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5G Antenna Gain Enhancement Using a Novel Metasurface

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Abstract: This article presents a Sub-6 GHz microstrip patch antenna (MPA) with enhanced gain using metamaterial (MTM) superstrate. The source MPA operates at 4.8 GHz and has a peak gain of 5.3 dBi at the resonance frequency. A window-shaped unit cell is designed and investigated through the material wave propagation technique. The unit cell shows an Epsilon Near Zero (ENZ)-Mu Very Large (MVL) behavior around 4.8 GHz. The unit cell has a fourfold geometry which makes it a polarization independent metamaterial. A double layer antenna is designed by placing a 4×4 MTM slab as a superstrate above the MPA at a height of $0.208\lambda_0$; where λ_0 is the free-space wavelength at the resonance frequency of the antenna. Impedance matching and gain of the source antenna is improved using the metamaterial. The simulation as well as measurement results show that novel antenna system has a peak gain of 7.68 dBi at 4.8 GHz and an impedance bandwidth of 0.22 GHz. The overall dimension of the antenna is $75 \times 60 \times 15$ mm3. The proposed antenna operates in the Sub-6 GHz band and is suitable for 5G applications.

Keywords: Metasurface; 5G; gain; directivity; polarization

1 Introduction

In the last few decades, mobile wireless communication technology has grown significantly through research and innovation and has experienced remarkable change. To keep up with such drastic changes, mobile operators have introduced advanced generations from time to time. Starting in the 1980s with the launch of 1G, 2G in the 1990s, 3G in 2001, and 4G in 2010. The next-in-line generation is 5G which seems to take over the entire communication industry. 5G technology uses two different frequency bands for its operations i.e., sub-6 GHz spectrum and the millimeter-wave spectrum. The sub-6 spectrum provides better coverage as compared to the millimeter-wave spectrum.

Lower frequency signals are less susceptible to interference from things like buildings, trees, traffic, and atmospheric conditions, which makes them a great choice for covering a large geographic area. Thus, low-frequency band is preferred by the cell providers since it allows for large coverage areas with fewer towers.

Microstrip patch antennas belong to a well-known class of lightweight, miniaturized, and low-profile antennas that have gained prominence in research and commercial applications in recent decades [1,2] . However, the poor directionality and low gain of the microstrip antenna still creates problems and bottlenecks in the performance of the whole communication system. To make the communication more efficient, the gain of the microstrip antenna needs to be improved. Many different techniques have been used in the past to enhance the gain of the microstrip antenna such as using partial substrate removal [3], by inserting slots in the antenna design [4,5], using parasitic elements [6–8], EBG structures [9–12], artificial magnetic conductors [13,14], and metamaterials [15–23]. The use of metamaterial in antenna design is more efficient and effective as metamaterials show some unusual and interesting properties such as negative permeability and negative index of refraction [24] which they get from their uniquely designed structure that is not found in naturally occurring materials. These properties can be utilized to improve the gain of a microstrip antenna.

In [19], a planar metamaterial based ameliorated high-gain ultra-wideband microstrip antenna is presented. The antenna has a super-wide operating band (3.06 GHz-36.4 GHz) and achieves a peak gain of 8.02 dB. The gain enhancement of a microstrip antenna was achieved by embedding nested tridimensional split ring resonators in low temperature co-fired ceramic (LTCC) substrate integrated with a rectangular patch antenna [20]. A high gain microstrip antenna inspired by a zero index metamaterial superstrate resonating at 10 GHz was proposed in [21]. The patch antenna was loaded with a triple layer metamaterial superstrate thus achieving a broadside gain of 7.8 dBi which is 80% higher than that of the patch antenna. However, due to the triple layer stack-up and the large distance of superstrate from the source antenna, its profile becomes very high. The antenna operates at 5.2 GHz and shows a gain enhancement of 1.5 dB after metamaterial loading. A dual band microstrip antenna with enhanced gain using left-handed split-ring resonator metamaterials loading is presented in [22]. The antenna operates in the Wireless Local Area Network (WLAN) bands (2.4–2.484 and 5.15–5.85 GHz) and shows a peak gain of 5.02 dB at the lower band and 4.5 dB at the upper band. In [23], a novel miniatured patch antenna using near zero index metamaterial is proposed with enhanced gain. The antenna has a small footprint of 44 mm × 58 mm and operated at 534 MHz with 2.11% impedance bandwidth. The antenna showed a gain of 7.27 dB. In [24], a planar high gain antenna using multilayer superstrate with negative refractive index is proposed. The metamaterial superstrate consists of 7 by 7 array of coupled resonators operating at 11.83 GHz. The gain for proposed multi-layer antenna was 17.1dBi. A compact high gain fractal shaped slotted patch with metasurface superstrate is proposed [25]. The proposed antenna showed a fractional bandwidth of 7.6% at 10.44 GHz with 7.57dBi gain. In [26], the broadside gain of a microstrip patch antenna was improved using a 7×7 array of near-zero index metamaterial unit cells. The antenna achieves a gain improvement of more than 2 dBi and half power beam width reduction of 20^0 in both E-plane and H-plane.

In this article, a low profile high-gain microstrip antenna with a novel MTM superstrate is presented. The superstrate consists of single 4×4 array of window-shaped MTM unit cells, placed at the height of 0.208 λ0 from the source antenna. The unit cell has a fourfold symmetry making it a polarization independent metamaterial. The measurements show that the proposed antenna shows a peak gain of 7.68 dBi at 4.8 GHz, which is 2.38 dBi higher than that of the source antenna. The remainder of this article is organized as follows. Section 2 discusses the design of the source MPA. Section 3 presents the design and analysis of the proposed MTM unit cell. Section 4 presents the

design of the proposed antenna with novel MTM superstrate and discusses its results and performance. Finally, a conclusion is drawn in Section 5.

2 Source Antenna

The allocated spectrums in the sub-6 GHz band for the 5G applications are 3.4–3.6, and 4.8–4.9 GHz. In this section a rectangular microstrip patch antenna resonating at 4.8 GHz frequency is designed. The MPA is realized on 1.524 mm thick Roger RO4003C substrate with a dielectric constant of 3.55 and loss tangent 0.002. The antenna parameters were optimized to get a resonance at 4.8 GHz. The geometry of the source antenna is depicted in Fig. 1a. A single section quarter-wave transformer was inserted in the design to match the patch impedance to the feed. The MPA shows a simulated return loss of -18 dB at 4.8 GHz in Fig. 1b. The effective bandwidth of the antenna is calculated to be 0.125 GHz i.e., from 4.75 GHz to 4.875 GHz. For the XZ-plane at 4.8 GHz the antenna has a HPBW of 86.7^0 with side lobe level of -15.2 dB and the main lobe direction is 0^0. Whereas for the YZ-plane at 4.8 GHz the antenna has a HPBW of 130.8^0, a side lobe level of -7.9 dB, and main lobe direction at 4^0.

(a)   (b)
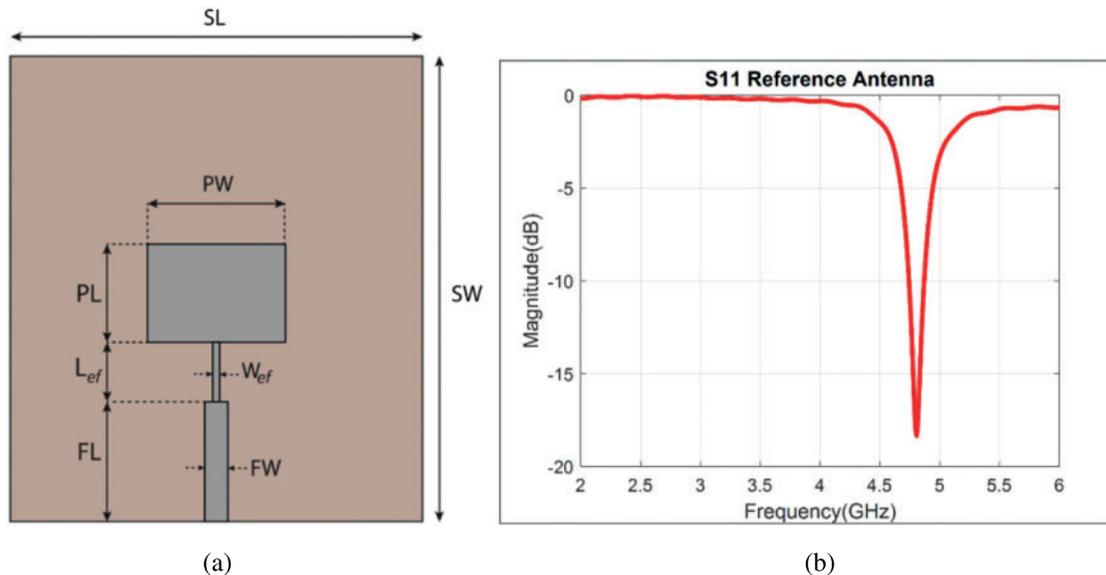
Figure 1: Source MPA (a) Top View: The optimized parameters are SL = 75 mm, SW = 60 mm, PL = 15 mm, PW = 20.5 mm, FL = 18 mm, FW = 3.5 mm, Lef = 12 mm, Wef = 0.5 mm, (b) Simulated S-Parameter

3 Metamaterial Design

In this section, the design of the novel MTM structure is presented. The MTM is a window-shaped periodic structure having a four-fold symmetry which makes it a polarization-independent MTM. The MTM unit cell is designed on 0.4 mm thick Roger RO4003C substrate with dielectric constant 3.55 and loss tangent 0.0027. Fig. 2a illustrates the geometry of the proposed MTM unit cell. The periodicity of the unit cell is $p = 5$ mm. The periodic boundary conditions are applied to the unit cell as shown in Fig. 2b. The unit cell is simulated in Computer Simulation Technology (CST) Microwave Studio [27]. The effective parameters of the MTM are extracted using Smith's parameter extraction method [28].

(a)   (b)
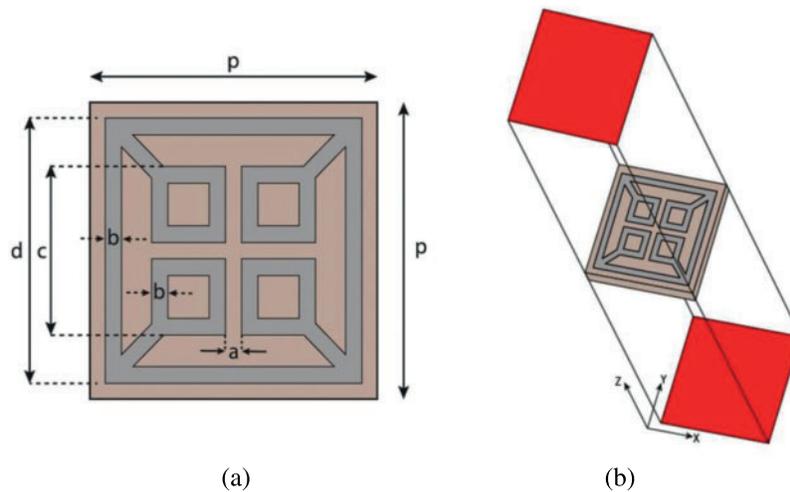
Figure 2: MTM unit cell (a) Top view, The dimensions are $p = 5\,mm$, $a = 0.3\,mm$, $b = 0.2\,mm$, $c = 1.7\,mm$, $d = 4.68\,mm$. (b) 3D view

The effective permittivity (ε_r) and permeability (μ_r) of the MTM are plotted in Fig. 3. The effective permittivity is observed to be very low around 4.8 GHz, whereas the effective permeability is very high. Thus, the MTM is acting as an Epsilon-Near-Zero (ENZ)-Mu-Very-Large (MVL) MTM around 4.8 GHz. As a result, this MTM responds heavily to the incident magnetic field and negligibly to the incident electric field, so the MTM is a magnetic field coupled structure. This is validated by strong magnetic field distribution and comparatively weak electric field distribution on MTM unit cell shown in Fig. 4.


(a)   (b)
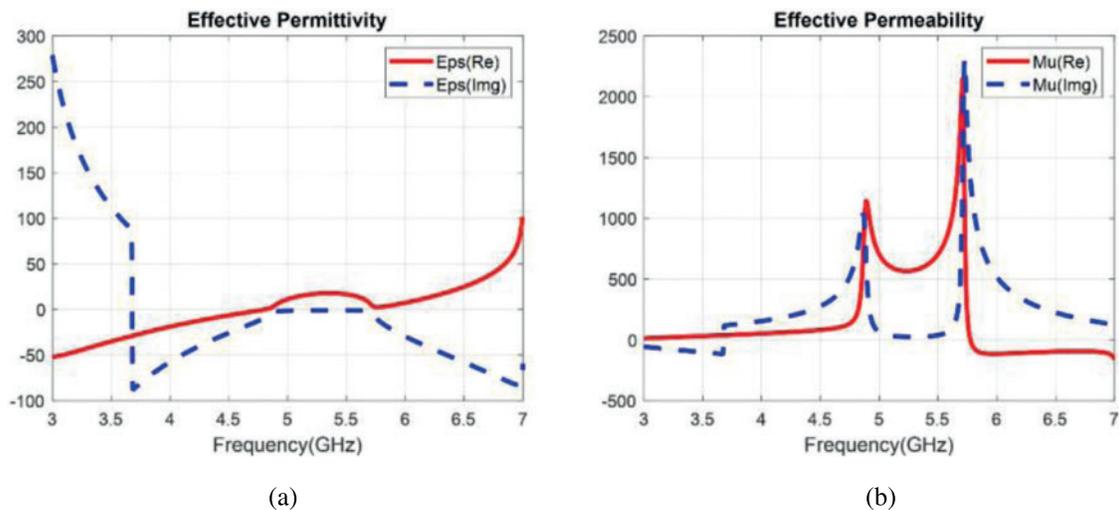
Figure 3: Effective parameters of the proposed MTM unit cell (a) Permittivity (b) Permeability

(a)   (b)
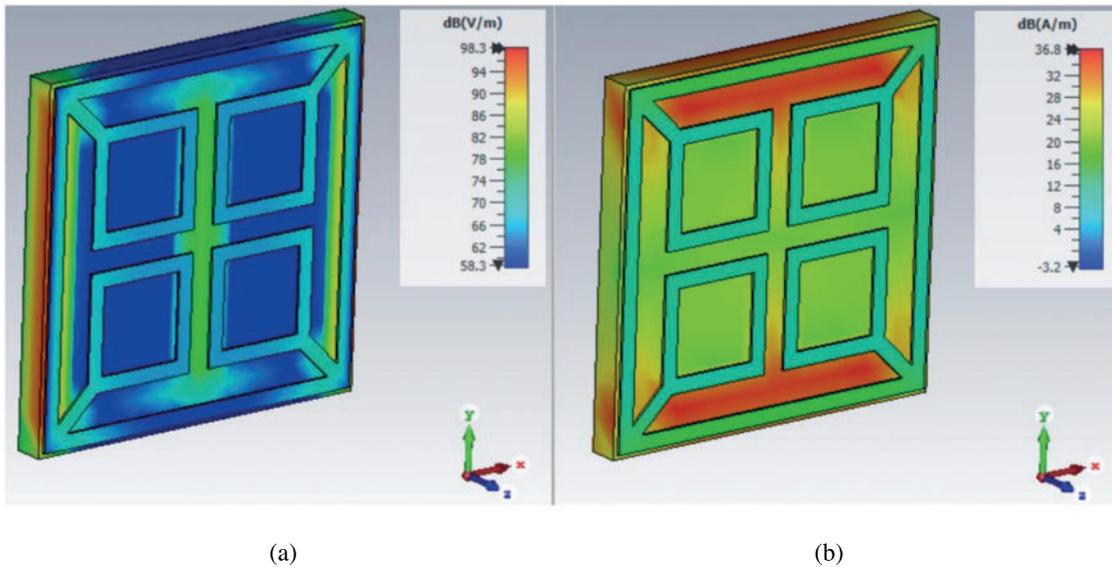
Figure 4: Field distribution on proposed MTM unit cell at 4.8 GHz (a) E-field (b) H-field

## 4 Proposed Antenna with Novel MTM Superstrate

Fig. 5 shows the structure of the proposed antenna with a novel MTM superstrate. The MTM slab is placed at the height (hgt) of 13 mm, i.e., $0.208\lambda_0$, from the source antenna. The simulation results show that an array of 4×4 MTM unit cells placed over the MPA acts efficiently and improves the antenna gain significantly. Thus, an array of 4×4 MTM unit cells is employed as superstrate above the source antenna to increase the antenna gain.

(a)   (b)
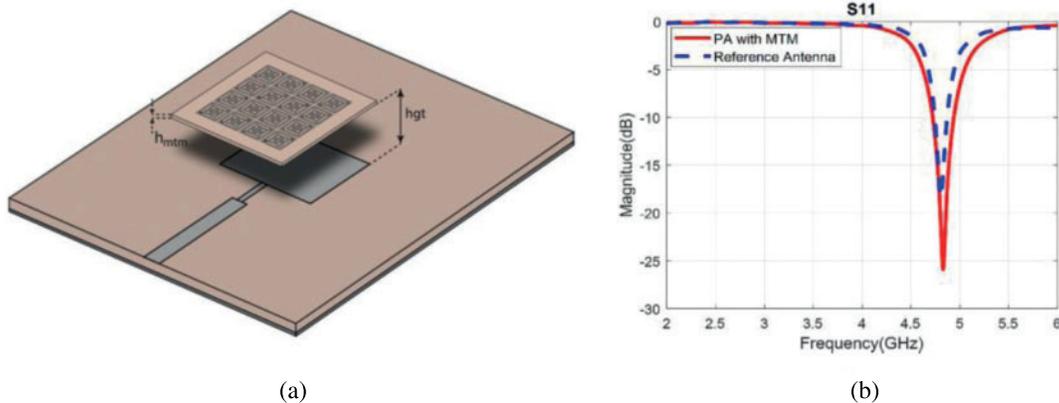
Figure 5: (a) Proposed antenna with 4×4 MTM superstrate; $h_{mtm} = 0.4$ mm, hgt $= 13$ mm (b) Simulated S11 for the Proposed Antenna

Fig. 5b shows the simulated S11 plot for the proposed antenna. The operational bandwidth of the antenna improves after the placement of the MTM superstrate. The effective bandwidth for the proposed antenna design is observed to be 0.21 GHz i.e., from 4.72 GHz to 4.93 GHz. The simulated gain variations against theta and frequency are plotted in Figs. 6a and 6b respectively. A significant

amount of gain enhancement is observed for the proposed antenna i.e., after placement of MTM superstrate the antenna achieves a peak gain of 7.68 dBi. Thus, a gain enhancement of 2.22 dBi was achieved.


(a)   (b)
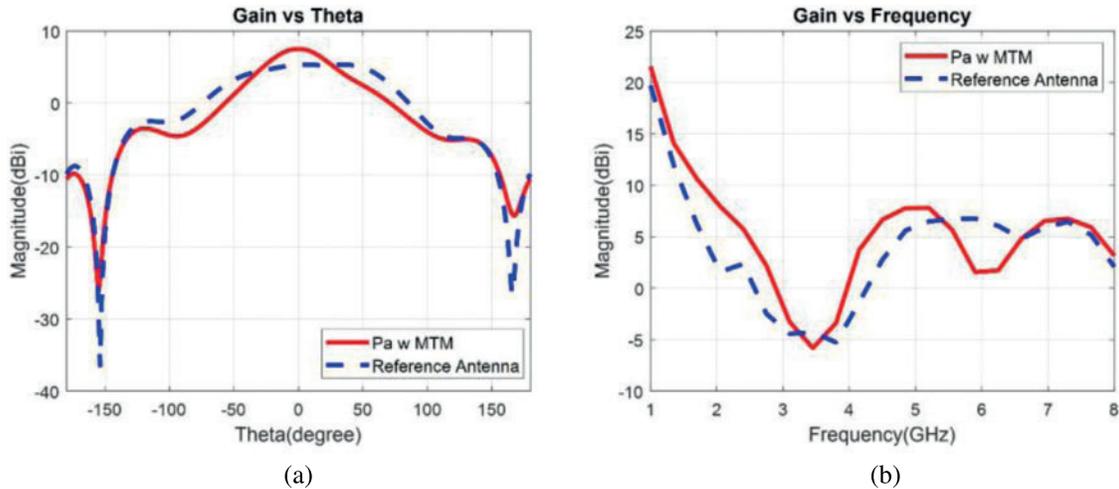
Figure 6: Simulated gain for proposed antenna (a) *vs.* Theta (b) *vs.* frequency

Fig. 7 shows the simulated radiation patterns of the proposed antenna for XZ-plane and YZ-plane. For the XZ-plane at 4.8 GHz, the antenna has an HPBW of 80.3^0 with side lobe level -17.6 dB and main lobe direction at 0^0. Whereas for the YZ-plane at 4.8 GHz the antenna has an HPBW of 61.7^0 with side lobe level -11.1 dB and main lobe direction at 0^0. Thus, for the XZ-plane the HPBW of the proposed antenna is reduced from 86.7^0 to 80.3^0 (6.4^0 reduction) and the side-lobe level is reduced by 2.4 dB. Similarly, in YZ-plane the HPBW is reduced to half i.e., from 130.8^0 to 61.7^0 (11.9^0 reduction), and the side-lobe level is reduced by 3.2 dB. This shows that the MTM superstrate is acting as a lens and focusing the electromagnetic beam.

(a)   (b)
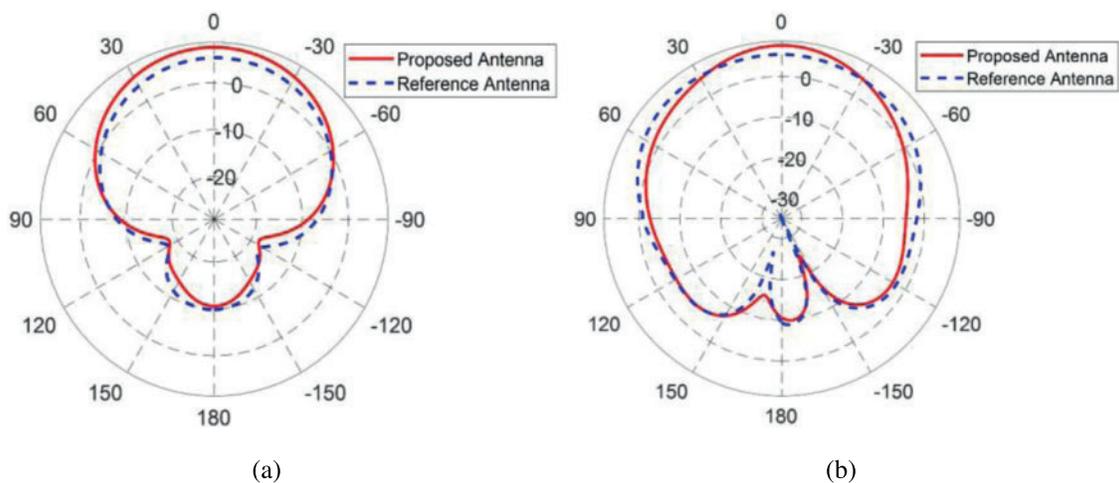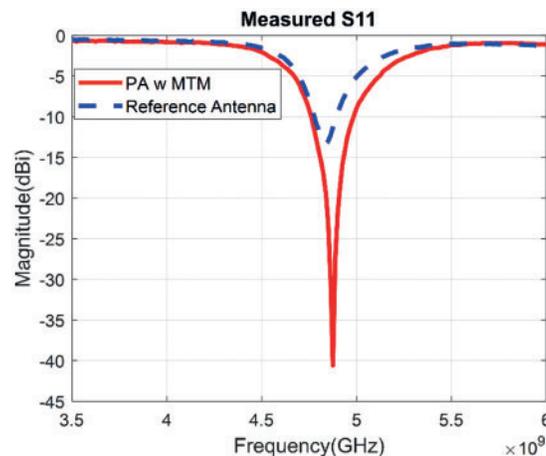
Figure 7: Radiation pattern of proposed antenna with 4×4 MTM superstrate at 4.8 GHz (a) XZ-plane (b) YZ-plane

To validate the proposed antenna design, the 4×4 MTM slab and the MPA were fabricated and analyzed in anechoic chamber and radiation patterns in E-plane and H-plane were measured. Fig. 8a shows the fabricated prototype of the proposed antenna while Fig. 8b shows its measurement setup in anechoic chamber. The S11 parameter of the fabricated prototype was measured using Agilent E8362 VNA and is plotted in Fig. 9. The measure S11 results match well with the simulation results i.e., after the placement of MTM superstrate the impedance bandwidth improves.

(a)   (b)
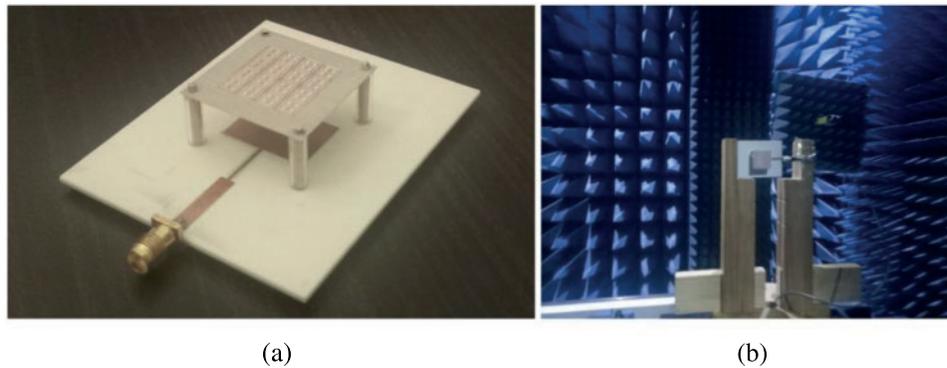
Figure 8: (a) Fabricated prototype of antenna with MTM superstrate (b) Measurement setup for radiation patterns


Figure 9: Measured S-parameters for source and proposed antenna

The radiation patterns in E-plane and H-plane for the fabricated prototype are shown in Fig. 10. It is evident that the gain of the antenna increases after the placement of MTM superstrate. The gain after the placement of MTM superstrate is measured to be 7.63 dBi which is 2.42 dBi higher than that of the source MPA. A slight difference is observed between simulated, and measurement results due to practical conditions and measurement errors.

To validate the four-fold polarization independence of proposed metasurface, the unit cell is simulated with Floquet ports for both TE and TM modes. The transmission response is given in Fig. 11. It can be observed that for different polarization angles the transmission response of proposed structure is uniform for both TE and TM modes.
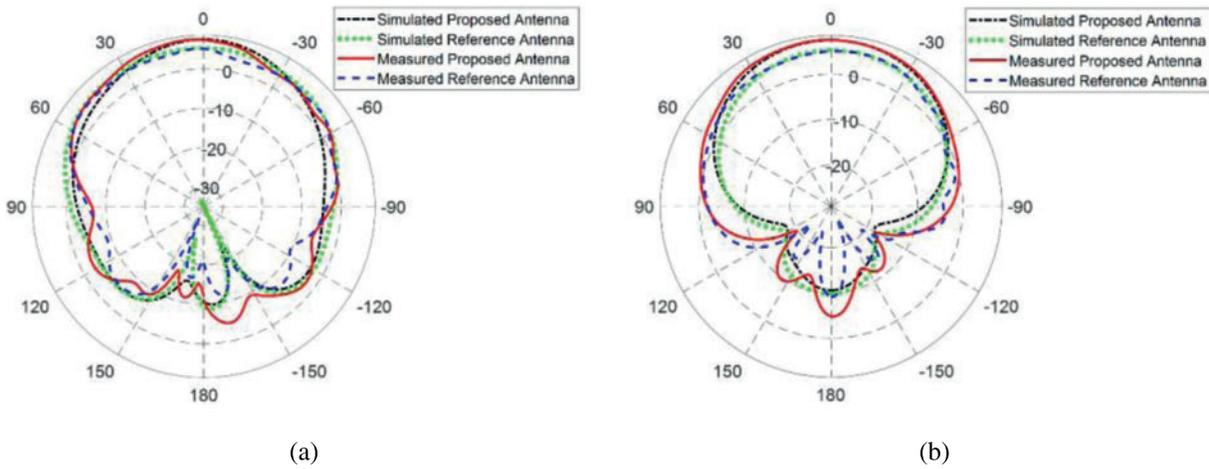
Figure 10: Simulated and measured radiation patterns for proposed antenna and source antenna at 4.8 GHz (RA). (a) XZ or H-plane. (B) YZ or E-plane
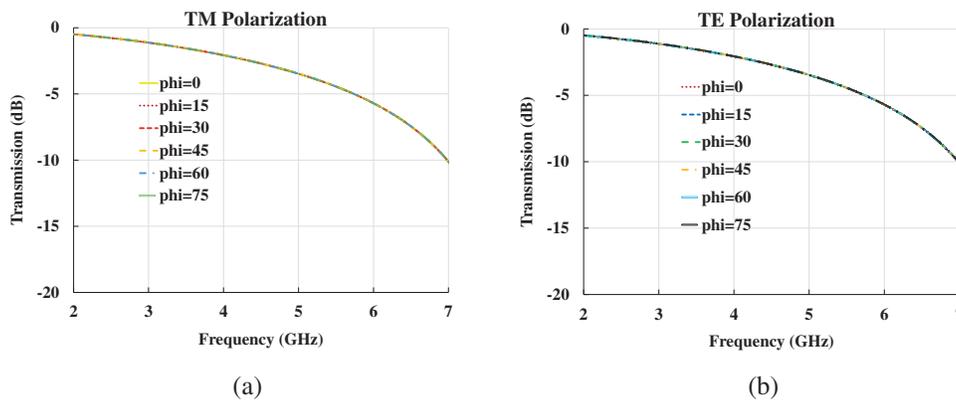
Figure 11: Transmission response of proposed meta surface for (a) TM polarization (b) TE polarization

Tab. 1 compares the antenna gain of different metamaterial based microstrip antennas with the gain of the proposed antenna. it is evident that the proposed antenna with metamaterial is more compact and low profile as compared to the previous reported work. The proposed antenna achieves a gain of 7.68 dBi with compact and less number of MTM unit cells with a profile of 13 mm.

Table 1: Comparison of different metamaterial based microstrip antennas with the proposed antenna

Ref	MTM unit cell size (mm³)	MTM array size	Height of MTM (mm)	Antenna gain (dBi)
[21]	$6 \times 6 \times 0.8$	$7 \times 7 \times 3$	23	7.8
[22]	$8.5 \times 8.5 \times 1.6$	$3 \times 3 \times 1$	3.2	5.02
[23]	$7 \times 7 \times 1.52$	$7 \times 7 \times 2$	28.4	7.1
[24]	$7 \times 9 \times 0.813$	$7 \times 7 \times 4$	19	17.1

(Continued)

Table 1: Continued

Ref	MTM unit cell size (mm³)	MTM array size	Height of MTM (mm)	Antenna gain (dBi)
[26]	$4.4 \times 4.5 \times 1.8$	$7 \times 7 \times 1$	35	7.65
This work	$5 \times 5 \times 0.4$	$4 \times 4 \times 1$	13	7.68

5 Conclusion

In this paper, a novel MTM design for the gain enhancement of a sub-6 GHz microstrip antenna resonating at 4.8 GHz is proposed. The MTM unit cell has a fourfold symmetry which makes it a polarization independent MTM. The MTM is acting as an Epsilon-Near-Zero (ENZ)-Mu-Very-Large (MVZ) MTM around 4.8 GHz. A 4×4 array of MTM unit cells is imposed as a superstrate on the source MPA. Using MTM superstrate, the gain of the source antenna is enhanced by 2.38 dBi. The measurement results match well with simulation results. The resonance frequency of the antenna lies in the sub-6 GHz band so the proposed antenna design can be used for 5G applications.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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