Metamaterials: Opportunities and Prospects for Antenna Design in Communication and Sensing

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Abstract

Metamaterials (MTMs) have garnered significant interest due to their unique electromagnetic properties, which differ from those of natural materials. These engineered materials have the potential to enhance the performance of antennas and sensors, particularly in the fields of communication and sensing. This paper examines the theoretical foundations of MTMs, their ability to manipulate electromagnetic waves, and their application in antenna design. We explore the benefits of MTM-based antennas, such as bandwidth enhancement, antenna miniaturization, and gain improvement. Additionally, we investigate the role of MTMs in the development of compact and multi-functional sensors. Despite these advancements, challenges remain, including design complexity, manufacturing costs, and material losses at higher frequencies. The paper also addresses future prospects, including the potential of MTMs in emerging technologies like 5G, IoT, wearable devices, and satellite communications, highlighting the role of MTMs in shaping the future of communication and sensing systems.

Keywords: Metamaterials, Antenna, communication, Sensors, electromagnetic

Introduction

The physical limitations of the atom arrangement in natural materials make their electromagnetic (EM) properties insufficiently flexible to precisely manipulate EM waves. EM metamaterials have been developed in recent years with the aim of overcoming this limitation, and their development has attracted a wide variety of interest from researchers in various fields (You et al., 2023). Metamaterials (MTM) are engineered materials with electromagnetic responses that differ from those of their constituent parts. MTM are composite materials whose material properties (acoustic, electrical, magnetic, or optical, etc.) are determined by their constitutive structural materials, especially the unit cells (Liu et al., 2015). The electromagnetic properties of these materials have been shown to be superior to those of natural materials. MTMs are produced by periodically integrating several extrinsic, low-dimensional, purposely made inhomogeneities into background substrates (Kumar et al., 2021).

The potential of additive manufacturing has significantly expanded the design possibilities of MTM architectures allowing for the production of highly intricate MTM with virtually unrestricted complexity. Their unique properties make them attractive in energy harvesting, sensors, wireless communication, biomedical, automotive, and aerospace applications (Lee et al., 2006).

The current progress of communication systems and sensors has conveyed voluminous challenges to these fields, particularly on antenna design. The antenna is a key element of any application associated with radio wave engineering. Therefore, it is crucial to consider the role of antenna design and development (Kumar et al., 2021). Researchers and engineers have been able to create antennas with novel characteristics using MTMs that are not possible with traditional materials (Lashab et al., 2023).

This paper is aimed at providing a thorough examination of the opportunities and prospects that MTMs present for antenna design, with an emphasis on communication and sensing applications. We will discuss theoretical principles, and recent developments, and identify problems and future research directions.

Theoretical Foundations of MTMs

MTMs manipulate electromagnetic waves differently from conventional materials due to their engineered structures, which exhibit negative permittivity ($\varepsilon < 0$) and permeability ($\mu < 0$) (Milias et al., 2021). Materials can be classified based on ε and μ, as shown in Figure 1. Materials in the first quadrant are classified as natural materials, possessing positive ε and μ. Those in the second and fourth quadrants possess negative permittivity and negative permeability, respectively. Materials in the third quadrant are classified as MTMs, possessing negative ε and μ, resulting in a negative refractive index. This gives MTM their unique electromagnetic properties (Kumar et al., 2021). The relationship between the material parameters ε and μ and the refractive index n is given by the equation:

$$\mathbf{n} = \pm\sqrt{\boldsymbol{\varepsilon}_{\mathbf{r}}\boldsymbol{\mu}_{\mathbf{r}}}$$

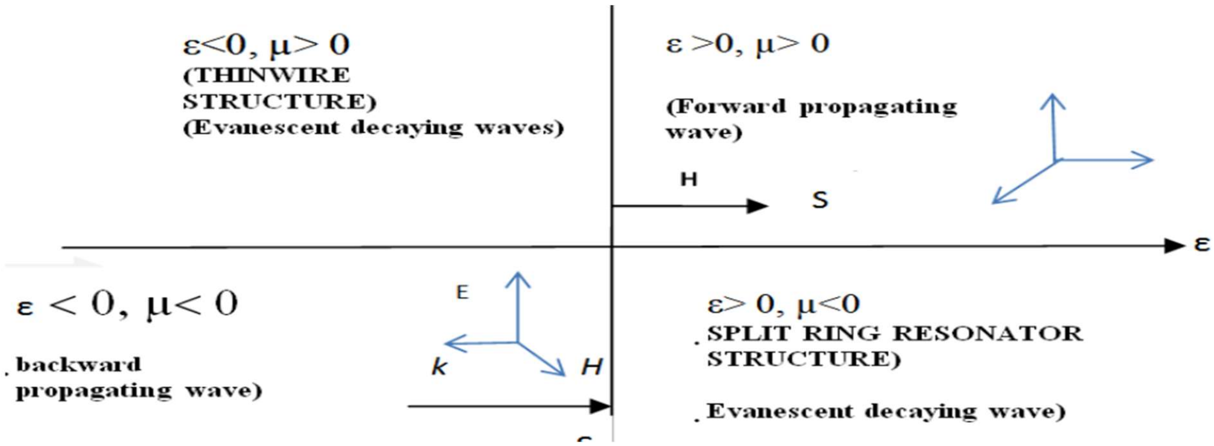


Figure 1: Classification of material based on μ and ε (Slyusar, 2009)

MTMs in the third quadrant are categorized as double-negative (DNG), negative index (NIM), or left-handed (LHM) materials. MTMs are gaining popularity owing to their unique ability to possess negative permeability and permittivity in certain frequency bands (Holloway & Kuester, 2019). Another appealing attribute of MTMs is their near-zero refractive index, which makes them suitable for a wide range of electromagnetic applications, from low microwaves to optical frequencies, including shielding, low-reflection materials, innovative substrates, antennas, and cloaking. The permittivity and permeability of these materials are engineered such that their real components do not approach zero, which is a characteristic not found in natural materials (Holloway & Kuester, 2019).

Electromagnetic MTMs are fabricated by systematically developing and organizing artificial structural parts to provide favorable and uncommon electromagnetic properties. Their advantage over conventional materials stems from their tunable responsiveness and tailored dielectric characteristics, allowing exceptional design flexibility (You et al., 2023). The periodic structures in MTMs produce resonance phenomena and electromagnetic bandgaps, which are critical for their operation (Banerjee et al., 2020). When the frequency of the incident electromagnetic wave matches the intrinsic frequency of the structure, resonance occurs, causing strong responses or oscillations at that frequency, resulting in a significant enhancement of the field owing to the efficient energy transfer from the incident wave to the resonant mode of the structure. Split-ring resonators (SRR) and antenna resonators are examples in which resonant effects can be observed. SRRs are designed to resonate at particular frequencies, creating regions of negative permeability, whereas antennas resonate at frequencies where efficiency is maximized (Liu et al., 2015).

Figure 2: An illustration of an electromagnetic metamaterial *(Gangwar et al., 2014)*

The bandgap effect occurs when specific frequency ranges of electromagnetic waves are prevented from travelling through a periodic structure, resulting in gaps in the frequency spectrum. Electromagnetic band gaps are formed at particular frequencies where wave propagation is blocked owing to electromagnetic waves' constructive and destructive interference in the MTM's periodic structure, an important attribute exploited in antenna design (Lee et al., 2006)

Application of MTMs in Communication Antenna

An MTM antenna is a mixture of one or more layers of metamaterial substrate that improves its performance. MTM antennas are a type of antenna that uses MTM technology to enhance antenna qualities such as electrically small antenna size, strong directivity, tunable operational frequency, array system, and increased efficiency. The MTM can increase the radiated power of an antenna (Parveen, 2018).

MTMs utilize their unique properties to overcome typical antenna limitations in terms of size, bandwidth, and efficiency, resulting in improved performance. MTMs exhibit properties that enhance the performance of antennas and antenna systems used for communication and sensing (Prasad et al., 2021). Figure 3 shows the antenna parameters that the application of MTMs can enhance.

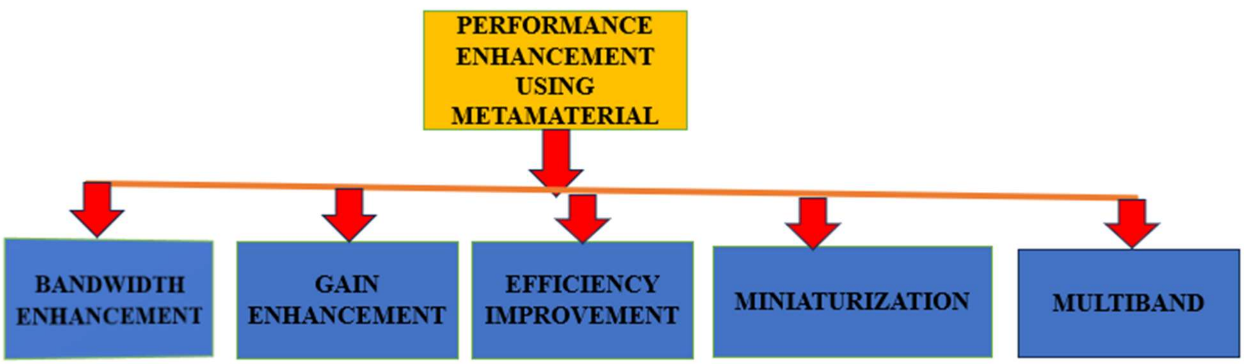


Figure 3: Various performance improvements of antennas by using metamaterials (Hussain et al., 2023)

Bandwidth Enhancement Using MTM

To enhance antenna BW. using metamaterials (MTM), MTMs can be integrated into the antenna design either as a component or as a superstrate placed above the radiation surface. MTM unit cells may be positioned above or below the superstrate. The antenna's BW depends on the superstrate's distance from the radiation surface and the number of MTM unit cells (Nghia et al., 2019).

Various techniques have been employed to enhance BW, such as manipulating effective permeability and permittivity, incorporating resonant structures, and designing multi-layered MTMs and metasurfaces. These methods are essential for modern communication systems (Kumar et al., 2021).

MTM structures are extensively explored in 5G antenna designs due to their potential for enhanced BW. A bibliometric review by Raut et al. (2021) identified different applications of MTMs in antenna design. For instance, planar MTM-based antennas provide impedance bandwidths of 3.08–11.7 GHz and 13.6–36.4 GHz. Further reviews indicated that single-element antennas, array antennas, and multi-input multi-output (MIMO) antennas exhibit BW enhancements. For single-element antennas, wideband types achieved a 58.3% BW increase at 2.84–5.17 GHz, while FSS-based dense dielectric (DD) patch antennas showed a 9% improvement at 28 GHz. In array and MIMO antenna types, the 2x2 array (CP) antenna and MTM-based 2-element antenna demonstrated 55.6% and 22.3% BW enhancements at frequencies of 4.75–7.25 GHz and 42–525 GHz, respectively.

Table 1: Comparison table for single-element antenna

S/NO	ANTENNA TYPE	PLATFORM USED	FREQUENCY RANGE (GHZ)	BANDWIDTH (%)
1	Low-RCS CP antenna	Not given	5.4	19.64
2	Wideband antenna	HFSS 2	2.84–5.17	58.3
3	FSS based dense dielectric (DD) patch	CST microwave studio	28	9
4	Magnetoelectric dipole antenna	HFSS	57–71	50
5	Metamaterial-based shared-aperture	HFSS	27–30	35
6	Metamaterial-based DRA	CST microwave studio	5–5.5	12.84
7	Metamaterial-based AVA	HFSS	24.8–34.52	35.95

Table 2: Comparison table for antenna array

S/NO	ANTENNA TYPE	PLATFORM USED	FREQUENCY RANGE (GHZ)	BANDWIDTH (%)
1	Wideband CP	HFSS	60	19.64
2	E-band 2 × 8 array	HFSS	77–86.5	11.62
3	2 × 2 array (CP)	HFSS	4.75–7.25	55.6
4	6 × 8 proximity-coupled array	CST microwave studio	27.5–28.5	9
5	Quad mode phased array	CST microwave studio	25–33	23.72
6	Ka-band	HFSS	24–31	24.4

Table 3: Comparison table for MIMO antenna

S/NO	ANTENNA TYPE	PLATFORM USED	FREQUENCY RANGE (GHZ)	BANDWIDTH (%)
1	Metamaterial-based 2 element	HFSS	4.2–5.25	22.3
2	DRA	HFSS	27.25–28.59	3.04

Miniaturization of Antenna using MTM

Various techniques are employed in designing miniaturized antennas using MTM. Methods such as the application of dielectric substrates with high permittivity, fractal geometry, shorting of pins, and shorting of walls, as well as interference in its structure. The application of defect ground structures (DNG) in which unit cells of size equal to the removed parts of the DGS has been reported to exhibit abnormal properties at the resonance frequency (Prasad et al., 2021). Figure 4 demonstrates a comparison of the dimensions of a microstrip antenna with a complementary split ring resonator (CSRR) design on the antenna plane. The results obtained from this method indicate a reduction in size of up to 40%.

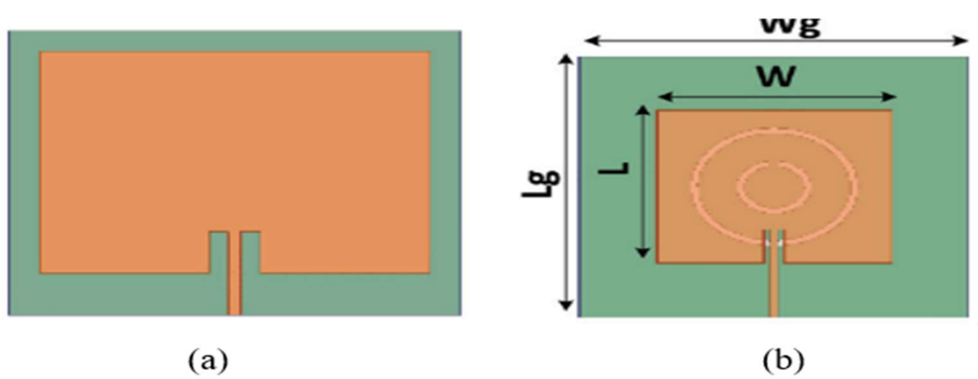
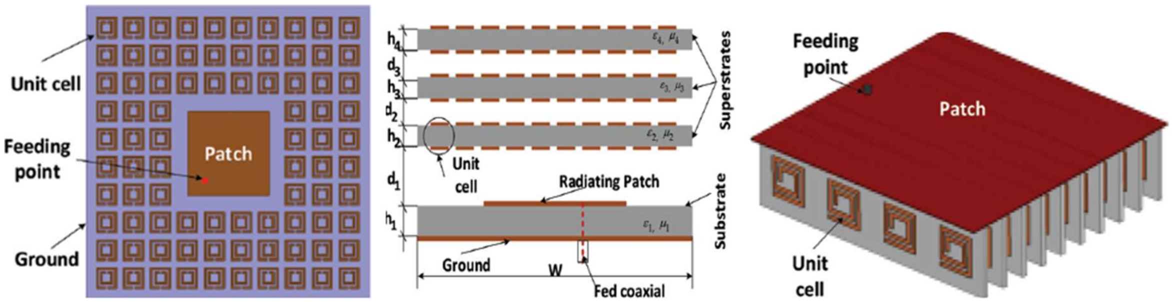


Figure 4: Comparison of the size of microstrip patch antenna MPA without loaded CSRR (a) and with loaded CSRR (b) *(Krzysztofik & Cao, 2019)*

In recent years, Internet of Things (IoT) devices have become increasingly important due to their ability to accommodate low power, high data rates, and long-range communication. As a result, the miniaturized MTM-based antenna has become an attractive solution for deployment in IoT applications. Traditional antennas operating at lower frequencies face size constraints that make their integration into IoT devices challenging. Researchers have demonstrated significantly smaller metamaterial antennas (57.8%) in size reduction than traditional antennas while maintaining high efficiency and performance, making them ideal for IoT devices (Jusoh et al., 2023).

Antenna Gain Improvement using MTM

For a given transmitted power, the gain of the antenna increases the range of communication and makes it more resistant to interference. The conventional antenna ground plane, however, does not offer enough surface wave suppression and in-phase reflection, resulting in a side and back lobe which lowers the gain of an antenna (Sehrai et al., 2020). A MTM in antenna design has been proposed during the last years as a promising, low-cost alternative for gain increase without significantly affecting the volume of the antenna. The incorporation of MTM can improve antenna gain by providing the in-phase reflection to electromagnetic waves which radiate toward the backside of an antenna, causing the back lobes that degrade the gain of an antenna (Milias et al., 2021). The applied MTM may be artificial magnetic conductors (AMCs) or artificial magnetic materials (AMMs), they can be applied as the environment of the antenna, using one or more superstrates above or below the radiated elements or using MTM as the loading of the antenna as shown in Figure 5.



(a) (b) (c)

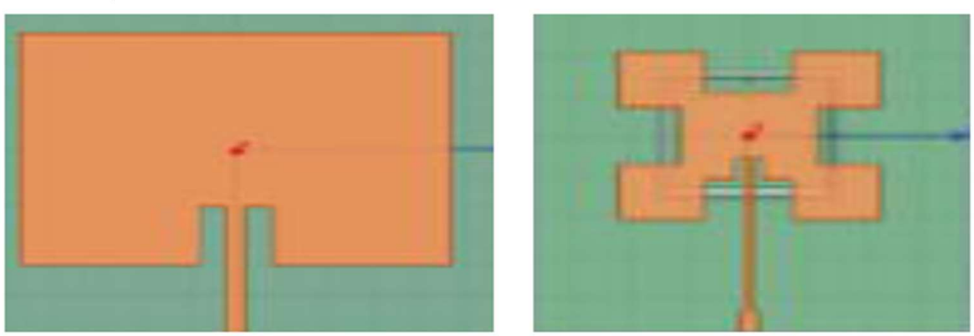
Figure 5: Models of metamaterials application in improving the power gain of the antennas: unit cells surrounding the radiated patch (a), metamaterials as superstrate (b), using the metamaterials as antenna loading (c) (Milias et al., 2021)

Multiband Antenna using MTM

Multi-frequency antennas with smaller dimensions than traditional ones can be designed using metamaterials (MTM). This is due to the symmetrically paired unit cell structures of MTM, which can support negative refractive indexes at resonant frequencies when applied as radiating components or as a loaded part of the ground plane of the antenna (Nghia et al., 2019).

The interest in designing multi-band antennas for communication using MTM has risen significantly, driven by the need to integrate multiple communication systems into a single device. Combining microstrip or fractal antennas can create multi-band antennas, with their size determined by the lowest frequency.

Figure 6 shows the simulation model of two antennas operating on multiple frequencies. By changing the size of the antenna or unit cell, the resonant frequency of the antenna can be adjusted (Prasad et al., 2021).



a b

Figure 6: a and b showing microstrip antenna without and with loaded CSRRc (Prasad et al., 2021)

Application of MTM in Sensors

The sensitivity and resolution of sensors are significantly enhanced through the application of MTM opening a door for the design of sensors with specific sensitivity. MTM sensors are employed in various fields such as agriculture and biomedical (Chen et al., 2012a). Metamaterials provide tools to significantly enhance the sensitivity and resolution of sensors finding application in agriculture, biomedical and many other fields. In agriculture the sensors are based on resonant material and employ SRR to gain better sensitivity. The use of MTM offers to sensors the enhanced resolutions and sensitivity, compact sensor design and multi-functional sensing (Chen et al., 2012).

Enhanced Resolution and Sensitivity

Due to diffraction limits, the resolution of conventional optical sensors has been reduced to approximately two hundred nanometers in visible light making features smaller than half wavelength of light unresolvable. Conventional optical sensors suffer from diffraction limits because during propagation the waves with high transverse evanescent waves decay exponentially. This occurs as a result of naturally occurring materials possessing positive permittivity and permeability. These limitations can be overcome through the application of MTM which can provide direct control and manipulation of the electromagnetic properties improving the resolution and sensitivity of sensors (Kim & Rho, 2015).

MTM are also applied to enhance the sensitivity of magnetic sensors use in large memories that are read by magnetic sensors, self-driving cars, airplanes, factories, smart cities, and space exploration. The magnetic field in the sensing area of the sensor which depends on a known factor that depends on the shell radii was enhanced and the concentration of the time-dependent magnetic field for frequencies of up to 100KHz by a MTM shell was demonstrated by (Navau et al., 2017).

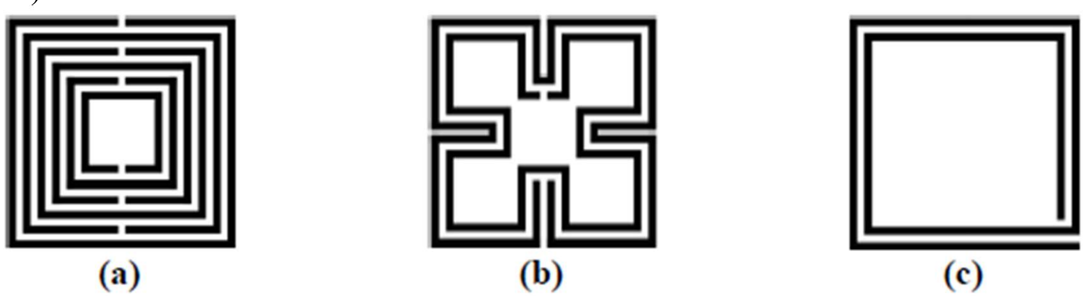


Figure 7: Metamaterial unit cells that are used for the sensor (a) Multiple SRR (b)Sierpinski SRR(c) Spiral Resonator (Gangwar et al., 2014)

Compact Sensor Designs

The miniaturization capability of metamaterials allows the development of compact and portable sensors, which are essential for applications like environmental monitoring, wearable health devices. 5G, and Internet of things (IoT). Compact metamaterial sensors have been created for environmental monitoring, offering high sensitivity in a portable form factor, making them ideal for field use. MTM are also employed in the design of Meta-Fractal wearable compact sensors and antennas for application in medical, communication, 5G, and IoT. Utilization of MTM in this design indicates efficiencies of 92% and increase bandwidth of 50% (Sabban, 2024). Figure 8 shows a compact metamaterial fractal wearable use in sensors.

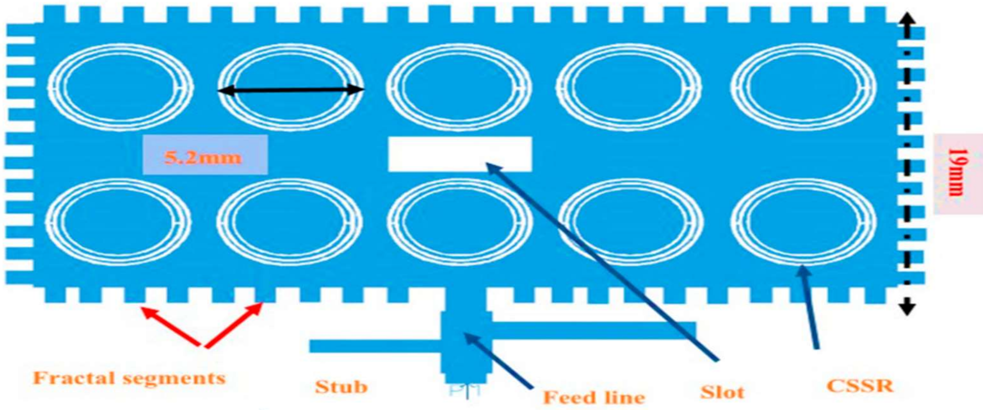


Figure 8: Compact metamaterial fractal wearable antenna (Sabban, 2024).

Compact wearable metamaterial circular patch antennas for IoT, biomedical, and 5G applications have been developed using metamaterials (MTM), delivering significantly better performance compared to designs without MTM. This design approach provides the benefit of an integrated, compact, and cost-effective feed network, achieved by combining the antenna feed with the antenna itself on the same printed circuit board. Utilizing efficient passive and active antennas can enhance the overall performance of communication systems. (Sabban, 2020).

Multi-functional Sensing

Metamaterials allow for the creation of multi-functional sensors that can perform a variety of sensing tasks at the same time, improving efficiency and versatility. Biomedical sensors using metamaterials can simultaneously monitor different physiological parameters, enhancing the diagnostic capabilities of wearable health devices (Zemouli et al., 2015).

Challenges and Future Prospects

Although MTM improves the qualities of antennas used in communication and sensors, their implementation creates challenges. To achieve electromagnetic features such as a negative refractive index, subwavelength structures needed to be precisely arranged. Furthermore, the design process requires complex computational modeling, which increases the challenge. These design and production methods are expensive and complex, which limits their commercial viability. MTM suffers from significant losses at microwave, millimeter, and optical frequencies. This occurs when electromagnetic waves encounter the metal component of the MTM, producing heat at high frequencies. This heat impacts the performance of metamaterial-based antennas at high frequencies. (Milias et al., 2021)

MTM can improve antenna properties such as directivity, although they often have restricted bandwidths. This limits their usefulness in wideband communication systems. The tiny bandwidth is due to their resonant nature, which typically stays to a narrow range of frequencies. These antennas are also susceptible to environmental factors like temperature and humidity. These modifications influence the electromagnetic characteristics of MTM-based devices, reducing their reliability. MTM scalability for mass production is also a concern, limiting its use in antenna and sensor designs. Although MTM-based antennas perform well in the lab, mass manufacture is tough. The intricate designs and sophisticated manufacturing procedures make it difficult to build them affordably enough for mass use (Kumar et al., 2021).

MTM based antenna possess high potential in future communication and sensing technologies. MTM properties can potentially enhance miniaturization for 5G and beyond antennas. They promise better performance without taking up much space, perfect for smartphones, IoT devices, and wearables. The improvement of beamforming and directionality of antennas plays a crucial role in the development of future wireless communication systems like 6G. These antennas can boost data transmission by controlling the direction of electromagnetic waves (Naqvi & Hussain, 2022).

MTM-based antennas could fit right into wearable gadgets that track health or even help with augmented reality. Made from stretchy materials, they could be part of clothing and smart textiles that monitor vital signs and more. These antennas could change the game in satellite communication too. They might improve signal gain while also cutting down on weight and size issues for satellites

Lastly, MTM could really enhance sensor abilities as well. These advanced sensors might detect environmental changes or biological stuff better than ever before. High sensitivity could lead to big advances in health diagnostics, environmental tracking, and even industrial automation (Saeidi et al., 2020).

Conclusion

Metamaterial-based antennas and sensors offer promising solutions for addressing key challenges in communication and sensing applications. Their ability to improve bandwidth, reduce antenna size, and enhance gain makes them valuable for modern wireless systems, including 5G and IoT technologies. However, the practical implementation of MTMs is hindered by challenges related to design complexity, manufacturing precision, and material losses at higher frequencies. While these obstacles limit widespread commercial use, ongoing research into new fabrication techniques and materials holds the potential to overcome these issues. In the future, MTMs could play a transformative role in the miniaturization and performance enhancement of devices for advanced applications, such as wearable technologies, satellite communications, and high-sensitivity sensors. As the field evolves, MTMs are expected to shape the development of next-generation communication and sensing systems, making them a key enabler of future technological advancements.

Reference

Banerjee, S., Pal, B. P., & Roy Chowdhury, D. (2020). Resonance phenomena in electromagnetic metamaterials for the terahertz domain: a review. In *Journal of Electromagnetic Waves and Applications* (Vol. 34, Issue 10, pp. 1314–1337). Taylor and Francis Ltd. https://doi.org/10.1080/09205071.2020.1713227

Chen, T., Li, S., & Sun, H. (2012a). Metamaterials application in sensing. In *Sensors* (Vol. 12, Issue 3, pp. 2742–2765). https://doi.org/10.3390/s120302742

Chen, T., Li, S., & Sun, H. (2012b). Metamaterials application in sensing. In *Sensors* (Vol. 12, Issue 3, pp. 2742–2765). https://doi.org/10.3390/s120302742

--g, P. B., Gangwar, K., & Gangwar, R. (2014). *Metamaterials: Characteristics, Process and Applications* (Vol. 4, Issue 1). http://www.ripublication.com/aeee.htm

Holloway, C. L., & Kuester, E. F. (2019). Electromagnetic metamaterials and metasurfaces: Historical overview, characterization, and the effect of length scales. In *Dielectric Metamaterials: Fundamentals, Designs, and Applications* (pp. 1–38). Elsevier. https://doi.org/10.1016/B978-0-08-102403-4.00006-2

Hussain, M., Awan, W. A., Alzaidi, M. S., Hussain, N., Ali, E. M., & Falcone, F. (2023). Metamaterials and Their Application in the Performance Enhancement of Reconfigurable Antennas: A Review. In *Micromachines* (Vol. 14, Issue 2). MDPI. https://doi.org/10.3390/mi14020349

Iffat Naqvi, S., & Hussain, N. (2022). Antennas for 5G and 6G Communications. In *5G and 6G Enhanced Broadband Communications [Working Title]*. IntechOpen. https://doi.org/10.5772/intechopen.105497

Jan Krzysztofik, W., & Nghia Cao, T. (2019). Metamaterials in Application to Improve Antenna Parameters. In *Metamaterials and Metasurfaces*. IntechOpen. https://doi.org/10.5772/intechopen.80636

Jusoh, A. Z., Husain, N. F., Malek, N. F. A., Isa, F. N. M., & Mohamad, S. Y. (2023). DESIGN OF MINIATURIZED ANTENNA FOR IOT APPLICATIONS USING METAMATERIAL. *IIUM Engineering Journal*, *24*(1), 122–137. https://doi.org/10.31436/iiumej.v24i1.2505

Kim, M., & Rho, J. (2015). Metamaterials and imaging. In *Nano Convergence* (Vol. 2, Issue 1). Korea Nano Technology Research Society. https://doi.org/10.1186/s40580-015-0053-7

Krishna Prasad, N. V., Babu, T. A., Phanidhar, S., Singampalli, R. S., Naik, B. R., Sarma, M. S. S. R. K. N., & Ramesh, S. (2021). POTENTIAL APPLICATIONS OF METAMATERIALS IN ANTENNA DESIGN, CLOAKING DEVICES, SENSORS AND SOLAR CELLS: A COMPREHENSIVE REVIEW. *Journal of Optoelectronic and Biomedical Materials*, *13*(2), 23–31. https://doi.org/10.15251/JOBM.2021.132.23

Kumar, N. S., Naidu, K. C. B., Banerjee, P., Babu, T. A., & Reddy, B. V. S. (2021). A review on metamaterials for device applications. In *Crystals* (Vol. 11, Issue 5). MDPI AG. https://doi.org/10.3390/cryst11050518

Lashab, M., Belattar, M., Hocine, S., & Ahmed, H. (2023). Metamaterial Applications in Modern Antennas. In *Metamaterials - History, Current State, Applications, and Perspectives*. IntechOpen. https://doi.org/10.5772/intechopen.108267

Lee, Y., Hao, Y., & Parini, C. (2006). Applications of Electromagnetic Bandgap (EBG) structures for novel communication antenna designs. *Proceedings of the 36th European Microwave Conference, EuMC 2006*, 1056–1059. https://doi.org/10.1109/EUMC.2006.281115

Liu, R., Ji, C., Zhao, Z., & Zhou, T. (2015). Metamaterials: Reshape and Rethink. *Engineering*, *1*(2), 179–184. https://doi.org/10.15302/J-ENG-2015036

Milias, C., Andersen, R. B., Lazaridis, P. I., Zaharis, Z. D., Muhammad, B., Kristensen, J. T. B., Mihovska, A., & Hermansen, D. D. S. (2021). Metamaterial-Inspired Antennas: A Review of the State of the Art and Future Design Challenges. In *IEEE Access* (Vol. 9, pp. 89846–89865). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ACCESS.2021.3091479

Navau, C., Mach-Batlle, R., Parra, A., Prat-Camps, J., Laut, S., Del-Valle, N., & Sanchez, A. (2017). Enhancing the sensitivity of magnetic sensors by 3D metamaterial shells. *Scientific Reports*, *7*. https://doi.org/10.1038/srep44762

Nghia, C. T., Krzysztofik, W. J., Cao, T. N., Student, P., & Krzysztofik, W. J. (2019). *METAMATERIAŁY W ZASTOSOWANIU DLA POPRAWY PARAMETRÓW ANTEN METAMATERIALS IN APPLICATION FOR IMPROVING THE PARAMETERS OF ANTENNAS*. https://www.researchgate.net/publication/333162681

Parveen, K. (2018). Metamaterials: Types, applications, development, and future scope. In *International Journal of Advance Research*. www.IJARIIT.com

Sabban, A. (2020). New compact wearable metamaterials circular patch antennas for IoT, medical and 5G applications. *Applied System Innovation*, *3*(4), 1–24. https://doi.org/10.3390/asi3040042

Sabban, A. (2024). Novel Meta-Fractal Wearable Sensors and Antennas for Medical, Communication, 5G, and IoT Applications. *Fractal and Fractional*, *8*(2). https://doi.org/10.3390/fractalfract8020100

Saeidi, T., Mahmood, S. N., Alani, S., Ali, S. M., Ismail, I., & Alhawari, A. R. H. (2020). Sub-6G Metamaterial-Based Flexible Wearable UWB Antenna for IoT and WBAN. *2020 IEEE Intl Conf on Dependable, Autonomic and Secure Computing, Intl Conf on Pervasive Intelligence and Computing, Intl Conf on Cloud and Big Data Computing, Intl Conf on Cyber Science and Technology Congress (DASC/PiCom/CBDCom/CyberSciTech)*, 7–13. https://doi.org/10.1109/DASC-PICom-CBDCom-CyberSciTech49142.2020.00018

Sehrai, D. A., Muhammad, F., Kiani, S. H., Abbas, Z. H., Tufail, M., & Kim, S. (2020). Gain-enhanced metamaterial based antenna for 5G communication standards. *Computers, Materials and Continua*, *64*(3), 1587–1599. https://doi.org/10.32604/cmc.2020.011057

Slyusar, V. (2009). *Metamaterials on antenna solutions*. https://doi.org/10.1109/ICATT.2009.4435103

You, J., Ma, Q., Zhang, L., Liu, C., Zhang, J., Liu, S., & Cui, T. (2023a). Electromagnetic Metamaterials: From Classical to Quantum. *Electromagnetic Science*, *1*(1), 1–33. https://doi.org/10.23919/emsci.2022.0005

You, J., Ma, Q., Zhang, L., Liu, C., Zhang, J., Liu, S., & Cui, T. (2023b). Electromagnetic Metamaterials: From Classical to Quantum. *Electromagnetic Science*, *1*(1), 1–33. https://doi.org/10.23919/emsci.2022.0005

Zemouli, S., Chaabi, A., & Talbi, H. S. (2015). Design of a compact and high sensitivity temperature sensor using metamaterial. *International Journal of Antennas and Propagation*, *2015*. https://doi.org/10.1155/2015/301358