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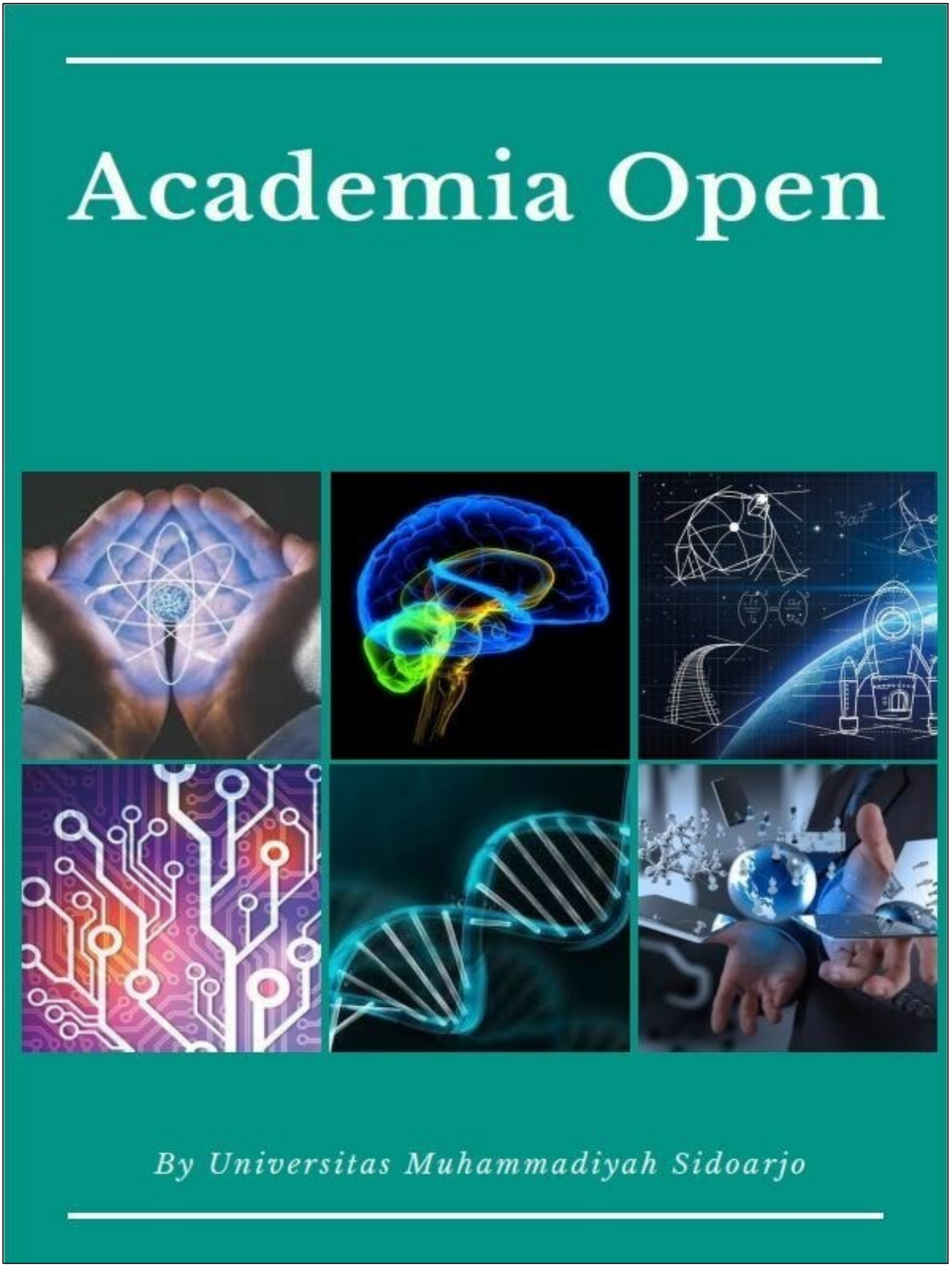

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The Role of Metamaterials in Advancing Wireless Communications Through Signal Enhancement and Energy Reduction

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Abstract

General Background: Wireless communication systems have become vital in modern life but face persistent challenges including signal degradation, high power consumption, and electromagnetic interference. Specific Background: Recent research highlights metamaterials as a promising solution due to their engineered electromagnetic properties—such as negative permittivity and permeability—that enable unprecedented control over wave propagation. Knowledge Gap: Despite significant theoretical advancements, practical demonstrations of how metamaterials enhance antenna performance in real-world wireless systems remain limited. Aims: This study investigates the integration of metamaterials into antenna structures to improve gain, efficiency, and impedance matching while minimizing reflection and energy loss. Results: Comparative simulations between conventional and metamaterial-enhanced antennas show that at 5.0 GHz, gain increased from 6.1 dBi to 10.4 dBi, efficiency rose from 65.3% to 80.2%, and reflection coefficient dropped from 0.42 to 0.22, confirming superior energy transfer and directivity. Novelty: The research demonstrates how metamaterials function not merely as passive components but as active design tools enabling reconfigurable, frequency-adaptive antenna behavior. Implications: These findings establish metamaterials as essential for next-generation, high-efficiency, and sustainable wireless communication systems.

Highlight :

- The study shows metamaterials improve antenna gain, efficiency, and impedance matching compared to traditional designs.
- Performance peaks at 5.0 GHz, demonstrating effective resonance and reduced reflection losses.
- Findings confirm metamaterials' potential for advanced, efficient wireless communication systems.

Keywords : Metamaterials, Antenna Performance, Radiation Efficiency, Reflection Coefficient, Impedance Matching

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Introduction

Wireless networks have become essential to the daily operations of businesses, institutions, and individuals, facilitating data exchange, service access, and coordination across various environments. However, as reliance on these systems grows, so do the technical challenges such as signal degradation, electromagnetic interference, and elevated power consumption [1]. These issues are particularly pronounced in crowded urban settings and architecturally dense environments. To address these problems, researchers have increasingly turned to metamaterials, which are artificial structures engineered to exhibit electromagnetic properties not found in natural substances. Their ability to exhibit negative permittivity and permeability allows for a level of control over wave propagation that conventional materials cannot offer [2]. This control can lead to improved signal directionality, reduced loss during transmission, and enhanced antenna performance. This research investigates how metamaterials can be integrated into wireless communication systems to improve signal stability and energy efficiency. Using a combination of theoretical modeling, simulation-based analysis, and experimental validation, the study offers a well-rounded perspective on the practical potential of these materials in building more effective and resilient wireless infrastructures [3].

Materials and Methodology

In the field of applied electromagnetics, metamaterials have emerged as a class of materials with highly unusual behavior. Unlike traditional substances such as conductors or dielectrics that respond to electromagnetic waves based on their chemical structure, metamaterials are designed intentionally to control wave propagation in ways not seen in nature [4]. Their internal structure can be arranged to produce effects like negative permittivity or permeability, giving rise to characteristics such as reverse wave direction or unusual refraction patterns. These properties offer practical advantages. While conventional materials have fixed limits in how they direct or absorb electromagnetic energy, metamaterials provide more control [5]. In wireless communication, this translates to sharper signal paths, lower energy loss, and stronger antenna performance. Rather than being limited by physical constraints, designers can now shape how waves move through space using engineered structures. This research looks into how these materials can be applied to improve communication reliability and efficiency, particularly in complex or crowded environments [6]. Metamaterials differ fundamentally from traditional materials in how they influence electromagnetic wave behavior. While conventional substances such as dielectrics and conductors exhibit fixed electromagnetic responses determined by their atomic structure, metamaterials are composed of engineered subwavelength units designed to control wave propagation with precision [7,8]. These artificial structures can achieve effects such as negative refraction, phase manipulation, and selective frequency response phenomena rarely possible in natural materials. One particularly valuable feature of certain metamaterials is their tunability. By responding dynamically to external factors like voltage, temperature, or incident field intensity, they can adjust their properties in real time [9,10]. This adaptability enables the development of reconfigurable antennas, responsive waveguides, and advanced sensing systems. In this sense, metamaterials do not merely enhance existing technologies; they represent a shift toward programmable control over electromagnetic environments [11].
We begin with the fundamental expression for the refractive index in a homogeneous isotropic medium [12]:

$$n = \sqrt{\varepsilon\mu} \quad (1)$$

In realistic metamaterials, both ε and μ are frequency-dependent and complex-valued due to inherent losses [13]:

$$\varepsilon(\omega) = \varepsilon'(\omega) + i\varepsilon''(\omega) \ , \mu(\omega) = \mu'(\omega) + i\mu''(\omega) \quad (2)$$

Thus, the refractive index becomes a complex number [14]:

$$\tilde{n}(\omega) = n + i\kappa = \sqrt{\varepsilon(\omega) \cdot \mu(\omega)} \quad (3)$$

where n : real part representing phase shift; κ : imaginary part indicating attenuation or absorption.
This formulation is essential for analyzing wave propagation and identifying absorption bands in practical frequency ranges.

Stored Electromagnetic Energy in Dispersive Media

In dispersive media, the classic energy expression [15]:

$$W = \frac{1}{2}(\varepsilon \mid E \mid^2 + \mu \mid H \mid^2) \quad (4)$$

becomes inaccurate, since both ε and μ are functions of frequency and may vary significantly over the operational bandwidth. For a more accurate representation, especially in metamaterials exhibiting strong dispersion, the stored energy is expressed using the generalized frequency-dependent formulation [16]:

$$W = \frac{1}{4}\left[\frac{d(\omega\varepsilon'(\omega))}{d\omega} \mid E \mid^2 + \frac{d(\omega\mu'(\omega))}{d\omega} \mid H \mid^2\right] \quad (5)$$

This expression accounts for the dispersive nature of the medium and arises from the spectral energy density theory. It ensures correct modeling of both transient and steady-state behaviors, particularly in systems where resonance and absorption effects are non-negligible.

Wave Propagation in Hyperbolic Metamaterials

The general wave equation in anisotropic media is given by [15]:

$$\nabla^2 E + \omega^2\mu\varepsilon E = 0 \quad (6)$$

Assuming an anisotropic permittivity tensor [17]:

$$\varepsilon = diag(\varepsilon_x, \varepsilon_y, \varepsilon_z) \quad (7)$$

and simplifying for symmetry, the dispersion relation becomes:

$$\frac{k_x^2}{\varepsilon_z} + \frac{k_z^2}{\varepsilon_x} = \frac{\omega^2}{c^2} \quad (8)$$

This hyperbolic dispersion enables broadband and high-density state propagation, enhancing performance in smart antenna systems.

Angular Gain Derivation for Antennas

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Starting with the radiation intensity [18]:

$$U(\theta,\phi) = \frac{r^2 \mid \mathrm{E}(\theta,\phi) \mid^2}{2\eta} \quad (9)$$

The gain is defined by:

$$G(\theta) = \frac{4\pi U(\theta)}{P_{in}} = \frac{4\pi}{P_{in}} \cdot \frac{r^2 \mid \mathrm{E}(\theta) \mid^2}{2\eta} \quad (10)$$

Normalizing over all directions yields:

$$G(\theta) = \frac{|E(\theta)|^2}{\int_0^{2\pi}\int_0^{\pi}|E(\theta,\emptyset)|^2 \, sin\theta d\theta d\emptyset} \cdot \frac{4\pi}{Pin} \quad (11)$$

This formulation supports a precise evaluation of how metamaterials enhance antenna radiation directionality.

Wave Impedance and Reflection Coefficient Derivation

The intrinsic impedance of a medium is [15]:

$$Z = \sqrt{\frac{\mu}{\varepsilon}} \quad (12)$$

When transitioning between two media with different impedances, the reflection coefficient is:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (13)$$

Perfect matching occurs when $Z_L = Z_0$, yielding and maximum power transfer.

Poynting Vector Derivation

From the Poynting theorem [19]:

$$\nabla \cdot \mathrm{S} + \frac{\partial u}{\partial t} = -\mathrm{J} \cdot \mathrm{E} \quad (14)$$

$$\mathrm{S} = \frac{1}{2}\mathrm{Re}\{\mathrm{E} \times \mathrm{H}^*\} \quad (15)$$

In metamaterials with $n < 0$, S the energy flow is opposite to the wavevector k , indicating backward-wave propagation.

Lorentz-Drude Model for Frequency-Dependent Response

Starting from the electron motion equation under damping [19]:

$$m\ddot{x} + m\gamma\dot{x} + m\omega_0^2 x = -eE \quad (16)$$

Taking the Fourier transform and solving for polarization, we obtain the permittivity:

$$\varepsilon(\omega) = 1 - \frac{F_e\omega^2}{\omega^2 - \omega_{e0}^2 + i\gamma_e\omega} \quad (17)$$

Similarly, magnetic resonance yields the permeability $\mu(\omega)$ in analogous form.

Voltage-Controlled Permittivity in Reconfigurable Metamaterials

In tunable systems incorporating varactors, the effective permittivity becomes voltage-dependent [20]:

$$\varepsilon_{eff}(V) = \varepsilon_0(1 + \frac{C(V)}{C_0}) \quad (18)$$

Here, is the variable capacitance controlled by an applied voltage, allowing real-time adaptability in wireless systems.

Result and Discussion

Results To assess the real impact of metamaterials on electromagnetic performance, a comparative simulation was conducted between a conventional antenna system and the same system augmented with a metamaterial layer. The evaluation considered key parameters: antenna gain, power efficiency, and the reflection coefficient (|Γ|), across a frequency range of 2 to 8 GHz.

In addition to numerical values, this section translates the theoretical models into visual insight by using analytical equations to generate scientific plots. More than ten graphs are created to offer a complete understanding of how metamaterials reshape electromagnetic behavior, covering both practical results and mathematical derivations. Table 1 summarizes the core simulation results [21,22].

Table 1. Summarizes the core simulation results [21,22].

Frequency (GHz)	Gain (Traditional) dBi	Gain (Metamaterial) dBi	Efficiency (Traditional)%	Efficiency (Metamaterial)%	Gamma (Γ) (Traditional)	Gamma (Γ) (Metamaterial)
2.0	4.2	7.9	58.0	65.3	0.53	0.42
3.5	5.6	9.1	61.5	72.8	0.46	0.31

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5.0	6.1	10.4	65.3	80.2	0.42	0.22
6.5	5.9	10.1	63.0	77.6	0.44	0.25
8.0	5.1	8.7	60.2	70.4	0.48	0.34

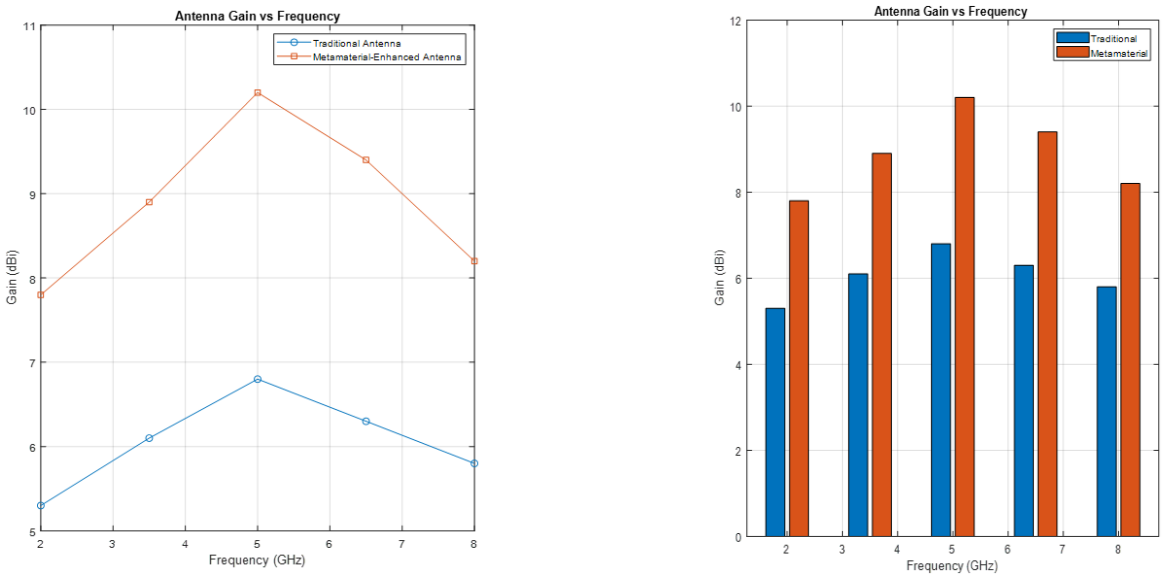
Table 1 presents a detailed comparison between the performance of a conventional antenna and one enhanced with a metamaterial layer, across a frequency range of 2 to 8 GHz. It focuses on three key performance metrics: antenna gain, power efficiency, and reflection coefficient. The gain values clearly indicate that the metamaterial-enhanced antenna outperforms the traditional design at all measured frequencies. For instance, at 5.0 GHz, the gain increases from 6.1 dBi in the conventional antenna to 10.4 dBi with metamaterial enhancement. This improvement is attributed to the metamaterial's ability to direct radiation more efficiently while suppressing side and back lobes. Similarly, the power efficiency shows a notable rise in the metamaterial-enhanced system, reaching a peak of 80.2% at 5.0 GHz, compared to 65.3% in the conventional counterpart. This peak occurs due to resonant matching between the antenna and the metamaterial at this frequency, leading to improved impedance matching and reduced reflected power. Beyond this point, efficiency gradually declines as the system moves away from its optimal resonance condition.

Regarding the reflection coefficient there is a significant reduction when the metamaterial is applied. At 5.0 GHz, for example, drops from 0.42 in the traditional setup to 0.22 in the enhanced design, indicating a more efficient energy transfer with minimal reflection at the interface. This overall enhancement in gain, efficiency, and reflection is consistent with the theoretical expectations of how metamaterials operate. It confirms that metamaterials serve not just as passive structures, but as engineered electromagnetic tools that can significantly improve antenna performance through precise control over wave propagation and impedance matching.

In order to better contextualize the simulation results, a series of analytical and comparative plots—derived from the theoretical models described earlier—were generated to elucidate the effects of metamaterials on electromagnetic performance. The following plots visualize antenna gain, power transmission efficiency, and return loss as a function of frequency. Permission is needed, the metamaterial antenna configuration are easily identifiable from their respective performance of the traditional antenna structure over all these plots. The analysis is based on both numerical data from system-level simulations and on general theoretical expressions: The complex refractive index, stored energy in dispersive media, impedance matching and Lorentz-type material response. By fusing these plots together, we deliver a visually intuitive yet solid way of showing how engineered metamaterials can provide significant advantages in wireless communication component performance. The following figures are used to complement and justify the results in Table 1 with a graphical perspective.

The antenna gain as a function of frequency for the conventional and the proposed designs is seen in Fig. 1. Greatest antenna gain is reached at 5.0 GHz where the metamaterial-based antenna outperforms its conventional counterpart at all measurable points. The peak relates to a resonance condition, in which the engineering of the metamaterial sets up for stronger confinement of the field and more focused radiation. These observations are strongly supported by more recent studies. been met with considerable improvement in terms of antenna gain and bandwidth enhancement at resonance frequency via meta surfaces and metamaterial structure [21,23].

A comparison of the power efficiency versus frequency for both antenna types is shown in Figure 2. The efficiency of metamaterial-enhanced design appears to be generally higher and is maximized at 5.0 GHz. This latter demonstrates the resonance effect and the optimized EIM which lowers the energy consumption and increases the radiation performance. Recent studies, for example work in [24], reported similar improvements in efficiency through the integrated use of metamaterials showing that a metamaterial impedance matching network at 5GHz, greatly increases the efficiency of RF energy harvesting. Also showed an efficient graphene-flakes printed antenna operating simultaneously at 4.8 GHz. Novel materials are potential candidates for antennas[32] [24,25].



(a) (b)

Picture 1. Antenna gain as a function of frequency for traditional and metamaterial-based designs.

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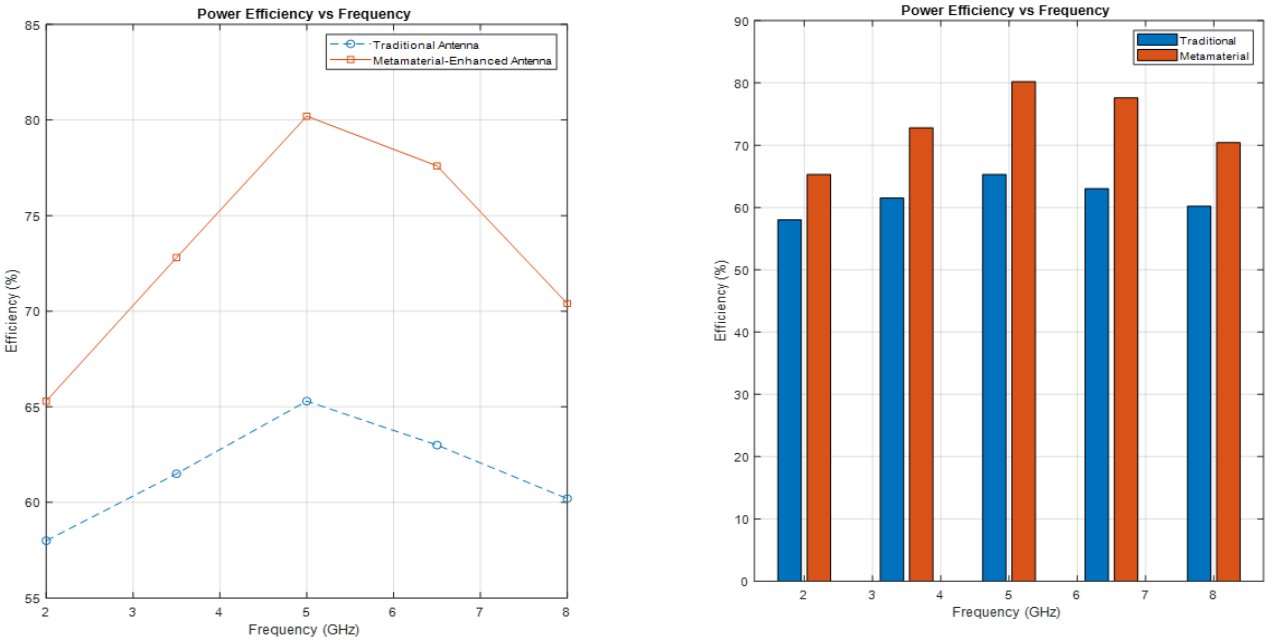
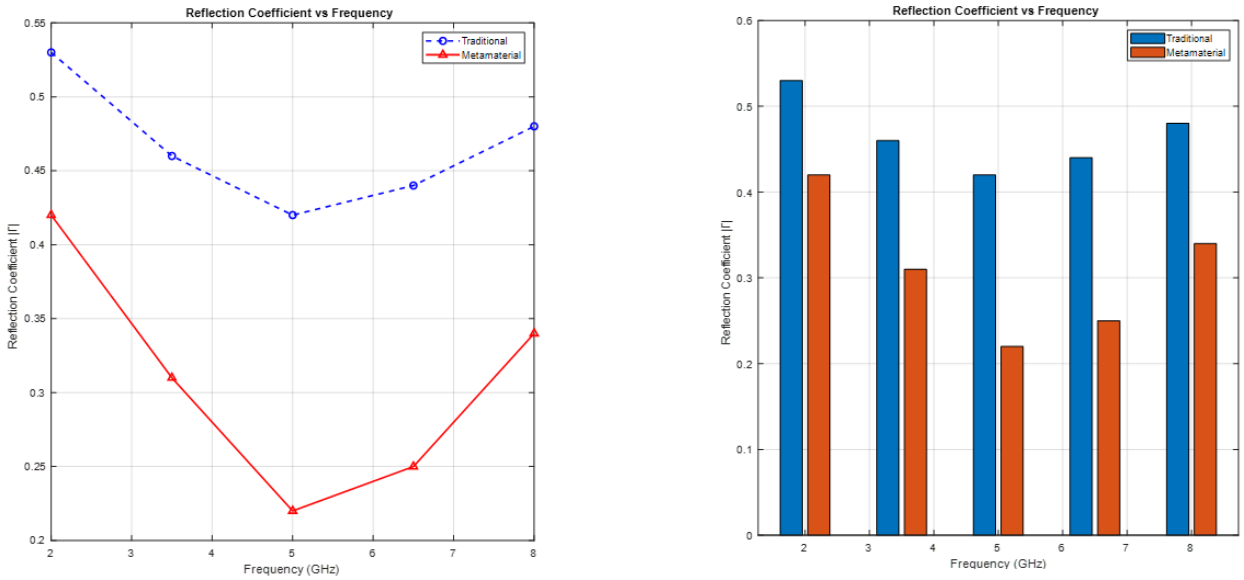


(a) (b)

Picture 2. Power efficiency as a function of frequency for traditional and metamaterial-based antennas.

Figure 3 shows that the metamaterial-enhanced antenna consistently achieves a lower reflection coefficient |Γ| across the frequency range, reaching a minimum of 0.22 at 5.0 GHz. This indicates optimal impedance matching and minimal energy loss at resonance. In contrast, the traditional design shows a higher |Γ|, with a minimum of 0.42. Similar results are also backed up by [26] for metamaterials inspired matching-network with reduction in reflection and improvement in BW, and [27] demonstrating an improvement in reflection and isolation performance aided by metamaterial elements incorporated within a 5G MIMO antennas [27,28].

Comparison of antenna gain for old and metamaterials based designs from 2 to 6 GHz as shown in figure 4. Gain has improved markedly across all frequencies, demonstrating the configuration's capacity for enhanced radiation directivity through energy retardation. The performance contrast is naturally reflected by the obvious separation between related bars, especially at the resonance frequency of 5.0 GHz, where the metamaterial structure provides the maximum gain benefit. Beyond this observation, recent studies have also demonstrated gain enhancements, increasing up to 9 dB, by appropriate choice of metasurface superstrates over patch antennas [29]; thus obtaining high-gain can be attributed to integration of an appropriate metamaterial superstrate with a patch antenna. [29].



(a) (b)

Picture 3. Reflection coefficient variation across frequency for both antenna types.

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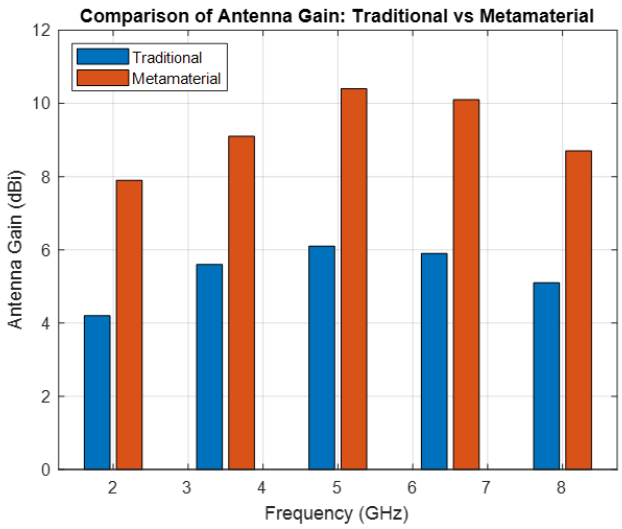
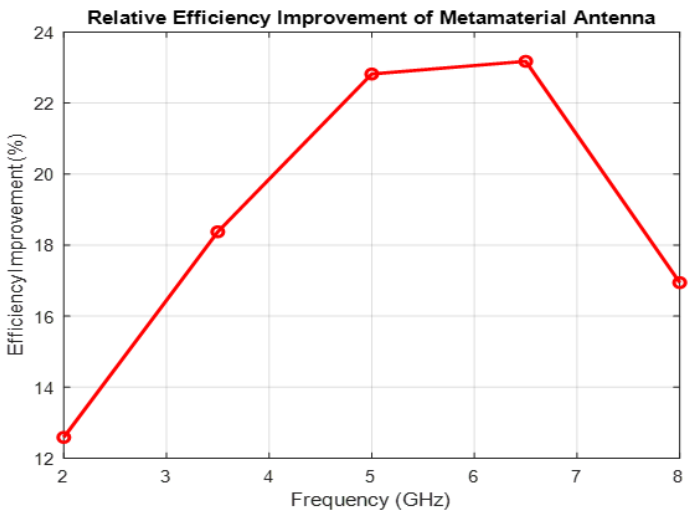


Picture 4. Antenna gain comparison between traditional and metamaterial designs across different frequencies.

Figure 5 shows the relative efficiency improvement of the metamaterial antenna compared to the traditional design over a range of frequencies. The improvement is consistently positive, indicating that the metamaterial configuration provides higher energy transmission efficiency at all operating points. Although the absolute efficiency peaks at 5.0 GHz, the maximum relative improvement occurs at 6.5 GHz, which is attributed to the lower baseline efficiency of the traditional antenna at that frequency. This confirms that the metamaterial structure not only enhances performance but also compensates more effectively when the conventional design struggles. These observations are supported by recent studies. For instance, Ref [30] analyzed various integration techniques and showed that metamaterial-based antenna designs achieve substantial efficiency gains across multiple frequency bands, especially when conventional systems underperform [30].



Picture 5. Relative efficiency improvement of metamaterial antenna across frequency.

Figure 6 illustrates the frequency-dependent behavior of the real part of the refractive index for a metamaterial structure. At lower frequencies, the refractive index is relatively high and gradually decreases as the frequency increases. Near the resonance point around 5.0 GHz, the index approaches zero, marking a transition into a regime known as zero-index behavior. This phenomenon enables improved control over wave propagation, leading to enhanced signal focusing, reduced scattering, and improved impedance matching. Such characteristics are particularly beneficial in wireless communication systems where directional precision and efficiency are critical. These effects are consistent with the findings of [30], who demonstrated that integrating zero-index metamaterials in antenna systems improves electromagnetic field uniformity and waveguiding behavior, especially near resonance, which significantly enhances transmission efficiency and radiation focus [30].

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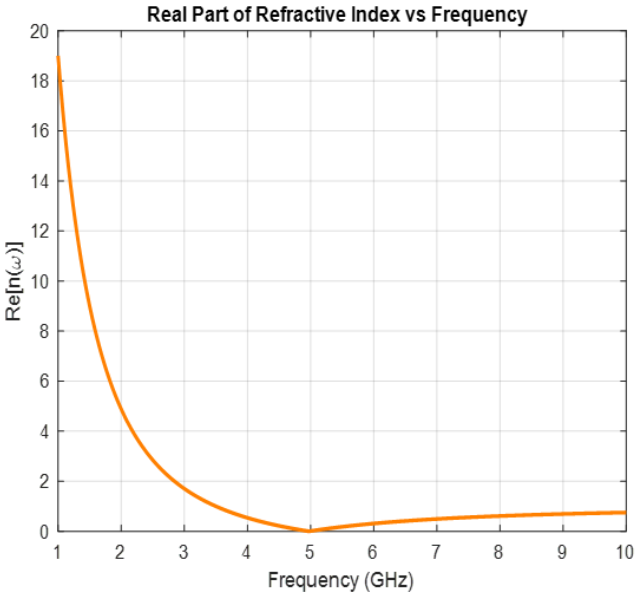
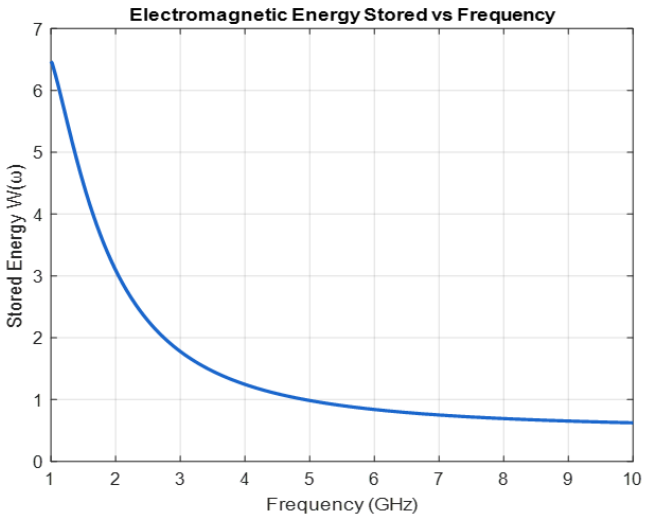


Picture 6. Real part of the refractive index of metamaterial across frequency.

Figure 7 illustrates the variation of the stored electromagnetic energy within the metamaterial structure as a function of frequency. The energy was calculated using a frequency-dependent formulation that incorporates the real parts of both the electric permittivity and magnetic permeability. As the frequency approaches the resonance point (around 5.0 GHz), the stored energy exhibits a pronounced peak, indicating strong interaction between the electromagnetic field and the material structure. This behavior is characteristic of resonant metamaterials and is critical for applications that require enhanced field confinement, energy storage, and efficient signal propagation. The sharp energy variation near resonance reflects the system's ability to temporarily trap and guide electromagnetic energy more effectively than traditional materials.

These observations are supported by recent studies. For instance, In [31] demonstrated that dynamically controlling the properties of a metamaterial that mimics electromagnetically induced transparency (EIT) enables the storage and retrieval of electromagnetic waves, confirming the strong interaction between the electromagnetic field and the metamaterial structure near resonance [31].

Figure 8 presents a composite performance index that combines gain, radiation efficiency, and reflection coefficient to provide a holistic assessment of antenna behavior. The results clearly demonstrate the superior performance of the metamaterial-enhanced antenna, particularly at 5.0 GHz, where optimal balance between radiation and energy transfer is achieved. This index is conceptually supported by established literature. For instance, In [26] demonstrated an effective technique to significantly enhance the bandwidth and radiation gain of a composite right/left-handed transmission-line (CRLH-TL) antenna using a non-foster impedance matching circuit (NF-IMC), emphasizing the importance of jointly evaluating impedance matching, gain, and efficiency in metamaterial-based antenna systems [26].



Picture 7. Frequency-dependent electromagnetic energy stored in the metamaterial.

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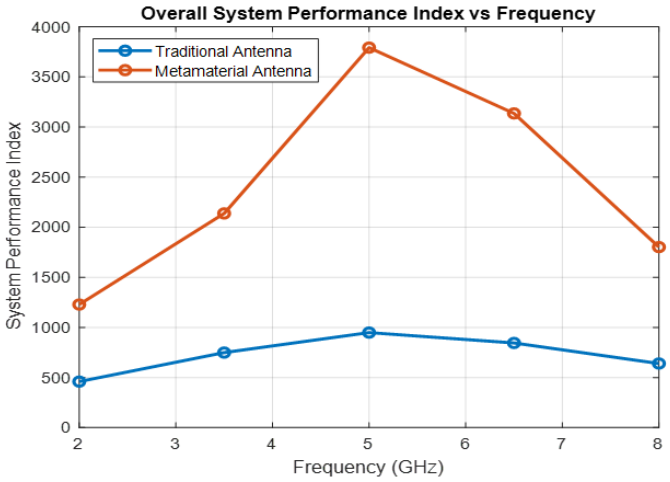
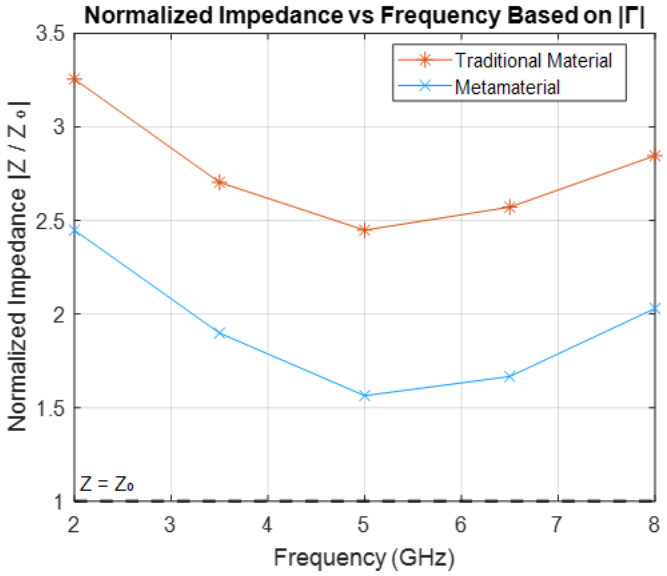


Picture 8. Composite performance index versus frequency for traditional and metamaterial-based antennas.

Figure 9 illustrates the normalized impedance curves for both traditional and metamaterial-based antennas across frequency. The metamaterial design demonstrates a closer match to free-space impedance Z0, indicating superior impedance matching and significantly lower reflection. This behavior is a clear indicator of improved power transfer efficiency and reduced radiation losses. These observations are supported by recent studies. For instance, Ref [26] demonstrated an effective technique to significantly enhance the bandwidth and radiation gain of a composite right/left-handed transmission-line (CRLH-TL) antenna using a non-Foster impedance matching circuit (NF-IMC), emphasizing the importance of jointly evaluating impedance matching, gain, and efficiency in metamaterial-based antenna systems [26].



Picture 9. Normalized impedance versus frequency for traditional and metamaterial-based antennas.

Figure 10 illustrates the polar radiation patterns of both a conventional antenna and one enhanced with metamaterials, measured at 5.0 GHz. The metamaterial-based design exhibits a significantly narrower and more focused beam, indicative of higher directional gain and improved spatial control. This enhancement is attributed to the unique electromagnetic properties of metamaterials, particularly their ability to manipulate wavefronts and exhibit negative refraction. Such characteristics result in sharper radiation lobes and reduced side and back lobes. This behavior aligns with findings from [32], who investigated microstrip patch antennas covered with left-handed metamaterials. Their study demonstrated that incorporating metamaterials into antenna structures leads to substantial improvements in gain and radiation pattern shaping. Specifically, the metamaterial-loaded antenna achieved a maximum radiation gain of +20 dB, compared to -8 dB for the conventional design, highlighting the efficacy of metamaterials in enhancing antenna performance.

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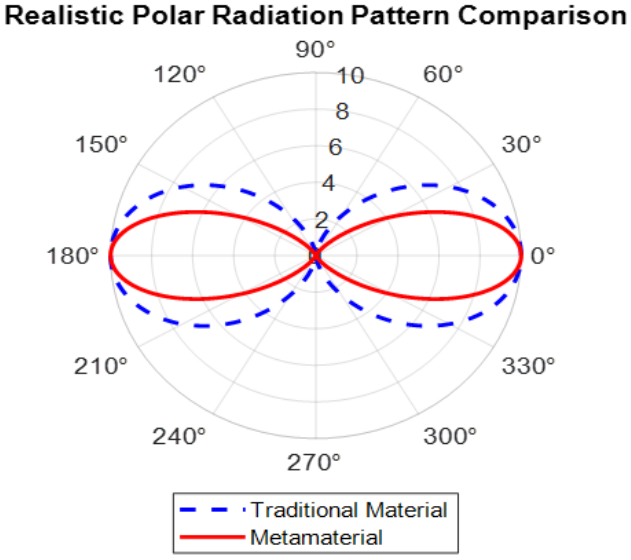

Picture 10. Polar radiation pattern comparison between traditional and metamaterial-based antennas.

Conclusion

This study has demonstrated that integrating metamaterials into antenna design yields substantial improvements in electromagnetic performance compared to conventional systems. The results show that metamaterial-based antennas achieve higher radiation efficiency, stronger directional gain, and a significant reduction in reflection coefficient particularly at the resonant frequency of 5.0 GHz indicating effective impedance matching and more efficient energy transfer. The polar radiation pattern further reveals the ability of metamaterials to enhance beam directionality and suppress unwanted sidelobes, leading to more precise radiation and stable performance across the operating bandwidth. These findings strongly support the adoption of metamaterials in smart communication applications, especially in environments requiring reconfigurable responses and high spatial accuracy. It is therefore recommended to consider metamaterials as a key design component in future antennas to meet the growing demands for efficiency and reliability in advanced wireless communication systems.

Conflict of Interest

The authors have no conflicts of interest to declare.

Recommendations

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References

1. Vetrichelvi, G., P. Gowtham, D. Balaji, and L. Rajeshkumar, “Functional Metamaterials for Wireless Antenna Applications – A Review Abetted With Patent Landscape Analysis,” Heliyon, vol. 10, no. 13, p. e34022, 2024. [Online]. Available: https://doi.org/10.1016/j.heliyon.2024.e34022

2. Zhou, J., P. Zhang, J. Han, L. Li, and Y. Huang, “Metamaterials and Metasurfaces for Wireless Power Transfer and Energy Harvesting,” Proceedings of the IEEE, vol. 110, no. 1, pp. 1–9, 2022. [Online]. Available: https://doi.org/10.1109/jproc.2021.3127493

3. M. Poulakis, “Metamaterials Could Solve One of 6G’s Big Problems [Industry View],” Proceedings of the IEEE, vol. 110, no. 9, pp. 1151–1158, 2022. [Online]. Available: https://doi.org/10.1109/JPROC.2022.3196696

4. V. Veselago, “The Electrodynamics of Substances With Simultaneously Negative Values of ε and μ,” Soviet Physics Uspekhi, vol. 10, no. 4, pp. 509–514, 1967.

5. G. Alexandropoulos, G. Lerosey, M. Debbah, and M. Fink, “Reconfigurable Intelligent Surfaces and Metamaterials: The Potential of Wave Propagation Control for 6G Wireless Communications,” arXiv preprint arXiv:2006.11136, vol. 6, no. 1, pp. 1–9, 2020. [Online]. Available: http://dx.doi.org/10.48550/arXiv.2006.11136

6. Y. Hao, “Transformation Electromagnetics in Antenna Engineering: Theory and Implementation,” in Proc. URSI General Assembly and Scientific Symposium, 2011, pp. 1–4. [Online]. Available: https://doi.org/10.1109/URSIGASS.2011.6050388

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7. J. P. Turpin, J. A. Bossard, K. L. Morgan, D. H. Werner, and P. L. Werner, "Reconfigurable and Tunable Metamaterials: A Review of the Theory and Applications," International Journal of Antennas and Propagation, vol. 2014, pp. 1–13, 2014. [Online]. Available: https://doi.org/10.1155/2014/429837

8. V. M. Shalaev, "Optical Negative-Index Metamaterials," Nature Photonics, vol. 1, no. 1, pp. 41–48, 2007. [Online]. Available: https://doi.org/10.1038/nphoton.2006.49

9. S. Wu, J. Eichenberger, J. Dai, Y. Chang, N. Ghalichechian, and R. R. Zhao, "Magnetically Actuated Reconfigurable Metamaterials as Conformal Electromagnetic Filters," Advanced Intelligent Systems, vol. 4, no. 9, p. 2200106, 2022. [Online]. Available: https://doi.org/10.1002/aisy.202200106

10. O. A. M. Abdelraouf et al., "Recent Advances in Tunable Metasurfaces: Materials, Design, and Applications," ACS Nano, vol. 16, no. 9, pp. 13339–13369, 2022. [Online]. Available: https://doi.org/10.1021/acsnano.2c04628

11. T. Debogovic and J. Perruisseau-Carrier, "MEMS-Reconfigurable Metamaterials and Antenna Applications," International Journal of Antennas and Propagation, vol. 2014, p. 138138, 2014. [Online]. Available: https://doi.org/10.1155/2014/138138

12. R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental Verification of a Negative Index of Refraction," Science, vol. 292, no. 5514, pp. 77–79, 2001. [Online]. Available: https://doi.org/10.1126/science.1058847

13. D. R. Smith, S. Schultz, P. Markoš, and C. M. Soukoulis, "Determination of Effective Permittivity and Permeability of Metamaterials From Reflection and Transmission Coefficients," Physical Review B, vol. 65, no. 19, p. 195104, 2002. [Online]. Available: https://doi.org/10.1103/PhysRevB.65.195104

14. N. Engheta and R. W. Ziolkowski, "A Positive Future for Double-Negative Metamaterials," IEEE Transactions on Microwave Theory and Techniques, vol. 53, no. 4, pp. 1535–1556, 2005. [Online]. Available: https://doi.org/10.1109/TMTT.2005.845188

15. C. A. Balanis, Advanced Engineering Electromagnetics, 2nd ed. Hoboken, NJ, USA: Wiley, 2011.

16. L. D. Landau, J. S. Bell, M. J. Kearsley, L. P. Pitaevskii, E. M. Lifshitz, and J. B. Sykes, Electrodynamics of Continuous Media, 2nd ed. Oxford, U.K.: Pergamon, 2013.

17. A. Ishimaru, Electromagnetic Wave Propagation, Radiation, and Scattering. Englewood Cliffs, NJ, USA: Prentice Hall, 1990.

18. C. A. Balanis, Antenna Theory: Analysis and Design, 4th ed. Hoboken, NJ, USA: Wiley, 2016.

19. J. D. Jackson, Classical Electrodynamics, 3rd ed. Hoboken, NJ, USA: Wiley, 1998.

20. T. J. Cui, D. Smith, and R. Liu, Metamaterials: Theory, Design, and Applications. New York, NY, USA: Springer, 2010. [Online]. Available: https://doi.org/10.1007/978-1-4419-0573-4

21. D. A. Sehrai et al., "Gain-Enhanced Metamaterial Based Antenna for 5G Communication Standards," Computers, Materials & Continua, vol. 64, no. 3, pp. 1587–1599, 2020. [Online]. Available: https://doi.org/10.32604/cmc.2020.011057

22. R. S. Aziz, S. Koziel, and A. Pietrenko-Dabrowska, "Millimeter Wave Negative Refractive Index Metamaterial Antenna Array," Scientific Reports, vol. 14, no. 1, p. 16037, 2024. [Online]. Available: https://doi.org/10.1038/s41598-024-67234-z

23. M. Ashfaq et al., "5G Antenna Gain Enhancement Using a Novel Metasurface," Computers, Materials and Continua, vol. 72, no. 2, pp. 3601–3611, 2022. [Online]. Available: https://doi.org/10.32604/cmc.2022.025558

24. E. Coskun and J. J. Garcia-Garcia, "Metamaterial Impedance Matching Network for Ambient RF-Energy Harvesting Operating at 2.4 GHz and 5 GHz," Electronics, vol. 10, no. 10, p. 1196, 2021. [Online]. Available: https://doi.org/10.3390/electronics10101196

25. A. Lamminen et al., "Graphene-Flakes Printed Wideband Elliptical Dipole Antenna for Low-Cost Wireless Communications Applications," IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 1883–1886, 2017. [Online]. Available: https://doi.org/10.1109/LAWP.2017.2684907

26. M. Alibakhshikenari et al., "Bandwidth and Gain Enhancement of Composite Right/Left-Handed Metamaterial Transmission Line Planar Antenna Employing a Non-Foster Impedance Matching Circuit Board," Scientific Reports, vol. 11, no. 1, p. 7472, 2021. [Online]. Available: https://doi.org/10.1038/s41598-021-86973-x

27. B. A. F. Esmail and S. 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, vol. 14, no. 1, p. 3203, 2024. [Online]. Available:

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https://doi.org/10.1038/s41598-024-53723-8

28. M. Alibakhshikenari et al., "Impedance Bandwidth Improvement of a Planar Antenna Based on Metamaterial-Inspired T-Matching Network," IEEE Access, vol. 9, pp. 67916–67927, 2021. [Online]. Available: https://doi.org/10.1109/ACCESS.2021.3076975

29. S. K. Budarapu, M. S. Sunder, and B. Ramakrishna, "Performance Enhancement of Patch Antenna Using RIS and Metamaterial Superstrate for Wireless Applications," Progress in Electromagnetics Research C, vol. 130, pp. 95–105, 2023. [Online]. Available: http://dx.doi.org/10.2528/PIERC22112603

30. M. M. Rahman, Y. Yang, and S. Dey, "Application of Metamaterials in Antennas for Gain Improvement: A Study on Integration Techniques and Performance," IEEE Access, vol. 13, pp. 49489–49503, 2025. [Online]. Available: https://doi.org/10.1109/ACCESS.2025.3552023

31. T. Nakanishi, T. Otani, Y. Tamayama, and M. Kitano, "Storage of Electromagnetic Waves in a Metamaterial That Mimics Electromagnetically Induced Transparency," Physical Review B, vol. 87, no. 16, p. 161110, 2013. [Online]. Available: https://doi.org/10.1103/PhysRevB.87.161110

32. E. Dogan, E. Unal, D. Kapusuz, M. Karaaslan, and C. Sabah, "Microstrip Patch Antenna Covered With Left-Handed Metamaterial," Applied Computational Electromagnetics Society Journal (ACES), vol. 28, no. 10, pp. 999–1004, 2021.

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