent requirements on antennas to maintain stable electromagnetic performance under mechanical confinement while being compact and small [3]. This paper presents a metasurface-inspired ultra-thin conformal antenna for flexible 5G applications. The conformal nature of the antenna makes it suitable for a variety of wearable and flexible communication



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systems. The proposed antenna is designed to resonate at the same frequency in both on-plan and off-plan bending conditions, thus ensuring robust radiation performance in practical deployment scenarios. Many microstrip, metasurface, and metamaterial-based antennas have been proposed for millimeter-wave and Ka-band applications at around 33 GHz [10]–[16]. These structures were able to improve the impedance bandwidth, gain, compactness, and radiation performance. More recent studies have highlighted the implementation of advanced optimization techniques and miniaturization approaches in future wireless systems [17], [18]. However, most of the existing designs suffer from one or more drawbacks, such as moderate gain, large size, complex feeding structures, fabrication sensitivity, limited or no experimental validation, and poor impedance matching performance [10]–[16]. Therefore, a light, low-cost, easy to implement, and efficient antenna structure with improved gain, bandwidth, and matching performance for 33 GHz applications is highly solicited. Meeting these requirements, this paper presents a compact circular microstrip patch antenna with an integrated 7×7 circular-ring metasurface superstrate for 5G applications at 33 GHz. The design is proposed to be implemented on thin FR-4 substrate and simulated using CST Studio Suite. The main objective is to improve impedance matching, -10 dB bandwidth, directivity, realized gain, and radiation characteristics with the proposed compact low-cost flexible configuration for Ka-band 5G and IoT wireless communication systems. The practical advantage of the proposed structure is its compact profile, simple feeding mechanism, low fabrication cost, and better electromagnetic performance, making it applicable for integration into space-limited and flexible wireless platforms.

1.1 Literature review

Recent research works include microstrip patch, metasurface, metamaterial, and defected ground plane antennas for 5G millimeter-wave applications near the 33 GHz frequency band. In [10], the feasibility of compact patch structures at millimeter-wave frequencies was presented where a 33 GHz microstrip patch antenna for 5G wireless communication was designed. However, the gain and bandwidth performances of this antenna remain limited, and further improvement is necessary. The antenna reported in [11] worked at around 33 GHz and showed reasonable impedance performance. While the work was mostly focused on sensing applications, its operating frequency and gain level qualify it for comparison with compact millimeter-wave antenna designs. However, the gain was still below 8 dB, indicating that more enhancement in radiation performance is needed. A Ka-band patch antenna with DGS slots and truncated corners was proposed in [12] to enhance impedance matching and bandwidth. Since this design is mainly intended for operation around 30 GHz, a comparison with 33 GHz antennas should be taken as frequency-dependent rather than a direct limitation on performance. The wideband bow-tie microstrip antenna in [13] showed good radiation properties for 5G applications but its operating band was below the frequency band aimed for in the present work and careful slot optimization was needed. A dual-band patch antenna was designed for 5G applications in [16], but its gain and impedance matching were not satisfactory. The gain and impedance matching of a dual-band Ka/V-band antenna designed for 5G body-centric network applications in [15] was also not very good. It achieved good impedance performance but at the cost of increased structural complexity. In [14], a compact parasitic mushroom patch antenna using DGS was presented for wideband 5G millimeter-wave operation. In this study, the gain of a miniaturized dual-band Ka/V-band antenna for 5G body-centric network applications was reported to be moderate., the paper presents the design of a compact circular microstrip patch antenna with an integrated 7×7 circular-ring metasurface superstrate for flexible 5G applications at 33 GHz. The proposed design targets improved S11, wider -10 dB impedance bandwidth, higher gain, and compact structure — all while holding suitability for low-cost flexible Ka-band wireless communication systems.

Table 1: Summary of Metasurface / Metamaterial Antenna Papers.

Ref	Frequency (GHz)	Bandwidth (GHz)	Gain (dBi)	Features	Limitation
[10]	33	1.132	7.128	Compact 33 GHz microstrip patch antenna for 5G communication with optimized matching and gain.	Mainly simulation-based; performance depends on defect/slot optimization.
[11]	33	2.10	7.07	Compact rectangular mm Wave antenna using RT/duroid 5880LZ; suitable for 5G and sensing	Application focus is medical sensing; experimental validation is limited.
[12]	30	29-34	7.0	Compact Ka-band patch antenna with CPW feed, DGS slots, and truncated corners for 5G applications.	Designed mainly around 30 GHz; comparison with 33 GHz designs should be considered frequency-dependent.
[13]	27.77	26.89 – 28.64	7.0	Compact bow-tie wideband microstrip patch antenna with measured validation for 5G	Operating band is below 33 GHz and requires careful slot optimization.
[14]	25.98 – 40.18	14.2	7.20	Compact parasitic mushroom patch antenna using DGS for wideband 5G mm Wave operation.	FR-4 substrate may increase losses at mm Wave frequencies.
[15]	33.5 / 60.8	1.20 / 1.16	6.02 / 7.08	Miniaturized dual-band Ka/V microstrip antenna for 5G body-centric network applications.	Designed mainly for body-centric networks; gain changes under on-body
[16]	33 / 46	1.0	7.83	Dual-band rectangular patch antenna with air-cavity technique for high-gain 5G/mm Wave operation.	Return-loss level is acceptable but not very deep compared with optimized

1.2 Manuscript focus, novelty, and limitations

This paper presents a design of a compact circular microstrip patch antenna with an integrated 7×7 circular-ring metasurface superstrate for flexible 5G applications at 33 GHz. The antenna is fabricated on a thin FR-4 substrate and its performance is simulated using CST Studio Suite. The major performance parameters under consideration in the present work are reflection coefficient, -10 dB impedance bandwidth, directivity, realized gain, radiation pattern, and surface current distribution. The work proposed here is unique by bringing together the compact circular patch with the circular-ring metasurface superstrate to enhance impedance matching, bandwidth, gain, and radiation properties while keeping the structure low-cost and compact for Ka-band 5G and IoT applications. Dielectric losses may be introduced at the millimeter-wave frequencies due to FR-4, and practical performance can be affected by fabrication tolerances, connector losses, and metasurface alignment. Future work includes bending and conformal measurements for further validation.

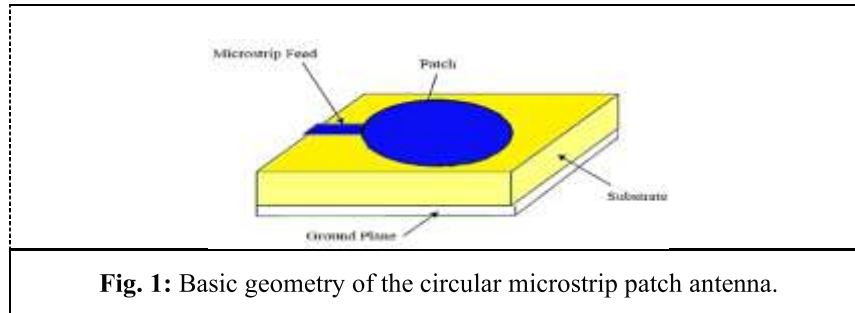
1.3 Paper organization

The remainder of this paper is organized as follows. Section 2 presents the theoretical formulation and design methodology of the circular microstrip patch antenna. Section 3 describes the proposed metasurface-integrated antenna structure, including the circular-ring metasurface superstrate, geometrical parameters, and fabrication setup. Section 4 discusses the simulated and measured results in terms of reflection coefficient, -10 dB impedance bandwidth, directivity, realized gain, radiation pattern, and surface current distribution. Finally, Section 5 concludes the paper and presents future research directions.

2. Methodology

2.1 Circular Patch Microstrip Antenna

A circular microstrip patch antenna, as shown in Fig. 1, consists of a metallic circular radiating patch printed on a dielectric substrate and backed by a continuous ground plane. Its main geometrical parameters are the patch radius (a), substrate thickness (h), and substrate relative dielectric constant (ϵ_r). Owing to its circular symmetry, the antenna's resonant behavior can be described using cylindrical coordinates. In this work, the circular patch is used as the main radiating element, while the metasurface superstrate is introduced later to improve impedance matching, bandwidth, gain, and radiation characteristics.

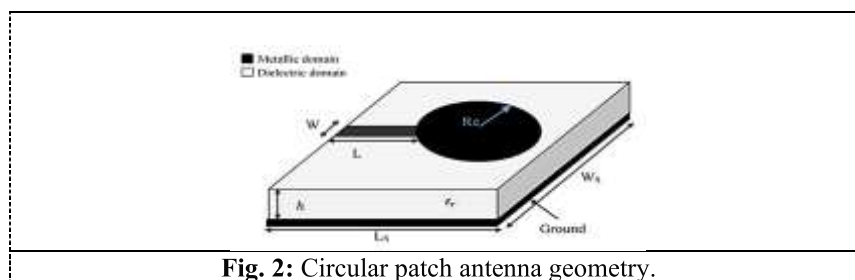


2.2 Resonant Frequency

Unlike rectangular microstrip patch antennas, the resonant frequency of a circular patch antenna, as shown in Fig. 2, is mainly determined by the effective patch radius and the dielectric properties of the substrate. Owing to the circular symmetry of the radiating patch, its resonant behavior is described using cylindrical coordinates. For the dominant TM_{11} mode, the resonant frequency is expressed as:

$$(f_r)_{11} = \frac{1.8412c}{2\pi a_e \sqrt{\epsilon_r}} \quad (1)$$

Where c is the speed of light in free space and a_e is the effective radius of the circular patch. The constant 1.8412 represents the first root of the derivative of the Bessel function associated with the dominant TM_{11} mode.



Due to fringing fields at the patch edges, the circular patch appears electrically larger than its physical radius. Therefore, the effective radius a_e is used to provide a more accurate estimation of the resonant frequency [8]. The intermediate design parameter F , which is related to the required resonant frequency and substrate permittivity, is defined as:

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\epsilon_r}} \quad (2)$$

The physical radius of the circular patch is then calculated as:

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi \epsilon_r F} \left[\ln \left(\frac{\pi F}{2h} \right) + 1.7726 \right] \right\}^{1/2}} \quad (3)$$

The effective radius is expressed as:

$$a_e = a \left\{ 1 + \frac{2h}{\pi a \epsilon_r} \left[\ln \left(\frac{\pi a}{2h} \right) + 1.7726 \right] \right\}^{1/2} \quad (4)$$

The input resistance of a circular microstrip patch antenna varies with the radial feed position and can be described using a Bessel-function-based expression. In this work, the feed position, as shown in Fig. 3, is optimized numerically using full-wave simulation to achieve proper impedance matching [8], [9]. The input resistance is given by:

$$R_{in}(\rho_0) = R_{in}(a_e) \frac{J_1^2(k\rho_0)}{J_1^2(ka_e)} \quad (5)$$

where $R_{in}(\rho_0)$ is the input resistance at the feed position, ρ_0 is the radial distance of the feed point from the patch center, $k = 2\pi/\lambda$ is the wave number, and J_1 is the first-order Bessel function of the first kind.

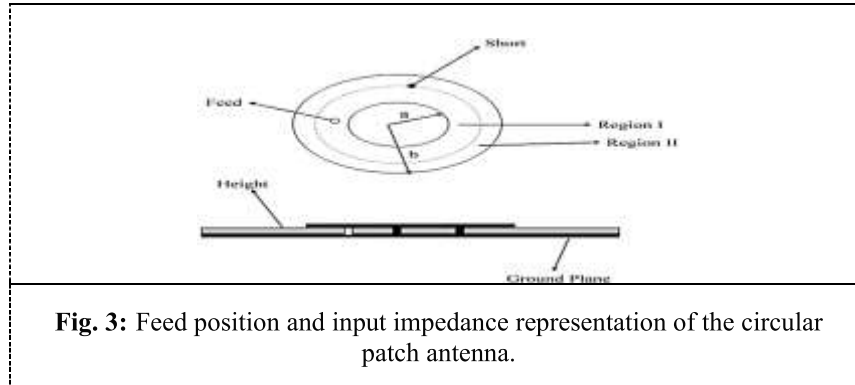
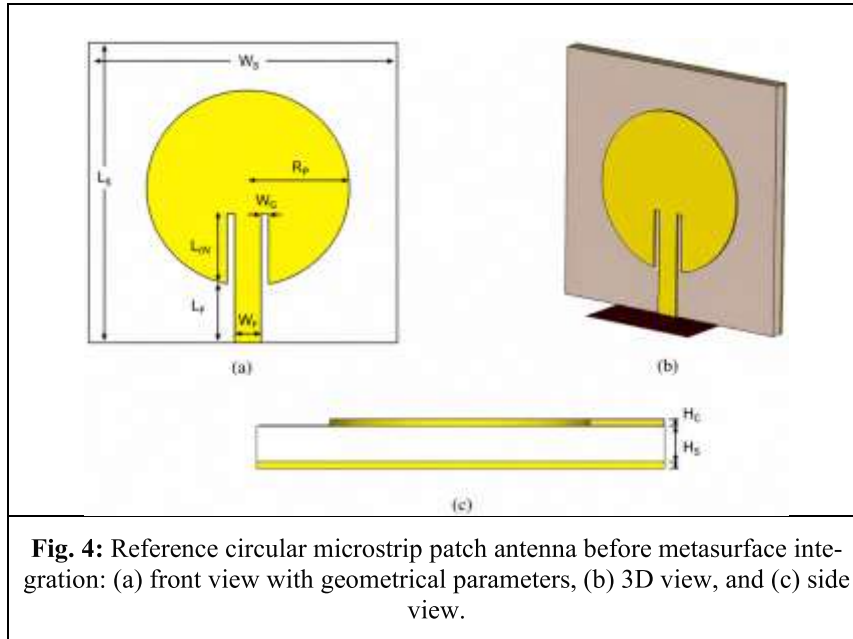


Fig. 3: Feed position and input impedance representation of the circular patch antenna.

3. Circular Microstrip Patch Design

The circular microstrip patch antenna used in this work is shown in Fig. 4. It was designed for a compact millimeter-wave operation at a frequency of 33 GHz and modeled using CST Studio Suite. This configuration is used as the basic radiating antenna before the metasurface superstrate is added. It is built on a thin FR-4 substrate of size 9 mm × 9 mm with a thickness of 0.2 mm. A continuous ground plane is placed on the underside of the substrate. The circular radiating patch and the inset-fed microstrip line are both printed on the upper side.

The radius of the circular patch is 1.306 mm; this value was chosen to enable resonance at Ka-band. To ensure proper impedance matching, a microstrip line of the inset-fed type is used; it has dimensions of 1.69 mm in length and 0.34 mm in width. The optimized dimensions for the inset length and gap width are 0.34 mm and 0.1 mm, respectively, to improve coupling between the radiating patch and the feedline. Copper has a thickness of 0.035 mm for the conducting layer. The complete set of parameters for the proposed metasurface-integrated antenna, including the 7 × 7 circular-ring metasurface superstrate, air-gap spacing, and overall assembly height, is tabulated in Section 3.1.

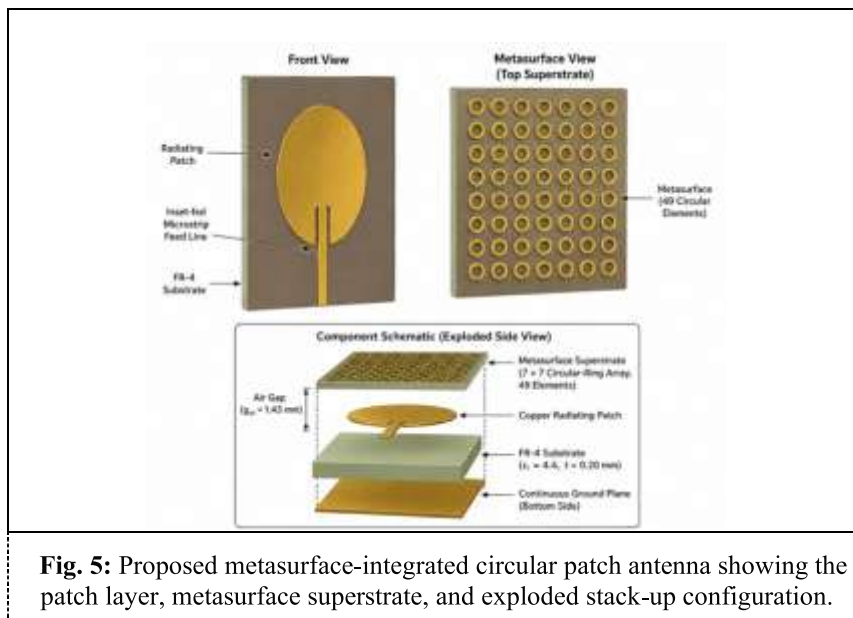


3.1 Circular Patch Metasurface Integration

The metasurface-integrated circular patch antenna, shown in Fig. 5, was designed for flexible 33 GHz 5G applications and modeled using CST Studio Suite. In this configuration, the reference circular patch antenna described in Section 3 is integrated with a 7×7 circular-ring metasurface superstrate consisting of 49 periodic elements. The metasurface is positioned above the radiating patch rather than on the back side of the substrate. The circular patch and inset-fed microstrip line are printed on the top side of the FR-4 substrate, while a continuous ground plane is maintained on the bottom side. Therefore, the proposed structure is not a defected ground structure; instead, it is a metasurface-superstrate-loaded circular patch antenna.

The metasurface superstrate is separated from the circular patch by an optimized air gap of 1.43 mm. This spacing is an important geometrical parameter because it controls the electromagnetic coupling between the radiating patch and the circular-ring metasurface elements. The total antenna height of 1.7 mm includes the optimized air gap of 1.43 mm, the FR-4 substrate thickness of 0.20 mm, and the copper layers. The overall metasurface-integrated antenna assembly has dimensions of $9 \text{ mm} \times 9 \text{ mm} \times 1.7 \text{ mm}^3$.

Based on the theoretical formulation presented in Section 2, the geometrical parameters were optimized using full-wave simulation. The circular-ring metasurface enhances the electromagnetic response by improving field coupling, impedance matching, -10 dB impedance bandwidth, directivity, and realized gain. The periodic arrangement of the 49 circular-ring elements helps control the surface field distribution and supports constructive interaction between the radiated field and the metasurface superstrate. The optimized geometrical parameters of the proposed metasurface-integrated antenna are summarized in Table 2.



The geometrical configuration of the proposed metasurface-integrated circular patch antenna is shown in Fig. 6. The figure illustrates the reference circular patch antenna, the circular-ring metasurface superstrate, and the enlarged metasurface unit-cell parameters. The 7×7 metasurface array is positioned above the radiating patch and separated by the optimized air gap, while the continuous ground plane remains on the bottom side of the FR-4 substrate. Therefore, the proposed configuration preserves the conventional microstrip patch structure and uses the metasurface as a superstrate layer for electromagnetic performance enhancement.

The circular-ring unit cells are uniformly arranged to improve field coupling, impedance matching, bandwidth, and radiation characteristics. The main unit-cell parameters include the metasurface period (P_m), ring gap (G_m), and outer ring diameter (D_m), as indicated in Fig. 6. The optimized geometrical parameters of the reference patch, metasurface superstrate, air-gap spacing, and overall antenna assembly are summarized in Table 2.

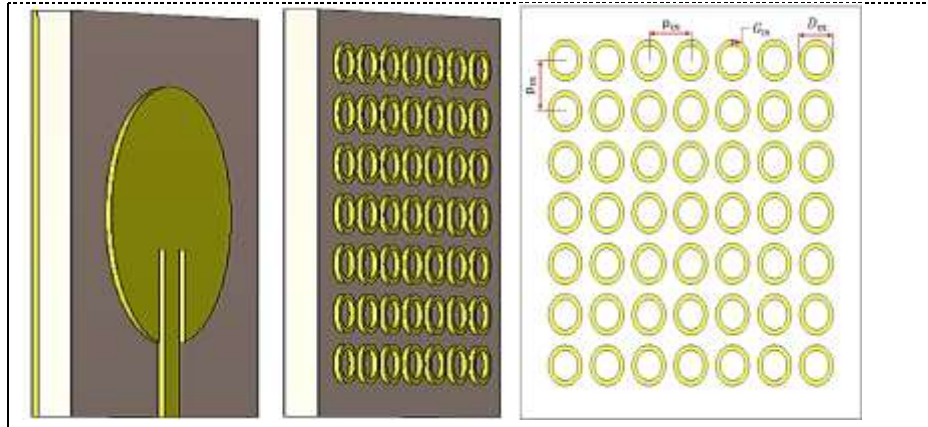


Fig. 6: Geometrical configuration of the proposed metasurface-integrated circular patch antenna and enlarged circular-ring unit-cell parameters.

Table 2: Optimized geometrical parameters of the proposed metasurface-integrated circular patch antenna.

Parameter	Symbol	Value
Substrate / antenna assembly length	L_s	9 mm
Substrate / antenna assembly width	W_s	9 mm
Overall antenna height	H_{tot}	1.7 mm
Circular patch radius	R_p	1.306 mm
Feedline length	L_F	1.69 mm
Feedline width	W_F	0.34 mm
Inset-feed length	L_{IN}	0.34 mm
Inset-feed gap width	W_G	0.10 mm
FR-4 substrate thickness	H_s	0.20 mm
Copper layer thickness	H_c	0.035 mm
Air gap between patch and metasurface superstrate	g_{air}	1.43 mm
Metasurface array configuration	$N_x \times N_y$	7×7 elements
Metasurface unit-cell period	P_m	0.50 mm
Circular-ring gap	G_m	0.05 mm
Outer diameter of circular-ring element	D_m	0.40 mm

The parameters (L_s) and (W_s) represent the overall substrate/antenna assembly dimensions. The total height (H_{tot}) includes the FR-4 substrate, copper layers, and the optimized air gap (g_{air}) between the circular patch and the metasurface superstrate.

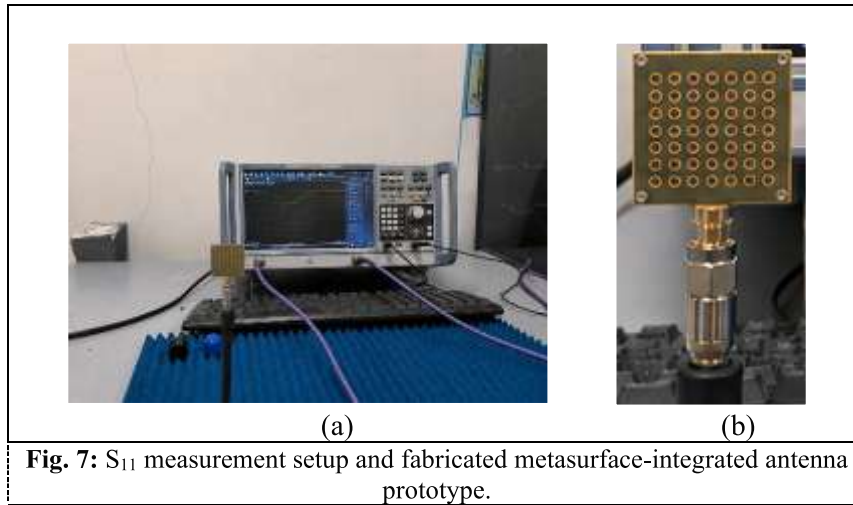
3.2 Fabricated Metasurface Integrated Antenna

The fabricated metasurface-integrated antenna was experimentally characterized by measuring the reflection coefficient (S_{11}) using a Vector Network Analyzer (VNA) over the millimeter-wave frequency range around 33 GHz, as shown in Fig. 7. The measurement setup consists of the VNA, coaxial measurement cable, millimeter-wave RF transition connector, and a stable test fixture used to hold the fabricated prototype during measurement. The RF transition was selected to be suitable for operation around 33 GHz in order to provide proper excitation and reduce mismatch effects at the feeding interface.

Figure 7(a) shows the complete (S_{11}) measurement setup, while Fig. 7(b) presents a close-up view of the fabricated metasurface-integrated antenna assembly. The photographed prototype includes the 7×7 circular-ring metasurface superstrate, the RF connector, and the mechanical supporting structure used to maintain the optimized air gap between the circular patch and the metasurface layer. Therefore, the physical appearance in the photograph represents the complete measurement assembly, including the connector and fixture, rather than only the electrically active antenna region.

The geometrical dimensions of the proposed antenna assembly are those reported in Table 2, where the overall antenna size is $9 \text{ mm} \times 9 \text{ mm} \times 1.7 \text{ mm}^3$. The connector and external supporting parts are used only for experimental excitation and

mechanical alignment during measurement and are not included in the reported antenna dimensions. This setup was employed to validate the simulated reflection-coefficient response and confirm the practical operation of the proposed antenna in the intended 33 GHz millimeter-wave band.



4. Results and Discussion

The performance of the proposed antenna was evaluated through full-wave simulation and experimental measurement over the frequency range of 30–35 GHz, as shown in Fig. 8. Three configurations were considered: the conventional circular patch antenna, the metasurface-integrated antenna, and the fabricated prototype. The comparison was conducted in terms of reflection coefficient, -10 dB impedance bandwidth, directivity, and realized gain. Figure 8(a) shows the reflection coefficient response. The conventional circular patch antenna resonates at 33.10 GHz with an S_{11} of -36 dB and a -10 dB impedance bandwidth of 1.5 GHz. After integrating the circular-ring metasurface superstrate, the resonance shifts to 32.45 GHz, while the impedance matching is significantly improved, achieving an S_{11} of -47 dB and a bandwidth of 3.7 GHz. The fabricated prototype resonates at 32.20 GHz with a measured S_{11} of -40 dB and a -10 dB impedance bandwidth of 2.9 GHz. These results confirm that the metasurface superstrate improves impedance matching and broadens the operating bandwidth compared with the conventional circular patch antenna. Figure 8(b) presents the directivity response. The conventional circular patch antenna achieves a directivity of 5.4 dBi, whereas the metasurface-integrated antenna achieves 8.7 dBi. The fabricated prototype shows a directivity of 8.1 dBi, indicating good agreement with the simulated metasurface-based antenna. Figure 8(c) shows the realized gain response. The conventional circular patch antenna provides a realized gain of 3.3 dBi, while the metasurface-integrated antenna achieves 8.2 dBi. The fabricated prototype achieves a realized gain of 7.3 dBi. The difference between the simulated and fabricated results, including the 0.25 GHz resonance shift, the 7 dB difference in S_{11} , and the 0.9 dB gain reduction, can be attributed to fabrication tolerances, FR-4 dielectric-loss uncertainty at millimeter-wave frequencies, conductor surface roughness, RF transition mismatch, connector losses, and slight variations in the air-gap spacing and metasurface alignment during measurement. Overall, the results demonstrate that the integration of the circular-ring metasurface superstrate enhances the impedance matching, -10 dB bandwidth, directivity, and realized gain of the proposed antenna. The fabricated prototype maintains good agreement with the simulated design, confirming the practical feasibility of the proposed metasurface-integrated circular patch antenna for compact 33 GHz Ka-band 5G applications.

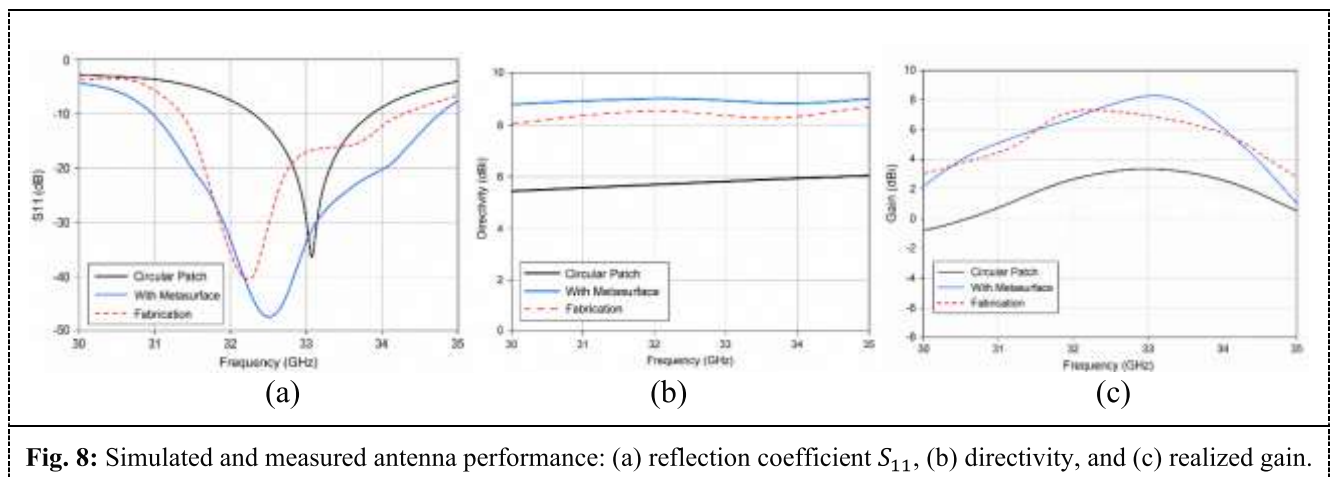


Table 3 summarizes the simulated and measured performance of the proposed antenna configurations in terms of resonant frequency, S_{11} , -10 dB impedance bandwidth, directivity, and realized gain. The results show that the circular-ring metasurface superstrate improves the impedance bandwidth from 1.5 GHz to 3.7 GHz, while increasing the directivity from 5.4 dBi to 8.7 dBi and the realized gain from 3.3 dBi to 8.2 dBi. The fabricated prototype achieves a measured bandwidth of 2.9 GHz, S_{11} of -40 dB, directivity of 8.1 dBi, and realized gain of 7.3 dBi, confirming good agreement with the simulated metasurface-integrated antenna.

Table 3: Summary of the simulated and measured performance results of the proposed antenna.

Antenna Configuration	Resonant Frequency (GHz)	S_{11} (dB)	Bandwidth (GHz)	Directivity (dBi)	Realized Gain (dBi)
Circular Patch	33.10	-36	1.5	5.4	3.3
With Metasurface	32.45	-47	3.7	8.7	8.2
Fabricated Prototype	32.20	-40	2.9	8.1	7.3

The simulated and measured radiation patterns of the proposed antenna in the E-plane and H-plane are shown in Fig. 9 for three configurations: the conventional circular patch antenna, the metasurface-integrated antenna, and the fabricated prototype. The metasurface-integrated antenna exhibits higher radiation intensity in both planes compared with the conventional circular patch, indicating the effectiveness of the circular-ring metasurface superstrate in improving the radiation performance.

In the E-plane, the metasurface-integrated antenna shows a stronger main lobe around 330° , while the fabricated prototype follows a similar radiation trend with slight variations. These differences can be attributed to fabrication tolerances, connector effects, measurement uncertainty, and possible air-gap or metasurface alignment variations. In the H-plane, the proposed antenna maintains a broader and more stable radiation response than the conventional patch. Overall, the measured and simulated patterns show acceptable agreement, confirming the improved radiation characteristics of the proposed metasurface-integrated antenna.

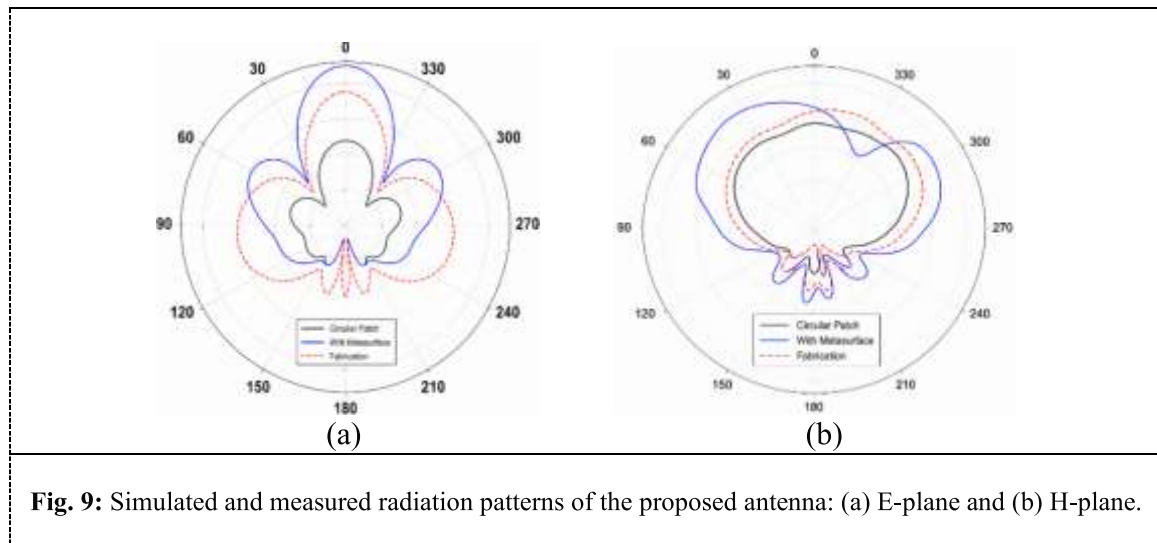
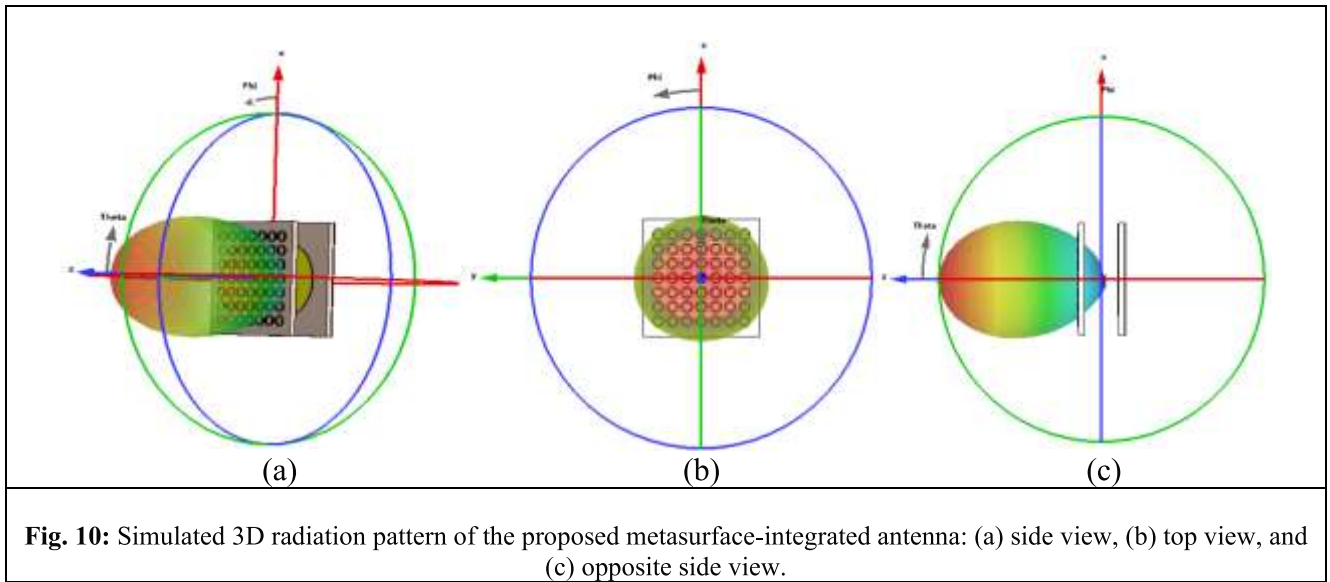


Fig. 9: Simulated and measured radiation patterns of the proposed antenna: (a) E-plane and (b) H-plane.

The simulated 3D radiation pattern of the proposed metasurface-integrated antenna, obtained using CST Studio Suite, is shown in Fig. 10. The radiation characteristics are presented from three different views to provide a clearer visualization of the far-field radiation behavior. Figure 10(a) shows the side view of the antenna radiation pattern, illustrating the main radiating direction with respect to the antenna structure. Figure 10(b) presents the top view, where the metasurface superstrate is visible above the radiating patch. Figure 10(c) shows the opposite side view, confirming the directional radiation behavior of the proposed antenna.

The 3D radiation pattern demonstrates that the radiated field is mainly concentrated in the desired direction, indicating improved directivity due to the integration of the circular-ring metasurface superstrate. Overall, the results confirm that the proposed metasurface-integrated antenna provides directional radiation performance suitable for compact 33 GHz Ka-band 5G applications.



The simulated surface current distributions of the proposed antenna are shown in Fig. 11. Figure 11(a) presents the current distribution of the reference circular patch antenna, where the current is mainly concentrated along the inset-fed microstrip line and the lower region of the circular radiating patch. This indicates effective excitation of the patch and proper coupling from the feedline to the radiating element.

Figure 11(b) shows the surface current distribution of the metasurface-integrated antenna. Strong induced currents are observed around the circular-ring metasurface elements, confirming the electromagnetic coupling between the radiating patch and the metasurface superstrate. This coupling contributes to improving impedance matching, enhancing field interaction, and increasing the radiation performance of the proposed antenna.

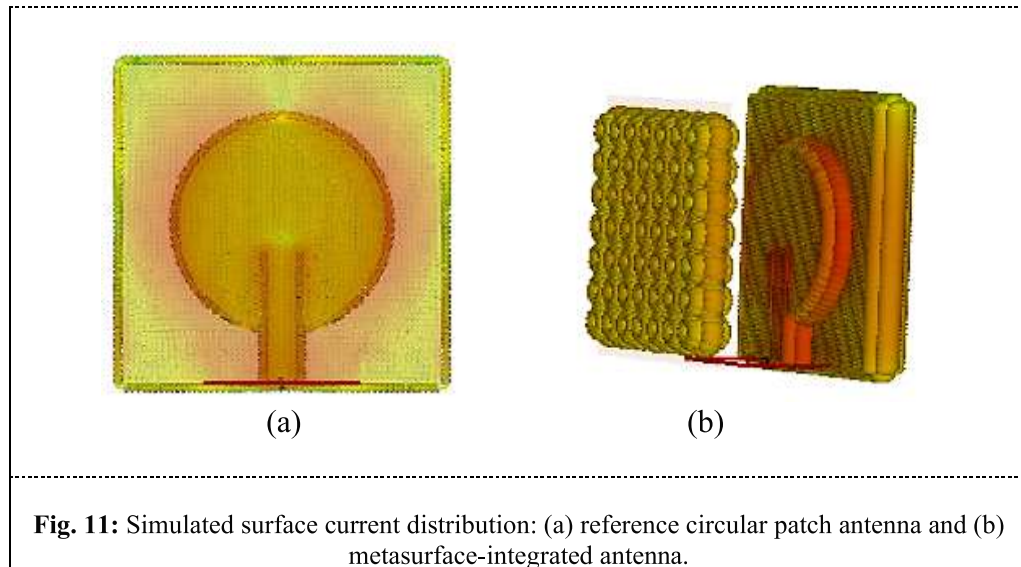


Table 4 presents a comparative analysis between the proposed antenna and previously reported millimeter-wave antenna designs in references [10]–[16]. The comparison is conducted in terms of operating frequency, antenna size, reflection coefficient (S_{11}), and gain, which are important indicators for evaluating compactness, impedance matching, and radiation performance.

As shown in the table, the proposed metasurface-integrated antenna achieves a compact overall size of $9 \times 9 \times 1.7 \text{ mm}^3$ with a measured S_{11} of -40 dB and a realized gain of 7.3 dBi . Although some reported designs provide higher gain, the proposed antenna offers a strong balance between compact size, excellent impedance matching, simple structure, and measured gain performance. These results confirm that the proposed circular-ring metasurface superstrate effectively enhances the antenna performance and makes the design suitable for compact 33 GHz Ka-band 5G applications.

Table 4: Performance comparison of the proposed antenna with related millimeter-wave antenna designs.

Ref	Frequency (GHz)	Antenna Size (mm ³)	S ₁₁ (dB)	Gain (dBi)
[10]	33	5.8 × 6.4 × 0.3449	−37.784	7.128
[11]	33	2.45 × 2.5 × 0.5	−19.33	7.07
[12]	30	10 × 11 × 0.502	−10	7.00
[13]	27.77	8 × 8 × 0.821	−25.45	7.00
[14]	25.98–40.18	12 × 13 × 0.8	−41.41	7.20
[15]	33.5 / 60.8	2.28 × 3.06 × 0.14	−14.85	6.02
[16]	33 / 46	18.4 × 12.4 × 0.1015	−20	7.83
[Proposed Work]	32.20	4 × 4 × 1.7	−40	7.3

5. Conclusion

This paper presented the design, simulation, fabrication, and experimental validation of a compact circular microstrip patch antenna integrated with a circular-ring metasurface superstrate for flexible 33 GHz Ka-band 5G applications. The proposed antenna was implemented on a thin FR-4 substrate with an overall assembly size of $9 \times 9 \times 1.7$ mm³. The metasurface superstrate consists of 49 circular-ring elements arranged in a 7×7 array and is separated from the radiating patch by an optimized air gap to enhance electromagnetic coupling, impedance matching, and radiation performance.

The obtained results demonstrate that the integration of the metasurface superstrate provides a clear improvement over the conventional circular patch antenna. The simulated metasurface-integrated antenna achieved an S₁₁ of −47 dB, a −10 dB impedance bandwidth of 3.7 GHz, a directivity of 8.7 dBi, and a realized gain of 8.2 dBi. The fabricated prototype showed good agreement with the simulated results, achieving an S₁₁ of −40 dB, a measured −10 dB impedance bandwidth of 2.9 GHz, a directivity of 8.1 dBi, and a realized gain of 7.3 dBi. The radiation pattern and surface current distributions further confirmed the enhanced field coupling and improved radiation characteristics introduced by the metasurface superstrate.

Overall, the proposed antenna offers an effective balance between compact size, enhanced bandwidth, strong impedance matching, and improved gain performance. These characteristics make it a promising candidate for compact Ka-band 5G and IoT wireless communication systems. Future work will focus on further bandwidth enhancement, bending analysis, and experimental validation under flexible and conformal operating conditions.

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