International Journal of Engineering and Applied Science October 6 University
https://ijeasou.journals.ekb.eg/
Online ISSN 3009-6448
Volume (2),Issue(2)
July 2025, pp:92-98

A Study on the Impact of Metamaterials on Performance of Antennas in Millimeter-Wave Networks.

Islam Osama[1,2*], Mohamed Elhefnawy [1], Ahmed Yahya[2]

1 Department of Electrical Engineering, Faculty of Engineering, October 6 University, 6th of October City, 12585, Giza, Egypt.
2 Department of Electrical Engineering, Faculty of Engineering, Al-Azhar University, Nasr City, 11884, Cairo, Egypt

* Corresponding author's email: islam_osama86.eng@o6u.edu.eg
https://doi.org/ 10.21608/ijeasou.2025.390028.1059

Received:28-05-2025
Accepted:1-07-2025
Published:07-07-2025

Abstract:
In fifth generation (5G) and later networks, the growing demand for high data rates in modern wireless communication systems has established millimeter-wave (mm-wave) frequencies as a fundamental resource. Nevertheless, especially regarding gain, bandwidth, and efficiency, conventional antenna designs usually find it difficult to meet the strict performance criteria at these high frequencies. Artificially designed objects with electromagnetic properties not usually found in nature have become a good way to solve these limitations: metamaterials. This paper presents a systematic mini-review of metamaterial-based performance enhancements in millimeter-wave antenna systems, focusing on key metrics such as gain, efficiency, and bandwidth. The analysis covers several approaches applied in the design and evaluation of mm-wave antennas enhanced by metamaterials, including advanced computational modeling and experimental characterizing methods. With some cases spanning 60% of the operational frequency range, literature reveals amazing increases in antenna gain—often above 13 dBi—and significant bandwidth gains. Furthermore, metamaterials have shown great radiation efficiency; in some cases, they reach 94% in particular configurations. Surface wave suppression, negative refractive index, and the development of resonant cavities—among other unique electromagnetic manipulating characteristics of metamaterials—are credited with the performance improvements. These developments have important consequences for the future of mm-wave communication systems since they enable more reliable and effective high data transfer over several applications, including radar systems, wearable technologies, and cellular networks, which emphasizes possible future directions for research and development in this fast-advancing field.

Keywords:
Metamaterials, Millimeter-wave, Gain, Bandwidth, Efficiency

1 Introduction

Fifth generation (5G) wireless communication technologies, which are largely enabled by the use of the millimeter-wave (mm-wave) frequency spectrum, have brought an era of unprecedented data rates and network capacity [1]. The higher frequencies, typically between 30 GHz and 300 GHz, offer a significant amount of unused bandwidth that is necessary to support bandwidth-demanding applications and the growing needs of networked devices [2]. However, mm-wave transmissions' inherent characteristics, such as increased path loss and susceptibility to atmospheric attenuation, pose significant challenges for traditional antenna designs [3]. Antennas with outstanding performance in gain, bandwidth, efficiency, and radiation properties are crucial for making the most of mm-wave networks' potential [4]. Considering these issues, metamaterials have attracted much interest as a groundbreaking category of artificially designed materials [1, 5-7]. Metamaterials, composed of periodic arrangements of sub-wavelength structures called unit cells, display distinctive electromagnetic properties absent in natural materials. These characteristics, such as the capacity to demonstrate negative permittivity and permeability, provide unparalleled manipulation of electromagnetic waves. Thus, metamaterials possess significant potential to improve the efficacy of antennas functioning in mm-wave networks [8]. The present research landscape of scholarly inquiry in this domain encompasses a diverse array of examinations pertaining to the design, fabrication, and characterization of metamaterial-enhanced millimeter-wave antennas. A multitude of research efforts have investigated various metamaterial configurations, including split-ring resonators (SRRs), meta-surfaces, and electromagnetic band gap (EBG) structures, alongside their integration with an assortment of antenna types, such as patch antennas, dipole arrays, and Vivaldi antennas.

Meta-surface is defined as two -dimensional thin surfaces that consist of sub-wavelength elements, it can offer powerful abilities in controlling the dimensions, phases and polarization of electromagnetic waves, leading to significant improvement in antenna gains and bandwidth. Electromagnetic band gap structures are another class of metamaterial used to suppress surface waves and improve antenna efficiency.

Comprehensive literature reviews and systematic surveys furnish critical contextual information regarding metamaterials, millimeter-wave technology, and their synergistic application in antenna systems, thereby elucidating the prospective advantages and challenges associated with their use [7, 9]. Despite significant advancements, the complete potential of mm-wave capabilities is sometimes hindered by constraints in traditional antenna designs. These limitations encompass low gain, restricted bandwidth, and diminished efficiency, particularly when considering the compact form factors required for several applications. paper [6] aims to address the knowledge gap by meticulously analyzing the diverse methodologies and numerical performance enhancements enabled by the incorporation of metamaterials into millimeter-wave antennas.

The integration of metamaterials with MIMO (Multi-output) antenna arrays is also an important research area, which promises high data rates and better network capacity in the mm-wave system.

The purpose of this paper is to: (1) review the various experimental and theoretical methods used to investigate metamaterial-enhanced mm-wave antennas; (2) present a thorough analysis of the performance improvements reported in the literature, with a focus on gain, bandwidth, efficiency, and radiation patterns; (3) investigate the mechanisms underlying these improvements; and (4) highlight the opportunities for the future and present challenges in this rapidly developing field.

The structure of this paper will continue with a study on the influence of integrating the metamaterials on the gain, bandwidth, and radiation efficiency of the antennas. Followed by a comparison between the previously published works on the integration of the metamaterial structures with the antennas. Finally, the benefits and challenges of implementing the metamaterial antennas with the future wireless communication systems are discussed.

2 Methodological in Metamaterial Antenna Research for Millimeter-Wave Applications

Experimental studies often use refined measurement techniques to mark the performance of fabricated antennas. The vector Network analyzer (VNA) is used to measure impedance and S-parameters at mm-wave frequencies. To determine the radiation patterns characteristics, the metamaterial antennas should be measured inside anechoic Chambers. Compact antenna Test Range (CATR) is also utilized to measure antennas working on these frequencies [10].

Theoretical and simulation methods play an important role in the design and analysis process equally. Full-wave electromagnetic simulators, such as CST Microwave Studio and ANSYS HFSS, are used solidly and massively to simulate their interaction with the behavior and antennas of metamaterial structures. These software tools allow researchers to analyze antenna properties such as S-parameters, bandwidth, gains, and radiation patterns under different design parameters. Other simulation equipment, including Remcom's XFTD and Comsol Multiphysics, is also used for specific aspects of metamaterial and antenna design. Complex geometric and electromagnetic interactions are inherent in metamaterial-based designs, which require the use of such advanced calculation simulators to adapt to performance and accurately predict behavior [11].

In addition, the full-wave simulators exhibit design optimization techniques, such as parameter sweeping and adaptation algorithms, are used to obtain the optimum dimensions of the simulated antennas to achieve the desired performance properties such as maximum gain at specific mm-wave frequencies and wide bandwidth [8, 9].

2.1 Gain Enhancement Achieved Through Metamaterial Integration

Integration of metamaterials has shown significant improvement in the performance of the mm-wave antennas. For example, the use of meta-surface with the feeding mm-wave antenna improved the gain by more than 13 dbi at 28 GHz as illustrated in figures (1) and (2) [8]. Similarly, figure 3 shows a microstrip antenna integrated with a meta-surface consisting of the split ring resonators (SRR) unit cells to improve the antenna gain by an increase of approximately 4.8 dBi [12].

A series-fed antenna employing metamaterial unit cells was reported in [13] to achieve a maximum gain of 14.1 dBi at 30.5 GHz as shown in figure 4. A metamaterial-integrated dipole array antenna achieved a peak gain of 11.21 dBi as illustrated in figure 5, representing an enhancement of more than 3 dBi compared to the dipole array alone [3]. Figure 6 shows the use of epsilon-near-zero metamaterial unit cells embedded in a Vivaldi antenna resulted in a gain ranging from 14 to 17.2 dBi in the Ka band (23 GHz to 40 GHz) [14]. Furthermore, optimized metamaterials integrated with a bow-tie antenna array achieved a maximum gain of 11.2 dB at 29 GHz [15]. The improvement in the antenna gain emphasizes the effectiveness of metamaterials integration to increase the directional properties of the mm-wave-antennas and overcome path loss of these frequencies.

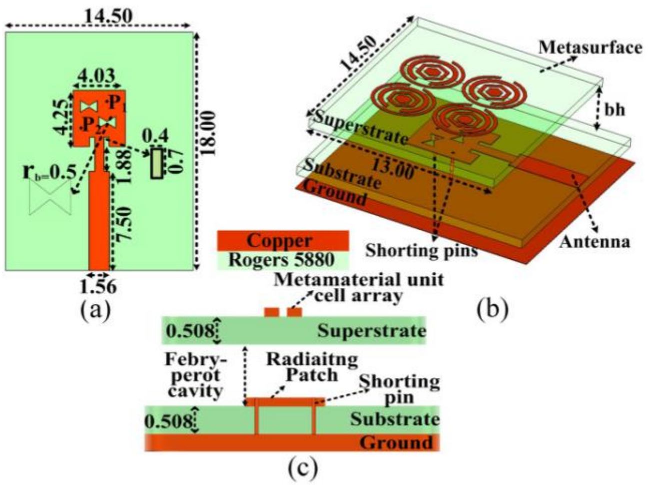

Fig.1. (a) Top view of the patch antenna with short pins. (b) Isometric view of the meta-surface antenna incorporating pins (c) Side view of the pin-loaded meta-surface antenna [8] .

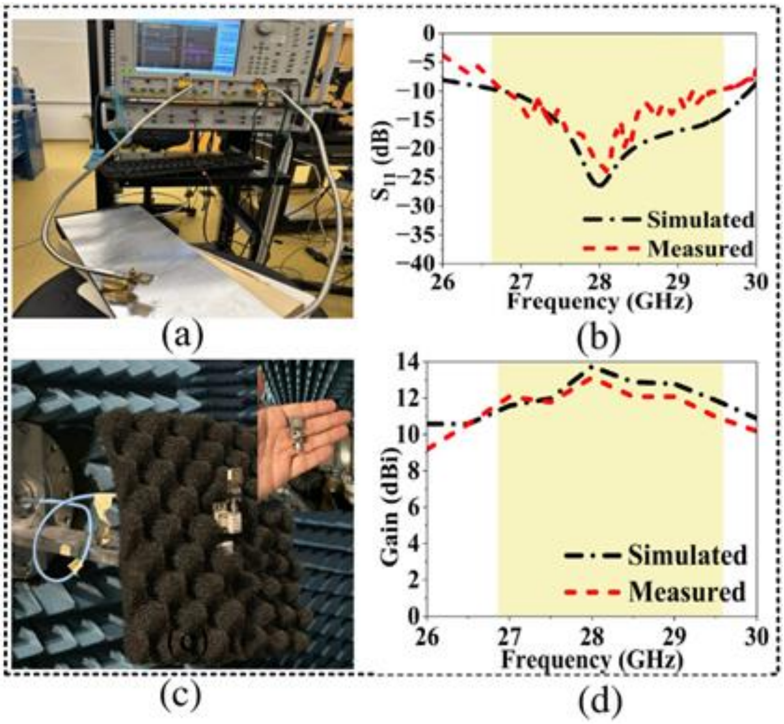

Fig.2. (a) Setup for S11 measurement. (b) Comparison plot of simulated and measured S11 values. (c) Configuration for radiation pattern measurement. (d) Graphs showing simulated versus measured gain results[8].

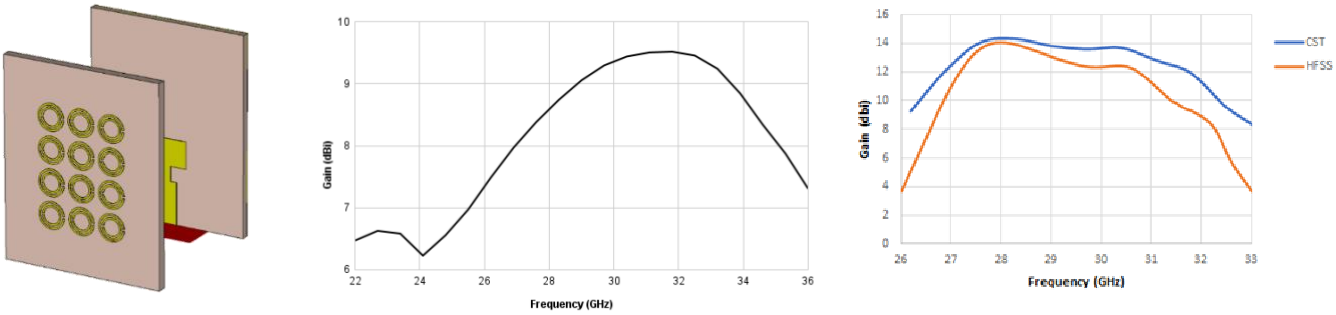

Fig.3. Proposed design, gain of the patch antenna without metamaterial, and gain of the patch antenna enhanced with metamaterial [12]

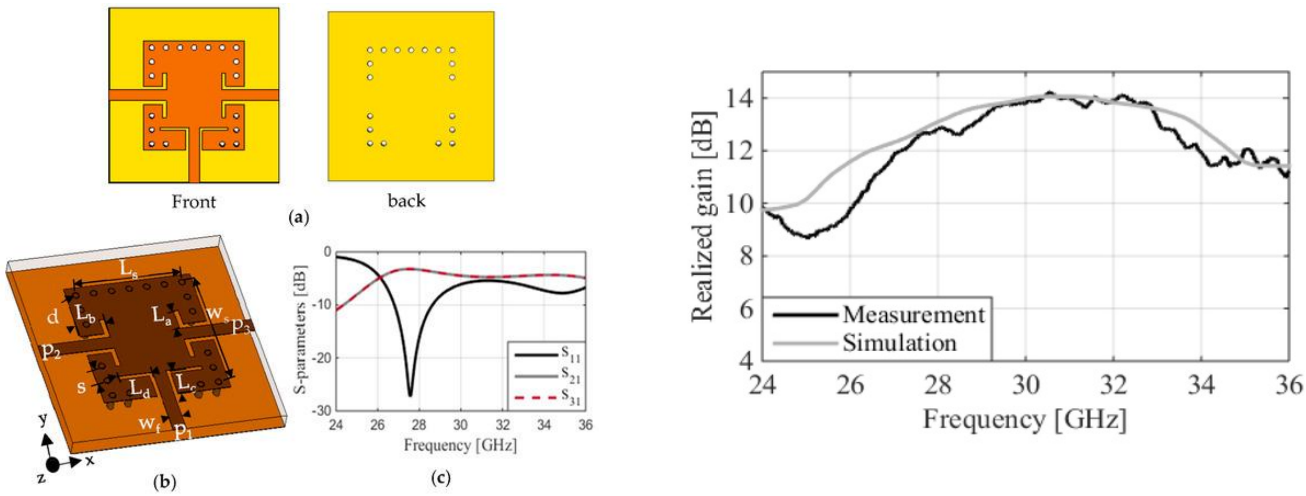

Fig.4. SIW power splitter setup and performance: (a) front and rear views, (b) structural layout along with simulated and measured antenna gain [13].

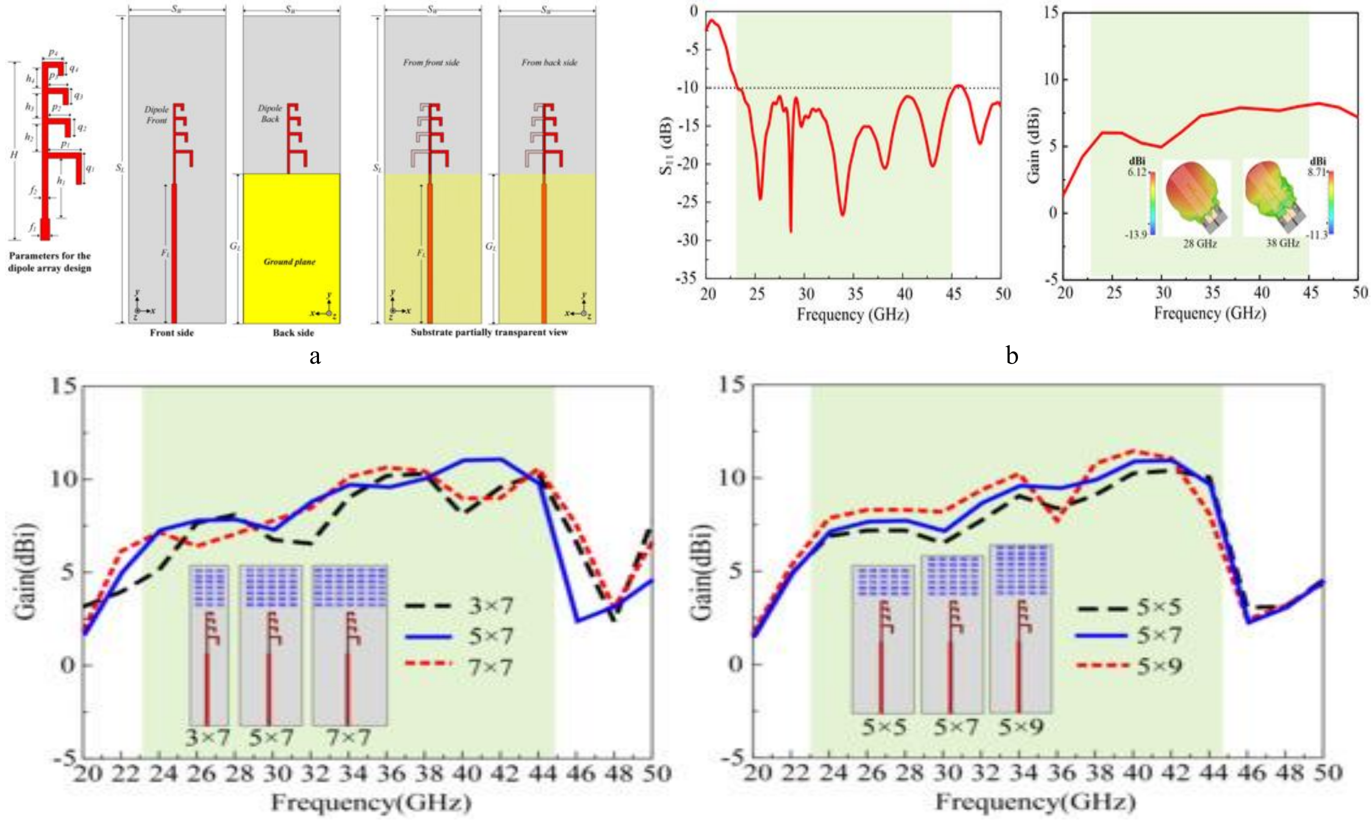

Fig. 5: Dipole array antenna: (a) views of each side and semi-transparent view showing the substrate. (b) Performance analysis includes reflection coefficient, and gain and 3D directivity at 28 GHz and 38 GHz. (c)The antenna's gain response is also examined with varying numbers of metamaterial cells: in the horizontal direction and in the vertical direction[3].

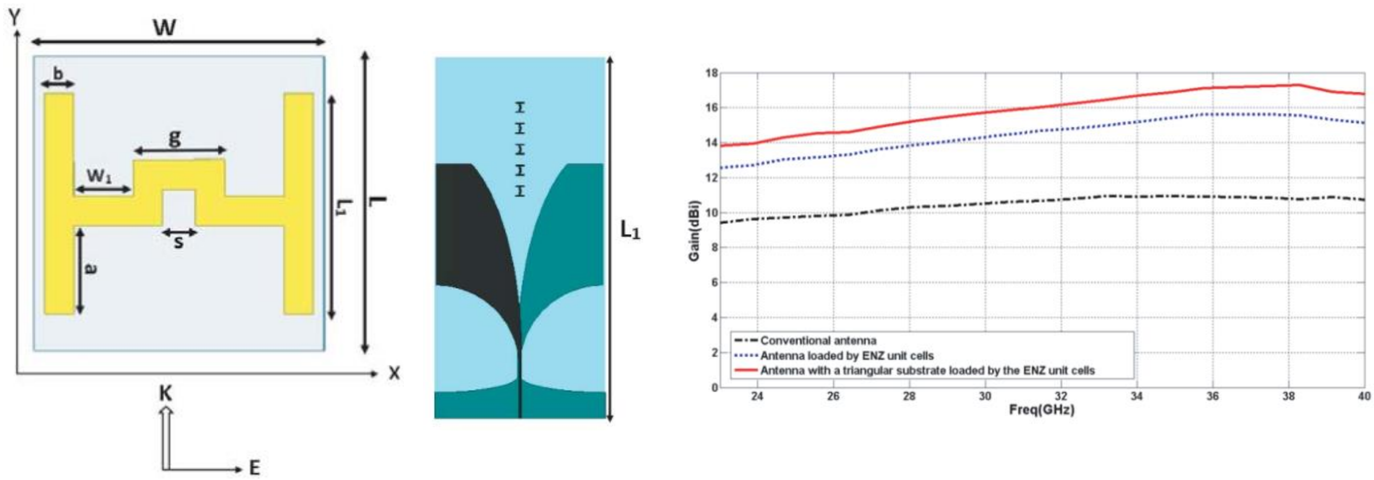

Fig.6. Structure of the proposed ENZ metamaterial unit cell, Modified Vivaldi antennas incorporating the ENZ unit cell, and a comparison of antenna gain between the conventional Vivaldi antenna and the two modified designs[14].

2.2 Bandwidth Enhancement Achieved Through Metamaterial Integration

Beyond gain enhancement, metamaterials have also contributed to significant improvements in antenna bandwidth. The integration of metamaterial with a series-fed dipole antenna array improved the frequency bandwidth and achieved a wide frequency range of 23.1 GHz to 44.8 GHz [3]. The previously reported metamaterial dipole array in [3] offered an operating bandwidth of more than 21 GHz (63.92%) that bandwidth can cover the 5G mm-wave frequency bands, as shown in figure 7. A microstrip antenna with a metamaterial surface showed bandwidth enhancement of 2.25% and 6.21% in separate simulation software [12]. An antipodal Vivaldi antenna with embedded epsilon near zero metamaterial unit cells demonstrated an ultra-wide bandwidth from 23 GHz to 40 GHz as indicated in figure 8 [14].

2.3 Efficiency Enhancement Achieved Through Metamaterial Integration

Efficiency is another critical antenna performance parameter that can be enhanced by metamaterial integration. Metamaterial inspired millimeter-wave antenna arrays have demonstrated high total efficiencies, reaching up to 95.87% [4]. A meta-surface-inspired antenna achieved a maximum radiation efficiency of around 94% at 28 GHz [8]. millimeter wave broadband MIMO antenna reported a radiation efficiency above 87% using meta-surfaces [16]. These high efficiency values suggest that metamaterials can help reduce losses and maximize radiation power by mm-wave antennas. Metamaterials also provide the ability to manipulate antenna radiation patterns. Figure 9 shows a series-fed dipole antenna with metamaterials, the proposed antenna performed symmetrical dual-beam E-plane radiation at ±20° at 28 GHz [13]. Integrated metamaterials with a bow-tie antenna array also showed symmetrical radiation [15]. The ability to control and shape radiation patterns is important for different applications, including radiation control and spatial multiplexing in mm-wave Network.

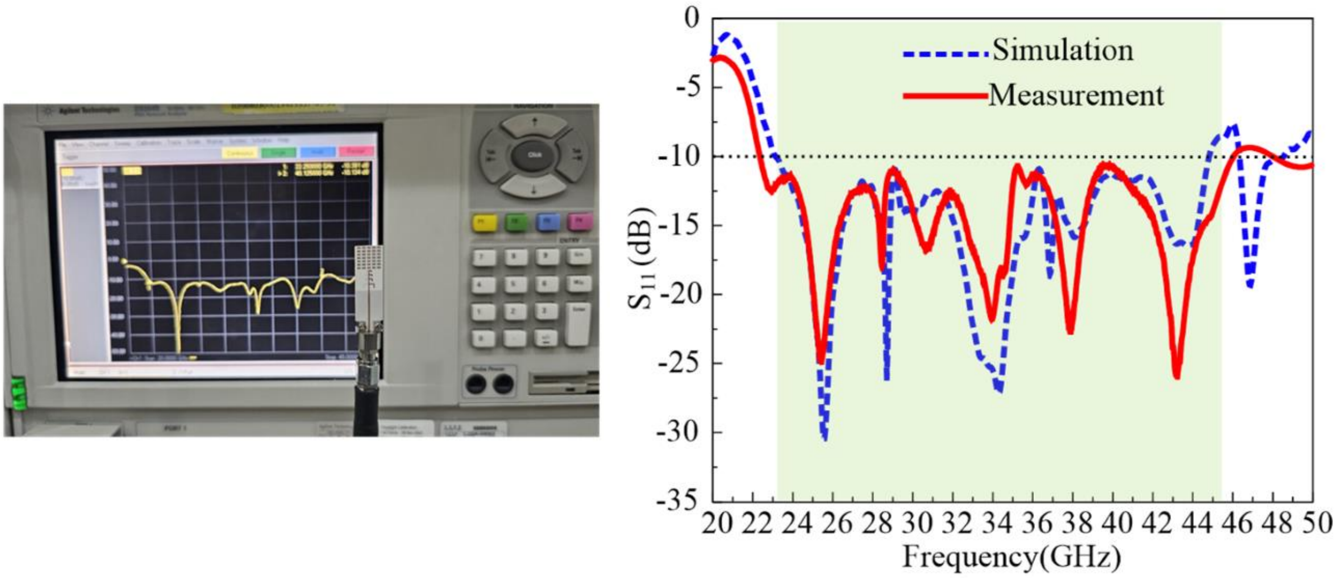

Fig.7. The reflection coefficient of the dipole array antenna incorporating metamaterial [3].

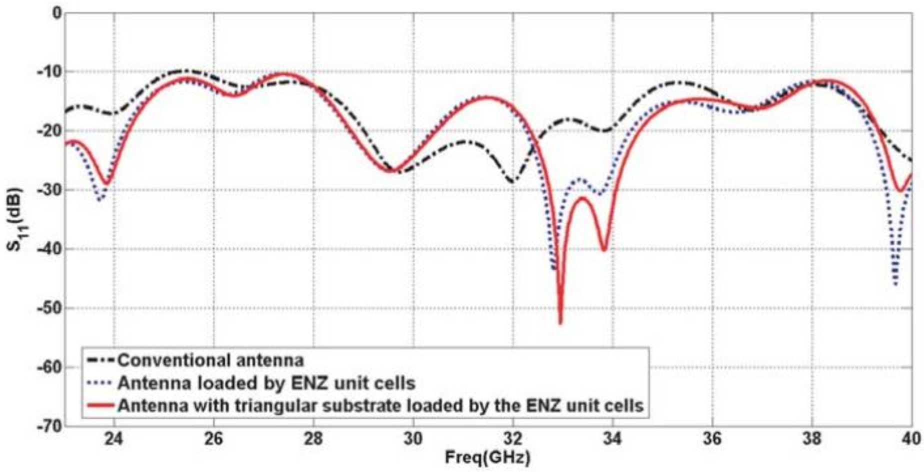

Fig.8.Reflection coefficient comparison of the conventional Vivaldi antenna and the two modified designs [14]

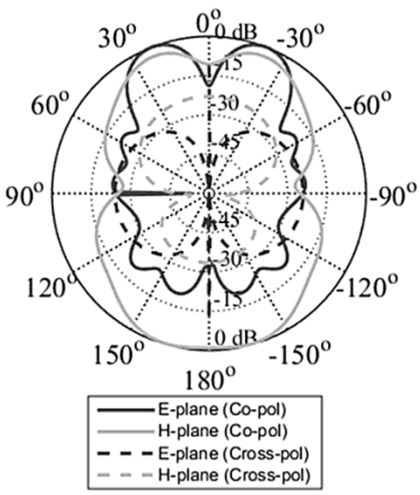

Fig. 9. E- and H-plane radiation patterns of the series-fed antenna operating at 28 GHz [13]

Table 1 Performance Comparison of Metamaterial-Enhanced Milli-meter-Wave Antennas

Reference	Metamaterial Structure Type	Operating Frequency (GHz)	Gain (dBi)	Bandwidth (GHz or %)	Efficiency (%)	Application Area
[3]	Metamaterial Array	23.1-44.8	11.21	63.92%	>64	5G
[4]	MIA Arrays	38	7.36-11.4	1.971-4.704 GHz	94.01-95.87	5G
[8]	Meta-surface	28	>13	Wide	~94	5G
[11]	NIM Superstrate	28	13.5	-	-	5G
[12]	SRR Metamaterial	28.5	~14.34	7.89% 27.51 - 29.76	-	5G
[13]	mm Unit Cells	26.9-34.75	9-10.5	7.85 GHz	-	5G
[14]	ENZ Unit Cells	23-40	14-17.2	Ultra-wide	-	5G
[15]	Optimized mm Array	26.5-29.5	11.2	Broad	-	5G
[16]	Meta-surfaces	23.9-30.7	9.4	Wide	>87	5G

To provide a consolidated view of performance improvement achieved through metamaterial integration in mm-wave antennas, Table 1 summarizes important conclusions from selected studies.

3 Discussion

The quantitative results presented in the previous section highlight the significant effect of metamaterials on improving the performance of the antenna operated in the millimeter wave network. Compared to traditional antenna design, metamaterial-based antennas continuously offer better performance in terms of high gain, wide bandwidth and high radiation efficiency. The mechanisms that metamaterials receive these improvements are versatile. The capacity of the metamaterial to suppress the surface waves reduces unwanted radiation and improves efficiency. Reflections in phase from metamaterials surfaces can increase further gain. High impedance surfaces provided by metamaterials can improve impedance matching and bandwidth. The negative refraction index displayed by some metamaterials can be utilized to focus on electromagnetic energy, leading to high advantages. In addition, the meta-surface can be designed to create a Fabry-Perot cavities over the antenna. Selected types of metamaterials can also change current distribution on radiation patches, increase the fringe parts and improve the radiation properties. Various metamaterial structures used in these studies, including SRR unit cells, meta-surfaces and ENZ (Epsilon-near-zero) structures, indicate that researchers are looking for different approaches to manipulate electromagnetic waves for antenna enhancement. The alternative with a particular structure often depends on specific performance requirements and intended applications. For example, meta-surfaces provide high levels of control over electromagnetic wave properties and are particularly effective for obtaining high gain and wide bandwidth in compact designs. SRR, with its resonance properties, can be tailored to specific frequency bands and used for miniature and bandwidth enhancement. While literature shows the benefits of metamaterials, there are some challenges and deviations. Providing broadband performance throughout the mm-wave spectrum is still an ongoing research area. There may be tradeoffs between different performance parameters, such as achieving a very high gain on the expense of bandwidth. In addition, the construction of complex metamaterial structures, especially at mm-wave frequencies where functional sizes are very low, can be challenging and can affect the total costs and practical conditions of these antennas. Integration of metamaterial can also affect other antenna properties, such as size and weight.

Conclusions

The study explores the effect of metamaterials on antenna performance in the millimeter wave network, which reveals their ability to cross the boundaries of traditional designs. High antenna gain, wide operational bandwidth, and high radiation efficiency are important for efficient implementation of the next generation of wireless communication systems. Furthermore, this study also indicates that metamaterial-enhanced mm-wave antennas could be useful in various fields such as cellular networks, portable devices, advanced radar, and regular communication systems, providing higher data rate, more capacity, improved control, and greater accuracy. Finally, future research should address limitations and investigate the metamaterials ability to offer wide bandwidths. It is important to simplify the antenna structure and reduce the overall costs. Integration of metamaterials with new technologies such as reconfigurable antennae can lead to more versatile mm-wave communication systems.

References

[1] S. Kumar and H. Singh, "A Comprehensive Review of Metamaterials/Metasurface-Based MIMO Antenna Array for 5G Millimeter-Wave Applications," *Journal of Superconductivity and Novel Magnetism,* vol. 35, no. 11, pp. 3025-3049, 2022.

[2] F. Wu, "Research on the Application of Novel Antenna Design in Millimeter-Wave Communication,"

Computing, Performance and Communication Systems, vol. Viol. 8: 25-30, 2024.
[3] D. Choi, M. A. Sufian, J. Lee, W. A. Awan, Y. Choi, and N. J. A. S. Kim, "Advanced Metamaterial-Integrated Dipole Array Antenna for Enhanced Gain in 5G Millimeter-Wave Bands," vol. 14, no. 19, p. 9138, 2024.
[4] I. T. N. Moti G. Beyene, "Metamaterial Inspired Millimeter-Wave Antenna Arrays for 5G Wireless Applications," *International Journal of Wireless and Microwave Technologies(IJWMT),* vol. Vol.15, no. No.1, pp. pp. 40-50, 2025.
[5] B. J. F. i. A. Virdee and Propagation, "Grand challenges in metamaterial antennas," vol. 1, ed: Frontiers Media SA, 2022.
[6] H. Al-Tayyar and Y. M. J. A.-R. E. J. Ali, "A Review on Metamaterial Used in Antennas Design: Advantages and Challenges," vol. 29, no. 1, pp. 106-117, 2024.
[7] M. Hussain, W. A. Awan, M. S. Alzaidi, N. Hussain, E. M. Ali, and F. Falcone, "Metamaterials and Their Application in the Performance Enhancement of Reconfigurable Antennas: A Review," (in eng), *Micromachines,* vol. 14, no. 2, Jan 30 2023.
[8] S. Tariq, W. T. Sethi, A. A. Rahim, F. Faisal, and T. Djerafi, "A metasurface assisted pin loaded antenna for high gain millimeter wave systems," (in eng), Scientific reports, vol. 15, no. 1, p. 12056, Apr 8 2025.
[9] R. Aggarwal, A. Roy, and R. J. P. E. R. B. Kumar, "Millimeter wave antennas: A state-of-the-art survey of recent developments, principles, and applications," vol. 104, no. January, pp. 147-169, 2024.
[10] G. I. J. P. I. E. R. L. Sajin, "Impedance measurement of millimeter wave metamaterial antennas by transmission line stubs," vol. 26, pp. 59-68, 2011.
[11] R. S. Aziz, S. Koziel, and A. J. S. R. Pietrenko-Dabrowska, "Millimeter wave negative refractive index metamaterial antenna array," vol. 14, no. 1, p. 16037, 2024.
[12] P. Mishra, R. Komatineni, and K. D. Kulat, "Millimeter Wave MPA using Metamaterial-Substrate Antenna Array for Gain Enhancement," in *2023 National Conference on Communications (NCC)*, 2023.
[13] B. A. Esmail, S. Koziel, and D. J. E. Isleifson, "Metamaterial-Based Series-Fed Antenna with a High Gain and Wideband Performance for Millimeter-Wave Spectrum Applications," vol. 12, no. 23, p. 4836, 2023.
[14] S. El-Nady, H. M. Zamel, M. Hendy, A. A. Zekry, and A. J. P. I. E. R. C. Attiya, "Gain enhancement of a millimeter wave antipodal vivaldi antenna by epsilon-near-zero metamaterial," vol. 85, pp. 105-116, 2018.
[15] Esmail, Bashar AF, and Slawomir Koziel. "Design and optimization of metamaterial-based highly-isolated MIMO antenna with high gain and beam tilting ability for 5G millimeter wave applications." *Scientific Reports* 14.1 2024: 3203..
[16] T. N. Cao *et al.*, "Millimeter-wave broadband MIMO antenna using metasurfaces for 5G cellular networks," vol. 2023, no. 1, p. 9938824, 2023.