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Research Article

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Posted Date: September 25th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-9527946/v1>

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Additional Declarations: No competing interests reported.

Implementation Of Metasurface with Slotted Ground Structure Utilizing a Monopole Patch Resonating in Millimeter-Wave Frequency Band

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Abstract— This manuscript reports the design, analysis and realization of a metasurface-based antenna structure featuring a slotted metallic ground (SMG) integrated with an isosceles triangular monopole (ITM) patch radiator and tapered a feed line targeting for millimetre-wave (mm Wave) operation. To manipulate the current distribution across the radiating patch and SMG, a nonuniform unit-cell metasurface is introduced which effectively enhance the bandwidth in the range of 3.5 – 40 GHz. Additionally, the metasurface suppresses the backward radiation and enhances the radiated power in the forward direction, as a result, an acceptable level of front to back ratio is achieved. The dimensions of the printed prototype are 25×20 mm² and it provides the broad operating impedance bandwidth in the range 3.5 – 40 GHz with the magnitude of the reflection coefficient $|S_{11}|$ consistently under –10 dB.. The proposed antenna accomplishes the peak measured gain with a radiation efficiency of 10 dBi and 96 percentage respectively, exhibits a unidirectional radiation pattern and is employed for point-to point communication.

Index Terms— Metasurface, High Front-to-Back Ratio, mmWave Antenna, Monopole Radiator, Slotted metallic Ground

I. INTRODUCTION

The increasing deployment of millimetre-wave (mmWave) wireless schemes for applications such as fifth-generation (5G) communications, automotive radar, deep-space communication and high-data-rate links has strengthened the demand for compact antennas offering high gain, adequate bandwidth, and stable radiation characteristics at frequencies above 24 GHz [1]–[3]. However, planar antennas operating in the mm Wave band often suffer from narrow impedance bandwidth and reduced radiation efficiency owing to surface-wave excitation and increased conductor and dielectric losses [4], [5].

Metasurface based structures have been extensively investigated as an effective means of enhancing antenna performance by enabling controlled manipulation of electromagnetic wave propagation through engineered subwavelength structures [6], [7]. When integrated with planar antennas, metasurfaces can function as high-impedance surfaces or phase-controlling layers, leading to improved gain and bandwidth without significantly increasing antenna size [8]–[12]. In [13], an 8 × 8 tapered metasurface, composed of rectangular patches, is employed to excite two distinct resonance modes (TM₀₁ and TM₀₂) enabling enhanced impedance bandwidth and improved radiation performance. In parallel, slotted or defected ground plane structures have been employed to modify current distribution and suppress surface waves, thereby improving impedance and radiation characteristics [14]–[16]. The insertion of slots in the metallic ground plane creates supplementary resonant modes and improves electromagnetic coupling between the radiator and free space [17]. When combined with monopole or patch-based radiators, slotted ground structures can significantly improve radiation characteristics without

increasing antenna size [18]. Despite these advances, most reported mm Wave designs apply metasurfaces and ground plane modifications independently or rely on multilayer configurations [19], [20] that increase fabrication complexity and sensitivity to alignment tolerances.

To report this communication gap, a metasurface-loaded ITM patch antenna with a metasurface layer and a slotted structure in the metallic ground is introduced, which is intended for millimeter-wave band application. In this proposed antenna, a metasurface layer is integrated with a slotted structure in the metallic ground to improve the radiation performance and impedance bandwidth.

II. ANTENNA OUTLINE AND DESIGN ANALYSIS

A. Structural Summary of the ITM-based Metasurface Antenna

The schematic diagram of the anticipated antenna operating in millimetre-wave frequency band illustrates in Fig. 1. The antenna is fabricated on a 0.787-mm-thick Rogers RO3003 substrate ($\epsilon_r = 2.3$), whose low dielectric constant and thin profile support efficient millimetre-wave performance by suppressing surface waves and limiting dielectric losses. A radiating element printed on substrate, is a compact isosceles triangular monopole (ITM) patch fed by a 50- Ω microstrip transmission line. Beneath the ITM, a nonuniform periodic metasurface composed of subwavelength unit cells is introduced on the SGS. These unit cells operate as artificial magnetic conductors (AMCs), thereby enhancing radiation efficiency and suppressing surface-wave propagation. The metasurface periodic interval is restricted to below $\lambda_g/2$ to ensure that grating lobes do not arise. Additionally, the incorporation of a rectangular slot in the SGS perturbs the surface current distribution on the ground plane, thereby introducing additional resonant modes while simultaneously enhancing impedance matching over an expanded frequency range. The finalized geometric parameters of the proposed design are summarized as follows, $L = 25$ mm, $W = 20$ mm, $P = 2$ mm, $Q = 2$ mm, $J = 10$ mm, $U = 3$ mm, $R = 1.5$ mm, $S = 1.3$ mm, $M = 1.5$ mm, $N = 2$ mm, $V = 2$ mm, $W_1 = 0.5$ mm, $W_2 = 15.5$ mm, $A = 13$ mm, $F = 2$ mm, $D = 8$ mm, $C = 0.5$ mm, $T = 0.5$ mm, $E = 8.2$ mm, $B = 6.2$, $G = 9$ mm, $\theta = 45^\circ$.

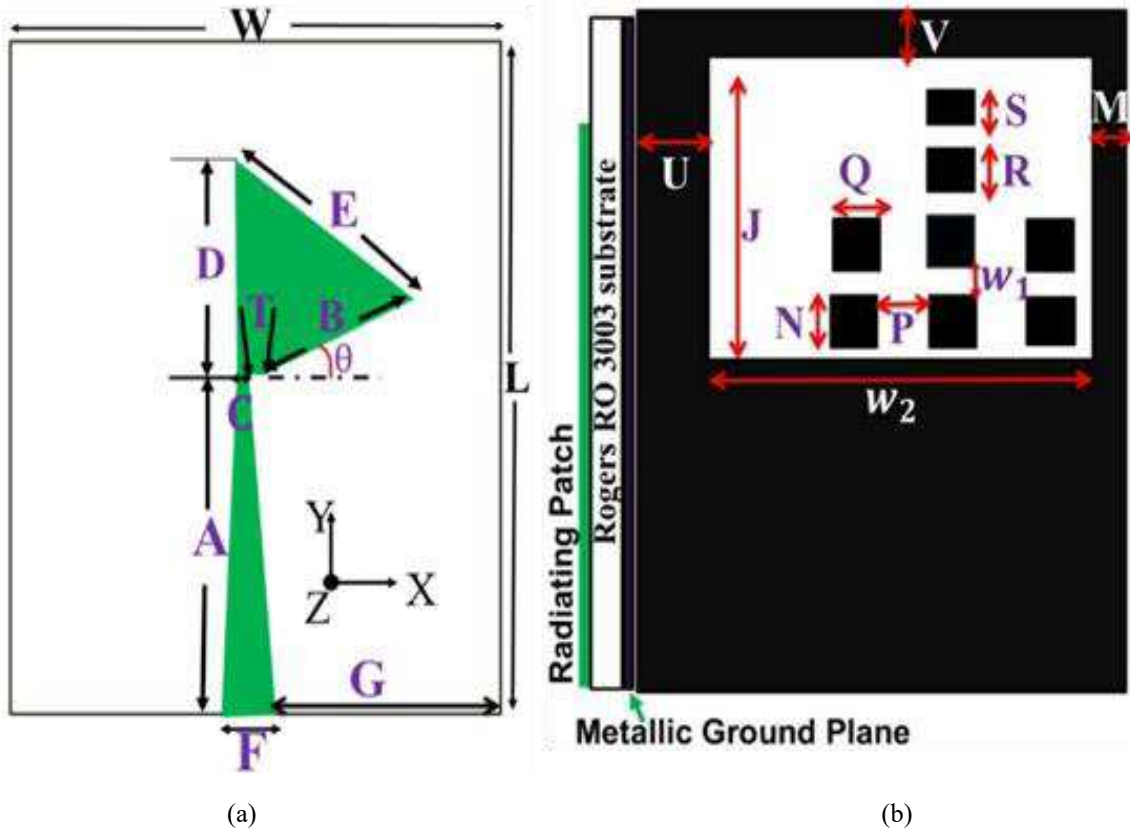


Fig. 1. (a) Bottom layer and (b) top layer outlines of the proposed metasurface based monopole antenna.

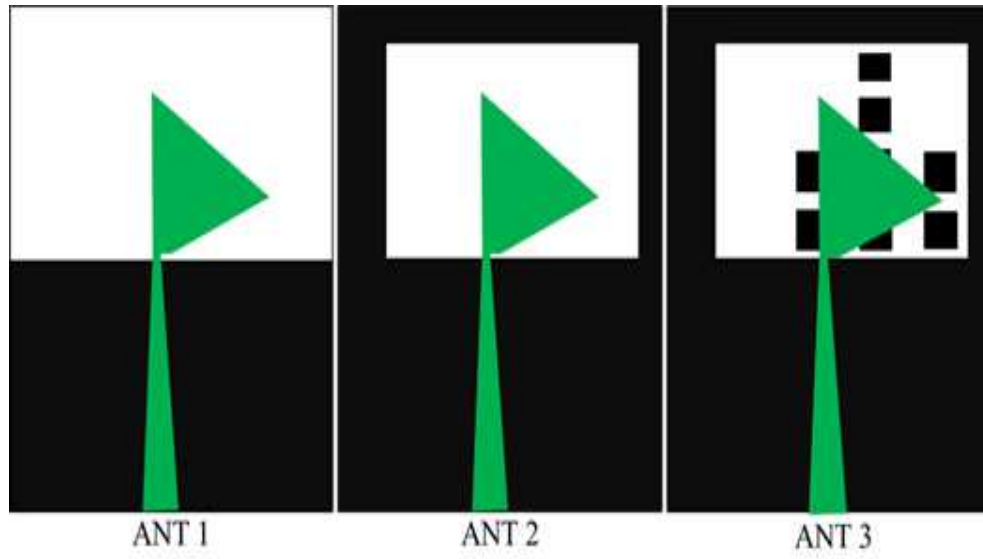


Fig. 2 Progression of Antenna 1 through Antenna 3

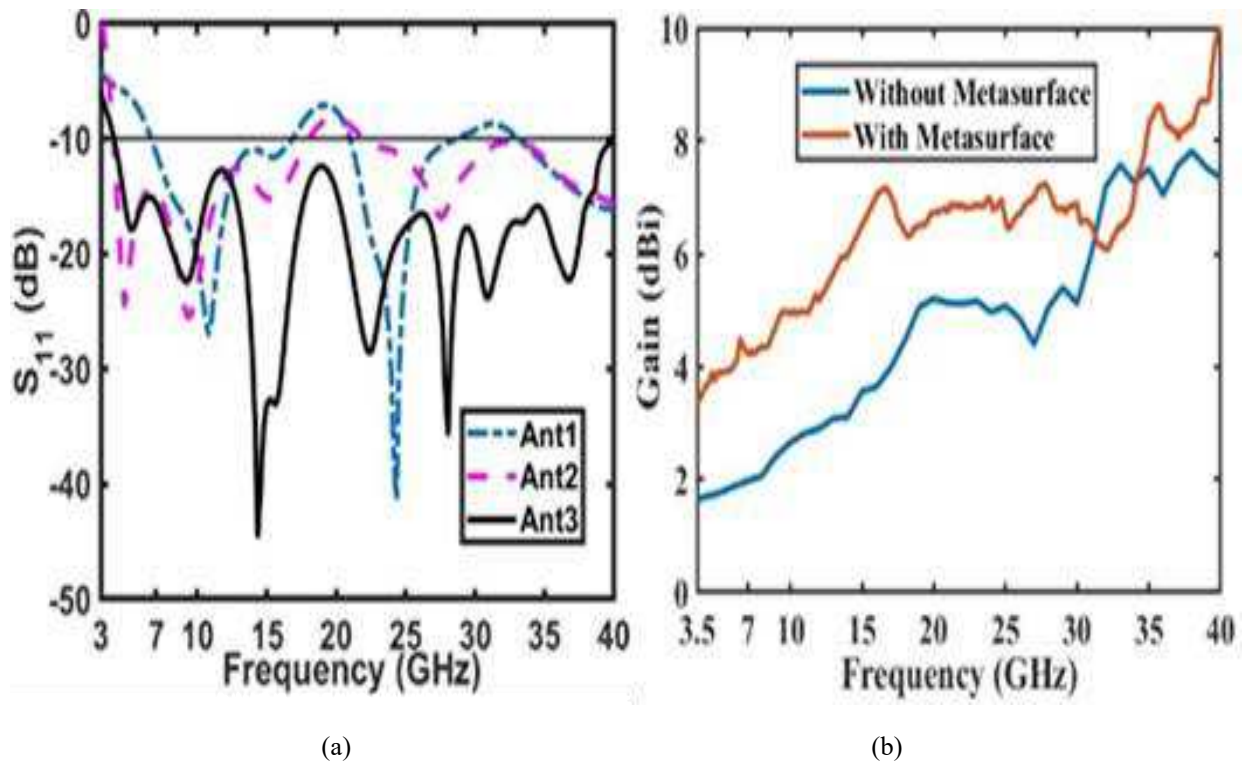


Fig. 3 (a) Reflection coefficient versus frequency of ANT 1 to ANT 3 (b) Simulated gain with and without metasurface

Fig. 2 shows the evolution of the proposed isosceles triangular monopole with metasurface from ANT 1 to ANT 3, which resulted in an optimized structure that could be used for mm-wave applications. Meanwhile, Fig. 3 (a) gives their corresponding simulated $|S_{11}|$ responses as evidence of how effective optimization was achieved. As

clearly visible in Fig. 2, incremental structural modification steps finally bring about the optimal structural configuration for the antenna under discussion. The proposed design basically comprises a conventional monopole construction assisted by a finite ground at the reverse side of the Rogers substrate and supports -10 dB bandwidth (see Fig. 3) within three ranges: from 7–15 GHz, from 22–28 GHz, and from 33–40GHz frequency ranges but this limited bandwidth constraint does not allow it to cover all mm-Wave and sub-6 GHz sub-bands because return currents are not allowed to spread fully due to short ground. Therefore, to address this issue the FGP is swapped with a slotted ground structure (SGS), referred to as ANT 2, as it creates longer, folded current paths without increasing antenna size. Consequently, as revealed in Fig. 3 (a), the bandwidth is significantly enhanced, extending from 22 to 40 GHz, while the lower resonance frequency drops to 3.5 GHz. Nevertheless, the overall gain of this antenna is limited to 1.9 dBi at 3.5 GHz, which can be seen in Fig. 3 (b). Hence, substantial modifications were implemented in ANT-3 by incorporating a metasurface on the backside of the radiator. The electromagnetic interaction between the metasurface elements and the monopole alter the current distribution, leading to the splitting of the fundamental resonance and the excitation of higher-order resonant modes, specifically the TM_{10} and TM_{20} modes. Consequently, the antenna maintains strong impedance matching and gain variation (3.9 -10 dBi) throughout the 3.5–40 GHz operating range, demonstrating the success of the implemented design enhancements.

B. Current Distribution

Fig. 4 depicts the surface current behavior across the ITM antenna at 10 and 35 GHz frequencies. From Fig. 4(a), it is evident that the surface currents at 10 GHz predominantly travel horizontally along the monopole patch. In addition, a small amount of current, highlighted by the maroon elliptical region, flows on the slotted ground plane and monopole patch. These horizontal currents on the monopole patch interfere with the intended vertical current distribution, resulting in distortion of the radiation pattern and impedance characteristics. In contrast, when the metasurface is introduced in proximity to the slotted ground, it effectively redistributes the surface currents by suppressing the undesired horizontal components and promoting dominant vertical current flow which shows that exhibits maximum current concentration near the feed point and on the patch (indicated in Fig. 4 (b)), confirming excitation of the dominant quarter-wavelength mode. Further, at 35 GHz, the surface currents on the patch and ground plane shown in Fig. 4(c) become irregular due to higher-order mode excitation, which leads to increased cross-polarization. In contrast, strong and well-confined currents are observed on the metasurface, as depicted in Fig. 4(d), effectively suppressing cross-polarized radiation.

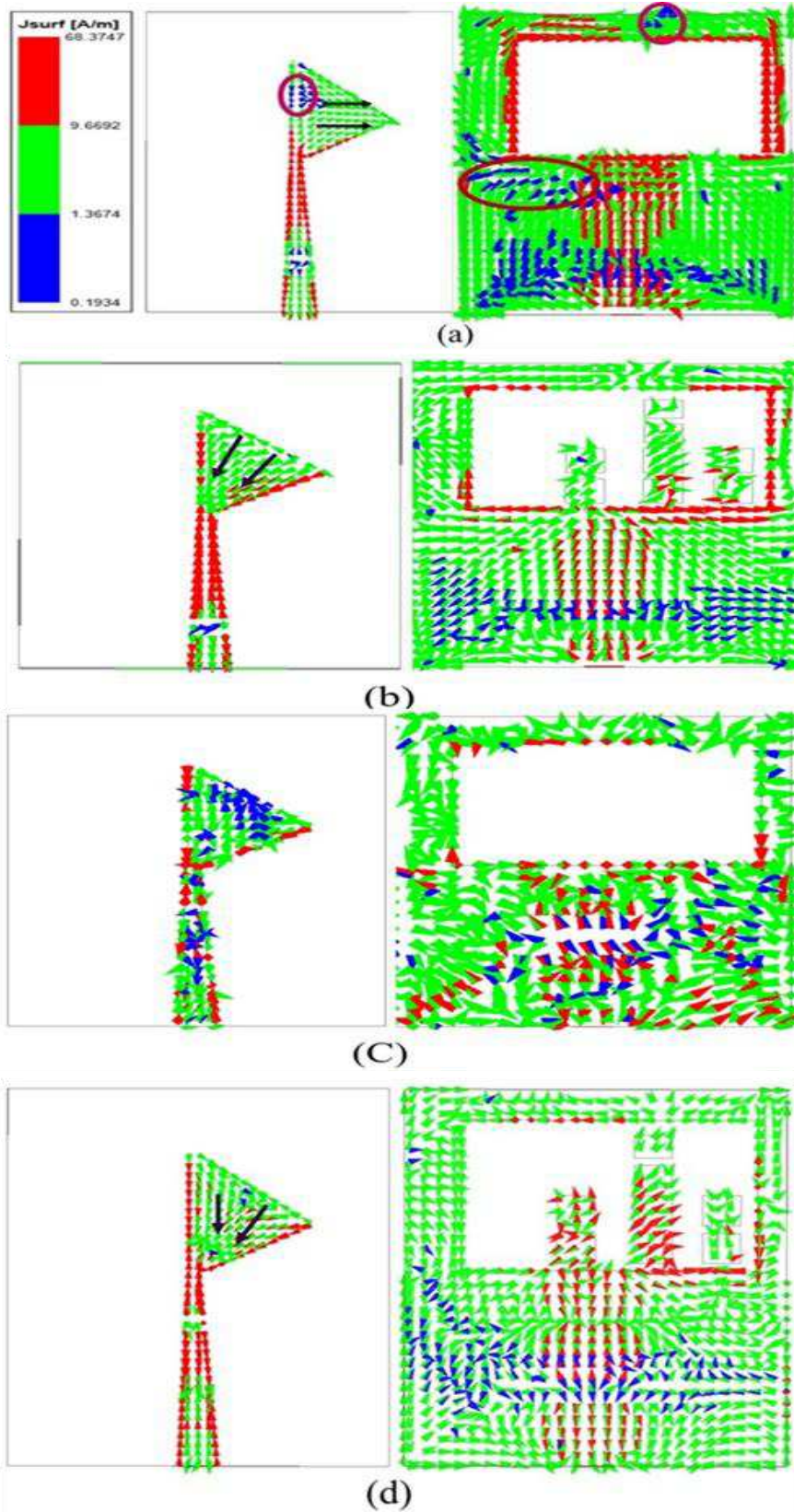


Fig. 4 Simulated surface current localizations on the isosceles triangular monopole (a) without and (b) with the unit cell metasurface, and on the slotted ground structure (c) without and (d) with the proposed unit cell metasurface at 10 and 35 GHz.

C. Analysis of Equivalent Circuit

The input impedance and the Circuit model of the proposed ITM antenna are depicted in Figure. 5 and 6 respectively. The resonant frequency corresponds to the point where the imaginary part shown in Fig. 5 of the antenna impedance vanishes, and only the resistive component remains. The antenna input impedance is modelled using a series RLC branch ($R_a-L_a-C_a$) representing the fundamental resonance, along with a parallel LC branch to capture higher-order resonant effects and metasurface coupling (represented in Fig. 5). Additionally coupling capacitor (C_c) accounts for the near field interaction between monopole patch and metasurface. The antenna achieves reasonably large frequency spectrum (3.5 – 40 GHz) due to multiple resonances energized by the proposed ITM antenna. The net input impedance of the circuit is obtained by combining the impedance of the series branch with the admittance of the parallel resonator(s). The series branch impedance is given by:

$$Z_s = R_a + j\omega L_a + \frac{1}{j\omega C_a} \quad (1)$$

The admittance of the coupling capacitor and the parallel LC resonator is expressed as:

$$Y_p = j\omega C_c + \sum_{n=1}^{\infty} j\omega C_n - \frac{j}{\omega L_n} \quad (2)$$

The total input admittance is therefore given by:

$$Y_{in} = \frac{1}{Z_s} + Y_p \quad (3)$$

and the corresponding input impedance is:

$$Z_{in} = \frac{1}{Y_{in}} \quad (4)$$

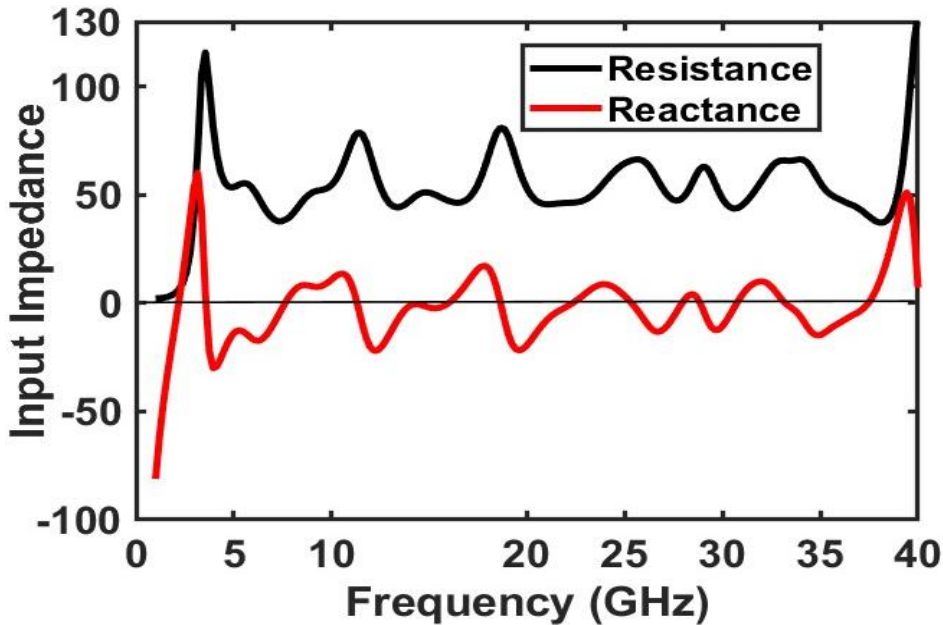


Fig. 5. Input impedance of the proposed ITM based metasurface antenna.

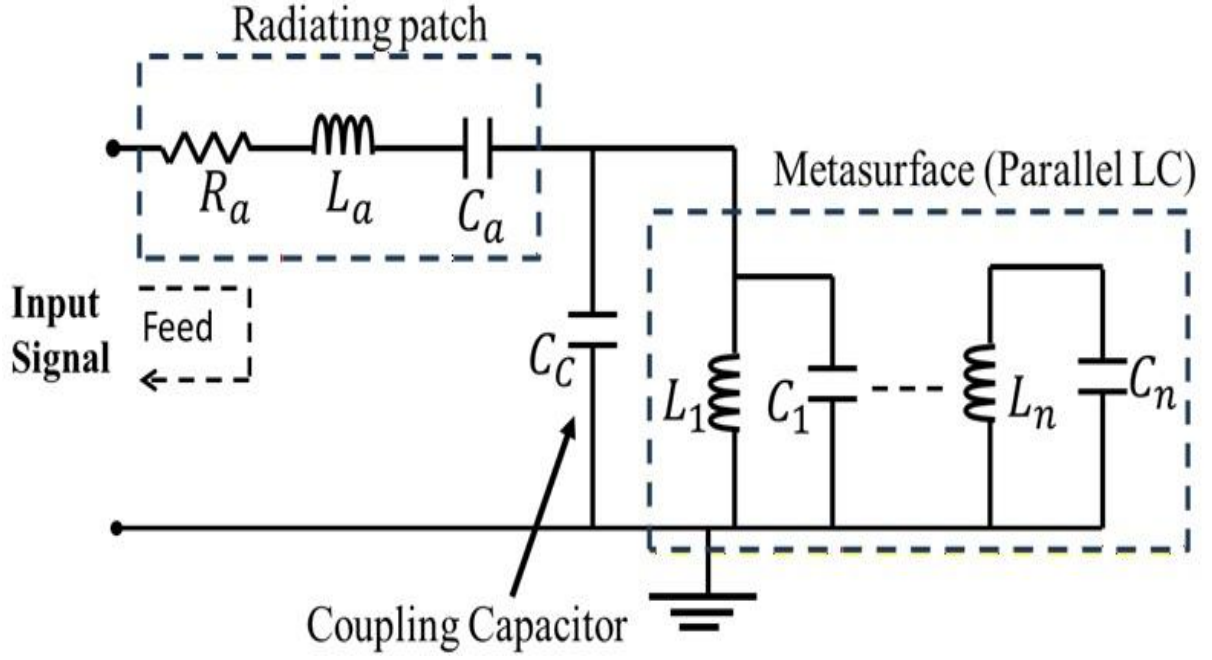


Fig. 6. Circuit model corresponding to the proposed ITM metasurface antenna.

III. PARAMETRIC INVESTIGATION OF ITM BASED METASURFACE ANTENNA

Fig. 7 represents the computed reflection coefficient (S_{11}) of the designed ITM antenna for rotation angles of 35° , 40° , 45° , and 50° over the 3.5–40 GHz range. The antenna validates several resonant points at each rotation angle, demonstrating its multiband capability. The impedance characteristics of the ITM antenna varies with the rotation angle θ . Increasing θ leads to deeper resonance dips and a wider bandwidth below -10 dB. The best performance is obtained at $\theta = 45^\circ$, where S_{11} is about -45 dB. This behavior is attributed to changes in the effective electrical path length and the redistribution of surface currents caused by the rotation of the triangular radiator. At smaller angles ($\theta = 35^\circ$ and 40°), the resonances are less pronounced and show slight frequency shifts, indicating reduced coupling efficiency.

Fig. 8 shows that when W_2 is increased from 14.5 mm to 16 mm, the lower resonance shifts from about 4.5 GHz to nearly 3.2 GHz. This shift is mainly due to the longer effective current path and stronger interaction between the ground structure and the slot. However, at $W_2 = 16$ mm, the ground current distribution becomes highly disturbed, which results in poor impedance matching in the millimeter-wave (mm-wave) region, especially near 20 GHz and 32 GHz. To avoid this issue, W_2 is set to 15 mm, providing a good balance between impedance matching and stable mm-wave performance. Alteration of simulated gain of the proposed ITM based metasurface antenna with respect to parameter P is depicted in Fig. 9. An increase or decrease in the unit-cell metasurface gap P from its optimal value of $P = 2$ mm leads to a reduction in the antenna peak gain from 10 dBi to 8 dBi. This is because the gap perturbs the designed electro-magnetic coupling and surface impedance, thereby disturbing the in-phase current, as a result, the gain is reduced.

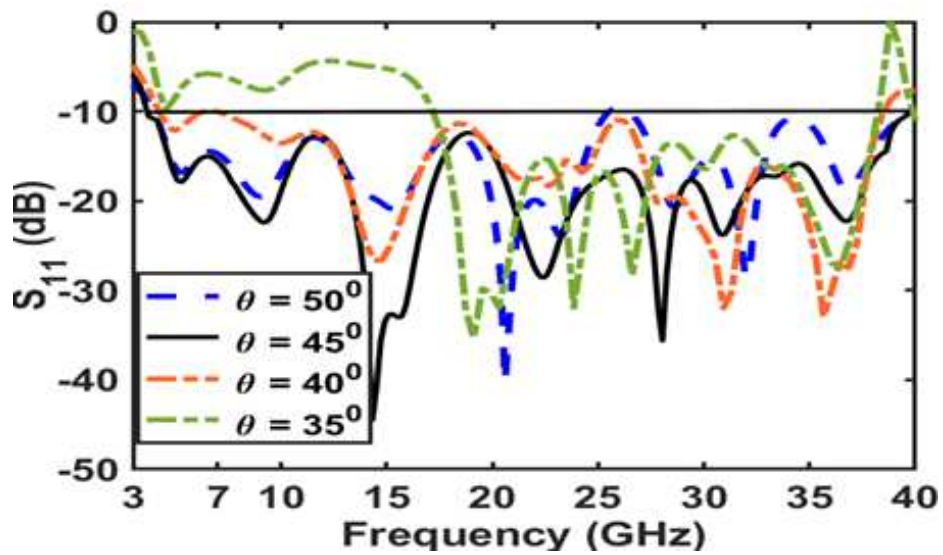


Fig. 7 simulated Scattering parameter (S_{11}) of the proposed ITM antenna for rotation angles $\theta = 35^\circ$, 40° , 45° , and 50°

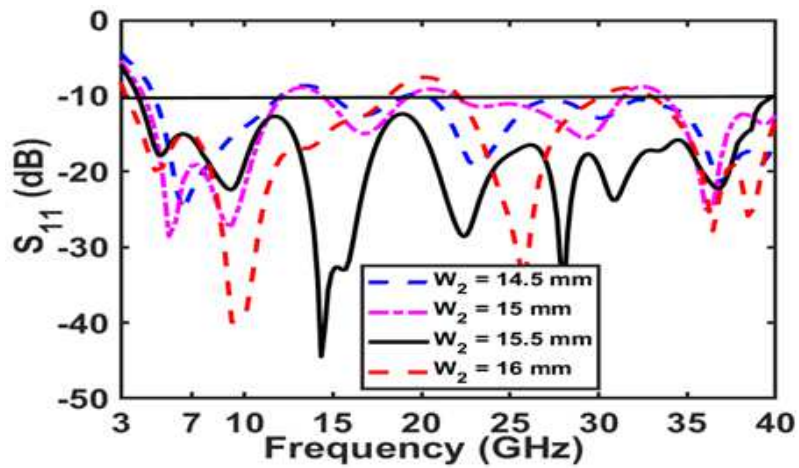


Fig. 8 Simulated Scattering parameter (S_{11}) for different values of w_2

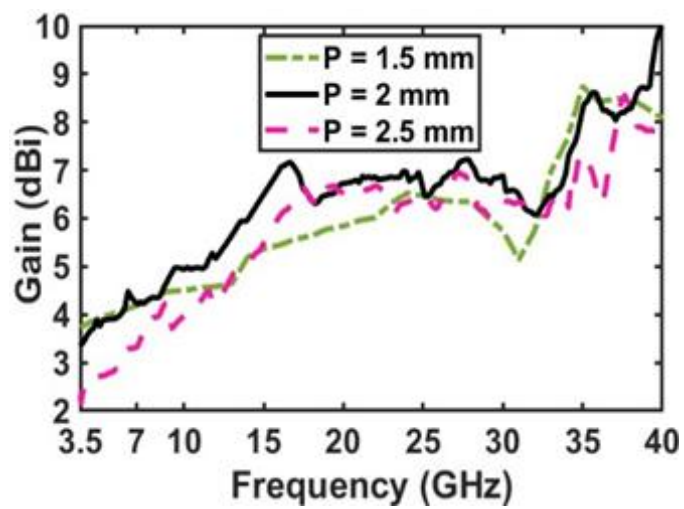


Fig. 9 Alteration of simulated gain with respect to parameter P .

IV. EXPERIMENTAL STUDY OF PROPOSED ITM ANTENNA

To endorse the simulation outcomes, the proposed antenna was manufactured and experimentally accessed. Figures 10 (a) and 10 (b) depict the fabricated prototype, while Fig. 10 (c) highlights the consistency between simulated and measured S_{11} outcomes, confirming that the antenna functions over the 3.5–40 GHz bandwidth range. The experimental findings align well with the simulation outcomes, indicating good consistency. As indicated in Fig. 11 (a), the gain variation of the designed antenna remains within 6 dBi across the 3.5–40 GHz band, and it is below 2 dBi over the 15–33 GHz frequency range. The radiation efficiency versus frequency is represented in 11 (b). The plot depicts that the radiation efficiency obtained from measurement and simulation remains within 94 % to 96 % across the working band. The comparison of measured and computed far-field radiation behavior at (a) 10 GHz and (b) 35 GHz is shown in Fig. 12. Experimental observations reveal that the front-to-back ratio surpasses 20 dB in the E- and H-planes at 10 GHz and 35 GHz. The enhanced directional performance arises from the metasurface, which effectively mitigates back radiation and strengthens the forward lobe. The features of the proposed antenna are evaluated against other reported antennas, as summarized in Table I.

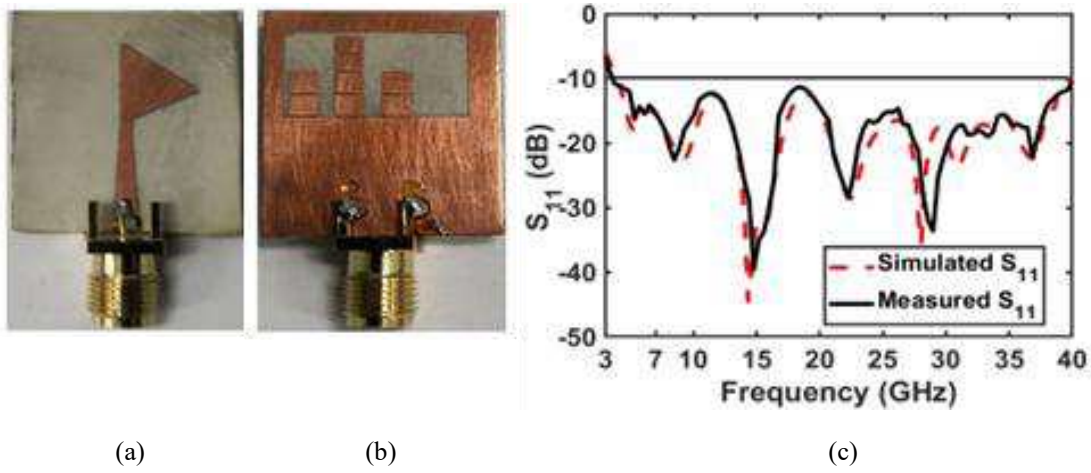


Fig. 10 (a) Fabricated prototype of Top View (b) Fabricated prototype of Rear View (c) Experimental versus simulated reflection coefficient response.

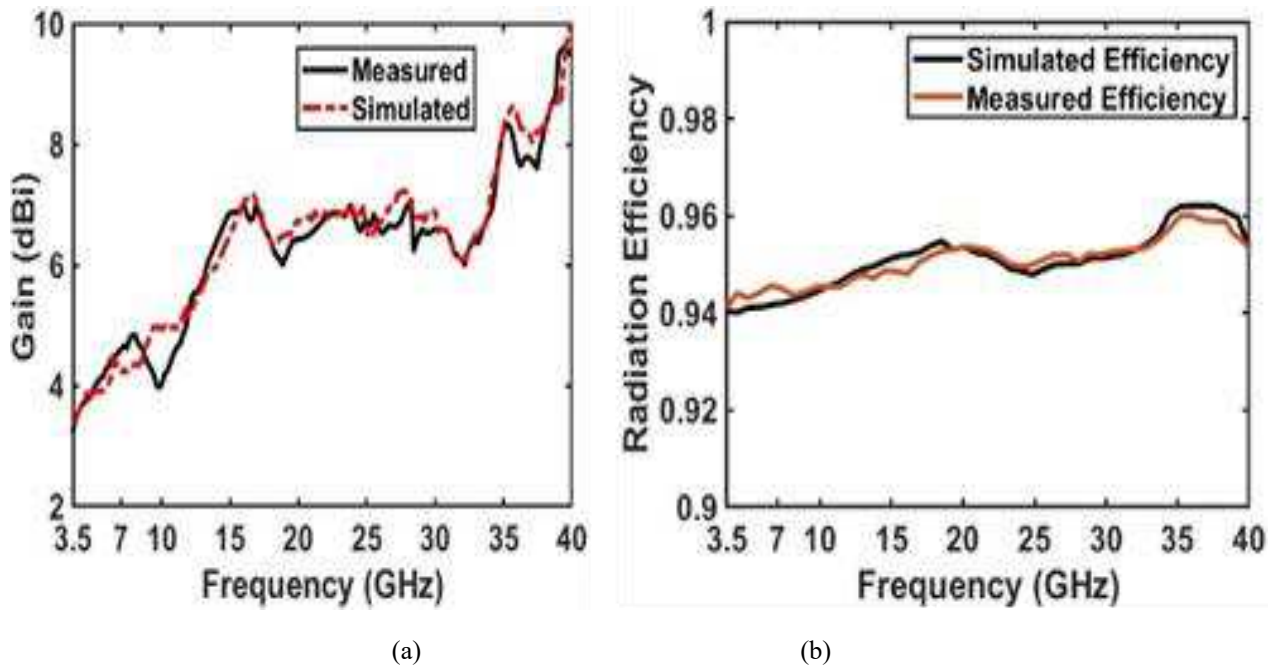


Fig. 11 Simulated and experimentally obtained (a) Gain (b) Radiation Efficiency of the ITM based metasurface antenna.

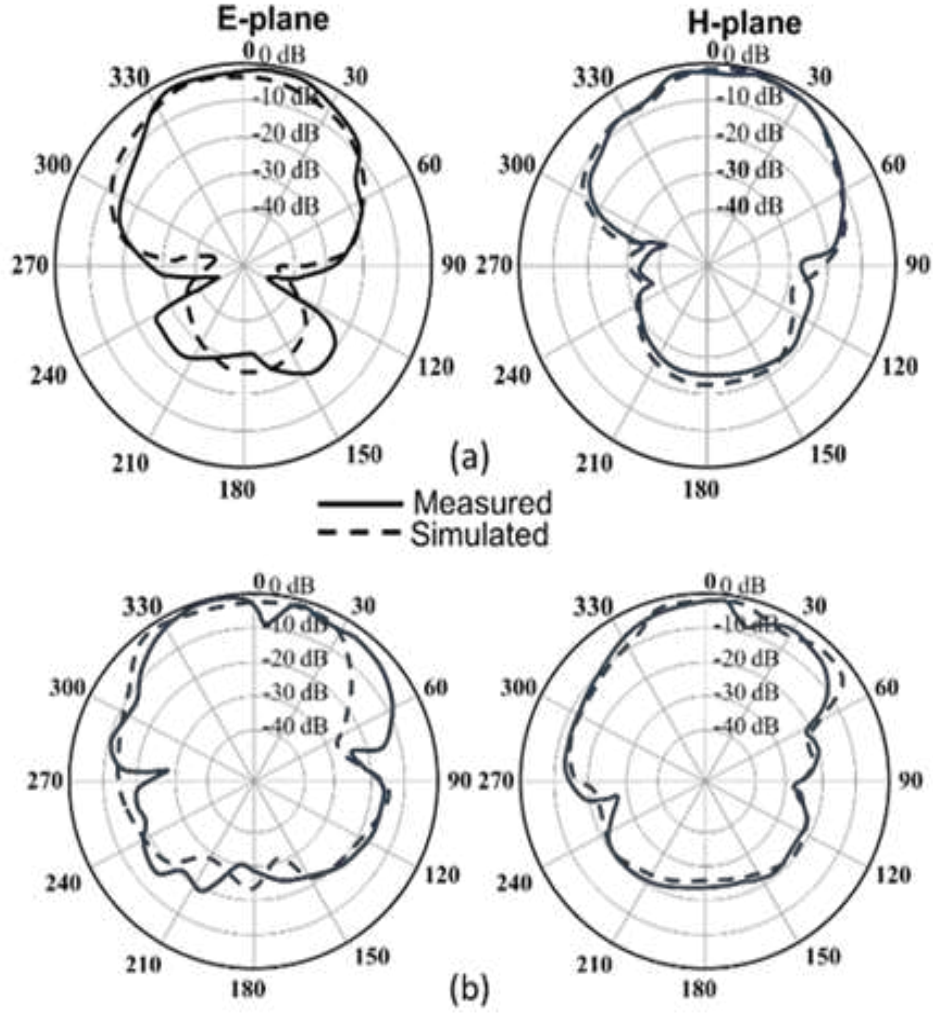


Fig. 12 Far-field radiation performance obtained from measurement and simulation at (a) 10 GHz (b) 35 GHz.

TABLE I

BENCHMARKING OF THE PRESENTED ANTENNA AGAINST EXISTING ANTENNAS

Ref.	Antenna Size (W×L)	IBW %	Peak Gain (dBi)	Average Efficiency	Radiation	Technique
5	16 × 70 mm ²	6.6	7.5	80 %		Array of Circular patch
9	30 × 30 mm ²	36	7	-		Phase Gradient Metasurface
12	109*109 mm ²	40	8.4	-		Flat-top Metasurface
13	71×71 mm ²	33	7.5	-		Metasurface
16	32×32 mm ²	18	12.4	86.25 %		Metasurface based array antenna
This work	20×25 mm ²	167	9.8	96 %		Monopole with Metasurface

V. CONCLUSION

A compact metasurface-based antenna with a slotted metallic ground and monopole patch radiator has been presented for mm-wave applications. The use of a nonuniform unit-cell metasurface effectively enhances the impedance bandwidth from 3.5 to 40 GHz while suppressing backward radiation and improving forward radiation. The developed antenna delivers a peak gain of 10 dBi with 96% radiation efficiency and maintains a unidirectional radiation behavior. Due to its wide bandwidth, compact configuration, and high performance, the antenna is an excellent candidate for point-to-point wireless communication applications.

FUNDING DECLARATION

The authors confirm that this work was carried out without funding for research, manuscript preparation, or publication

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