Volume 14, Issue 1, Page 96-102, 2025 https://doi.org/10.46810/tdfd.1572811 Research Article

BİNGÖL UNIVERSITY

Türk Doğa ve Fen Dergisi
Turkish Journal of Nature and Science
www.dergipark.gov.tr/tdfd

Design of A New Metamaterial and Investigation of Its Effect on The Gain of A Circular Patch Antenna

Bülent URUL[1*]

[1]Isparta University of Applied Sciences University, Vocational School of Technical Sciences, Electronics and Automation Department, Isparta, Türkiye
Bülent URUL ORCID No: 0000-0003-2656-2450

**Corresponding author : bulenturul@isparta.edu.tr*

(Received: 24.10.2024, Accepted: 20.01.2025, Online Publication: 26.03.2025)

Keywords
Metamaterials,
Antenna,
Gain

Abstract: Metamaterials have emerged as a revolutionary innovation in science and technology, offering properties not found in natural materials, such as negative refractive indices, which enable novel applications in photonics and optics. This study focuses on designing a novel metamaterial structure, with the specific goal of enhancing the performance of a circular patch antenna (CPA). The unique properties of metamaterials, particularly their ability to manipulate electromagnetic waves in unconventional ways, are leveraged to increase antenna gain and directivity. The proposed metamaterial, referred to as the four-armed symmetric metamaterial (FASM), was designed and simulated using CST software. The study explores the interaction between the FASM and the CPA by examining various configurations and distances between the two components. Simulation results reveal that applying the FASM in single and double layers significantly boosts the antenna's performance, achieving a maximum gain increase of 83.57% with a double-layer FASM at a specific distance. This finding demonstrates the potential of metamaterials to optimize antenna designs for improved efficiency and compactness, with applications spanning communication, radar, and satellite systems.

Yeni Bir Metamateryalin Tasarımı ve Dairesel Yama Antenin Kazancına Etkisinin İncelenmesi

Anahtar Kelimeler
Metamateryal,
Anten,
Kazanç

Öz: Metamalzemeler, fotonik ve optikte yeni uygulamalara olanak tanıyan negatif kırılma indisleri gibi doğal malzemelerde bulunmayan özellikler sunarak bilim ve teknolojide devrim niteliğinde bir yenilik olarak ortaya çıkmıştır. Bu çalışma, dairesel yama anteninin (DYA) performansını artırma özel hedefi ile yeni bir metamalzeme yapısı tasarlamaya odaklanmaktadır. Metamalzemelerin benzersiz özellikleri, özellikle elektromanyetik dalgaları alışılmadık şekillerde manipüle etme yetenekleri, anten kazancı ve yönlülüğünü artırmak için kullanılır. Dört kollu simetrik metamalzeme (DKSM) olarak adlandırılan önerilen metamalzeme, CST yazılımı kullanılarak tasarlanmış ve simüle edilmiştir. Çalışma, iki bileşen arasındaki çeşitli yapılandırmaları ve mesafeleri inceleyerek DKSM ile DYA arasındaki etkileşimi araştırmaktadır. Simülasyon sonuçları, DKSM'yi tek ve çift katmanlarda uygulamanın antenin performansını önemli ölçüde artırdığını ve belirli bir mesafede çift katmanlı bir DKSM ile %83,57'lik maksimum kazanç artışı elde ettiğini ortaya koymaktadır. Bu bulgu, metamalzemelerin haberleşme, radar ve uydu sistemlerini kapsayan uygulamalarda, anten tasarımlarının daha iyi verimlilik ve kompaktlık için optimize edilmesinde potansiyelini ortaya koymaktadır.

1. INTRODUCTION

Metamaterials are emerging as a revolutionary innovation in the world of science and technology, offering materials with properties not found in nature. These materials are structures where the coefficients of electrical permittivity (ε) and magnetic permeability (μ) can reach negative values, displaying extraordinary optical and electromagnetic characteristics. The discovery of these features has enabled scientists to go beyond the physical limits of traditional materials, opening up new technological opportunities. Particularly, properties such as negative refractive index provide innovative solutions across a wide range of applications, especially in photonics and optics.

Firstly in 1968, Veselago introduces the theoretical framework for materials where both the electric permittivity (ε) and magnetic permeability (μ) are negative. It discusses the unique electromagnetic wave propagation characteristics in such materials, including reversed Doppler and Vavilov-Cerenkov effects, and the concept of "left-handed" substances with negative refractive indices. While no real substances with these properties were identified at the time, the paper suggests potential experimental approaches and their implications for physics [1]. In 2000, Smith and colleagues succeeded in producing the first metamaterial with negative permittivity properties in the laboratory [2]. This was confirmed by experiments conducted in the microwave region of the electromagnetic spectrum, and this discovery rapidly turned metamaterials into a growing field of research.

One of the fundamental properties of metamaterials is having a negative refractive index. The refractive index is a value that expresses how a material bends light or other electromagnetic waves. While most materials in nature have a positive refractive index, metamaterials possess a negative refractive index. This means that light or electromagnetic waves bend in the "negative direction," contrary to what is typically observed. This characteristic was detailed in Pendry's theoretical work and later confirmed by numerous experimental studies [2-5]. The negative refractive index forms the basis for extraordinary applications, such as directing, controlling, and bending light. One of the most striking applications of metamaterials is super lens technology. Proposed by Pendry, this technology suggests that materials with a negative refractive index could offer far superior resolution than conventional optical lenses. Super lenses allow light to focus even on extremely small, unconstrained scales, enabling the imaging of nanoscale details. This technology holds great potential for revolutionizing fields such as biomedical imaging and semiconductor manufacturing [6, 7].

Although metamaterials offer extraordinary properties, their applicability faces some limitations. For example, producing and scaling metamaterials can be quite challenging. These structures, successfully manufactured in laboratory environments, need further development to be integrated into large-scale commercial applications [8]. Additionally, applying negative permittivity properties over broader frequency bands remains a significant challenge. Overcoming these issues could enable the wider use of metamaterials, particularly in areas such as telecommunications, energy storage, and sensor technologies [9].

In recent years, a notable trend in the development of metamaterials is the emergence of a new class of materials known as "topological metamaterials." These structures have the potential to revolutionize the manipulation and control of both optical and acoustic waves. Topological metamaterials allow waves to be transmitted without loss, thanks to their perfect edge modes, which can significantly enhance energy efficiency [10, 11].

Studies have shown that metamaterials have the ability to enhance antenna performance when used together with antennas. The primary reason for this is that metamaterials allow electromagnetic waves to be focused and help reduce losses during wave propagation. A study conducted in 2020 examined the effects of the parameters of electrical substrates and metamaterial lens layers on antenna gain. The study found that these materials increased gain by 22% in single-layer applications and by 87% in double-layer applications [12]. The use of such materials, especially in microstrip antennas, enables small antennas to achieve high gain and directional performance. Another study from 2022 demonstrated that using flower-shaped metamaterial (FSMM) structures, optimized by the particle swarm optimization (PSO) algorithm, resulted in a 77% gain increase in satellite communication antennas. Additionally, another study revealed that by employing metamaterial structures etched onto the antenna substrate using the Defected Ground Structure (DGS) method, antenna gain was increased by 12% [13, 14].

The article by Li et al. (2024) presents the design of a broadband metamaterial absorber based on a metal-dielectric disc-ring structure. The proposed absorber achieves over 90% absorption in the 1500–4000 nm wavelength range, demonstrating polarization insensitivity and wide-angle absorption properties. The design leverages surface plasmon resonance and cavity resonance to enhance absorption, with potential applications in infrared detection and imaging [15]. Another study in 2024 examines recent advancements in tunable metamaterial absorbers (MAs). It focuses on various tuning methods, such as optical excitation, thermal radiation, and electrical modulation, to optimize the electromagnetic absorption properties of these structures using innovative materials and designs. Additionally, it discusses future challenges and potential application areas[16].

In conclusion, the use of metamaterials in antenna designs significantly enhances antenna performance, enabling widespread applications in fields such as communications, radar, and defense systems. With further development of these materials, more efficient and compact antennas are expected to emerge in the future. It is evident that, in addition to the metamaterials found in current literature, there is an ongoing and future need for various forms of metamaterials to be used across different frequency bands.

In this study, the primary goal is to design a novel metamaterial that does not exist in the current literature. Following this, to facilitate comparison, the newly designed metamaterial will be used in various combinations with a circular patch antenna, which is frequently used as a reference antenna in many studies.

The impact of the new metamaterial on the performance of the circular patch antenna will then be analyzed.

2. MATERIAL AND METHOD

2.1. Design of A New Metamaterial

Materials exhibit different behaviors in response to electromagnetic waves based on their electrical permittivity (ε) and magnetic permeability (μ) coefficients. In natural materials, these coefficients are typically positive values. In contrast, special materials known as metamaterials, which are produced in laboratory settings, can have both electrical (ε) and magnetic permeability (μ) coefficients that are negative. Depending on these coefficients, the materials designed and produced in the laboratory exhibit a negative refractive index. To classify a cell as a metamaterial, its refractive index must be negative, determined by the values of ε and μ. This can occur in three scenarios: Case 1, where only ε is negative within a specific frequency range; Case 2, where μ is negative; and Case 3, where both ε and μ are negative. A cell exhibiting any of these conditions within a given frequency range can be identified as a metamaterial for that range. Various approaches, such as the Nicholson-Ross-Weir method and other robust techniques, are commonly employed in the literature to compute these material parameters [17,18].Thanks to these properties, metamaterials demonstrate electromagnetic characteristics that are not found in nature. To create such a metamaterial, a four-armed symmetric metamaterial (FASM) as shown in Figure 1 has been designed using the CST electromagnetic program. Both sides of the FASM have been designed in the same manner. The design parameters of the FASM are presented in Table 1.

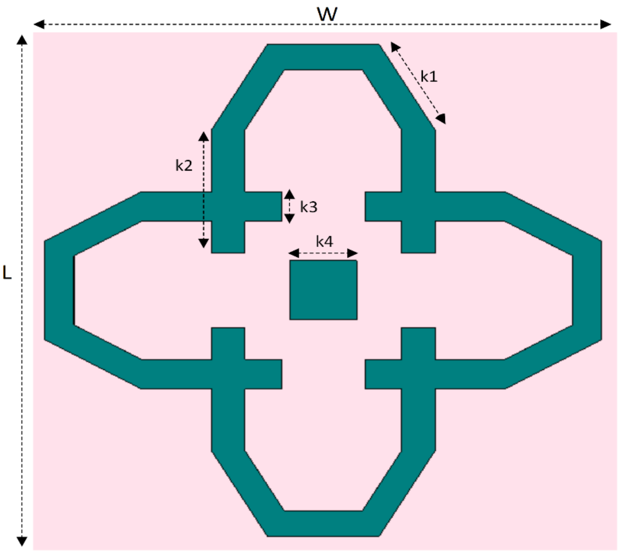

Figure 1. Four-armed symmetric metamaterial (FASM)

Table 1. FASM Design Parameters

Parameters	Value(mm)
Width(G)	5.5
Length(U)	5.5
Substrate Thickness	1.55
Metal Thickness	0.035
k1	1
k2	1.25
k3	0.3
k4	0.6

The FASM structure designed according to the parameters provided in Table 1 was simulated using the CST electromagnetic program, and the graphs of ε, μ and n refractive indices were obtained, as shown in Figure 2. The values given in the graph are the real parts of the expressions ,,. The simulation process was conducted in the frequency domain.

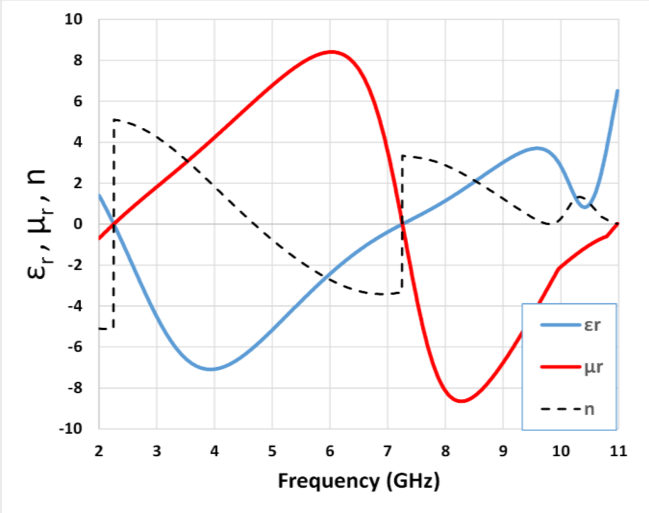

Figure 2. Graphs of ε_r, μ_r, n for the FASM

Upon examining Figure 2, it is clearly observed that the electrical permittivity of the FASM unit cell exhibits negative values between 2.38 GHz and 7.27 GHz. Similarly, it is noted that the cell demonstrates negative magnetic permeability between 7.27 GHz and 10.58 GHz. When these two observations are combined, it becomes evident that the refractive index (n) of the FASM cell is negative in the frequency range of 5.06 GHz to 7.27 GHz. Considering all these data collectively, it can be stated that the FASM unit cell exhibits metamaterial properties in a bandwidth of approximately 2.21 GHz. This characteristic indicates that the FASM cell has significant potential for advanced technology applications.

2. 2. Design of A Circular Patch Antenna (CPA)

In this study, a circular patch antenna was chosen as the reference antenna due to its ease of comparison, design, and production. The design process was carried out using the CST electromagnetic software, and a circular patch antenna (CPA) was designed on an FR4 substrate. The thickness of the substrate was selected as 1.55 mm, which is a standard used in the market. For the FR4 material, the loss tangent tan δ = 0.025 and Ɛr = 4.3 were chosen. All design parameters of the antenna were given in Table 2.

Table 2. CPA Reference Antenna Parameters

Parameters	Value(mm)
Width(W)	18
Length (L)	18
Substrate Thickness	1.55
Metal Thickness	0.035
R	7
m1	1.5
m2	3.6
m3	6.9

The antenna design, as shown in Figure 3, has been realized using an electromagnetic simulation program, with the parameters adjusted so that the resonance frequency of the antenna is 6.5 GHz.

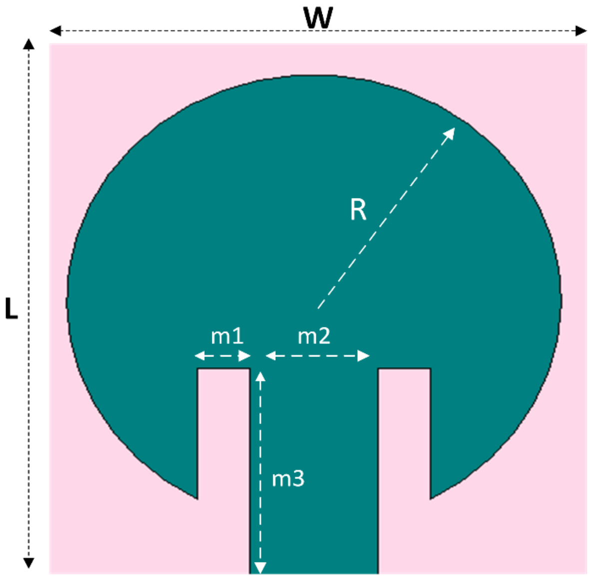

Figure 3. View of the reference antenna (CPA)

Subsequently, the antenna was simulated in the 5-8 GHz frequency range to obtain the gain and S11 values. Based on the simulation results, the antenna's return loss graph was generated, as illustrated in Figure 4.

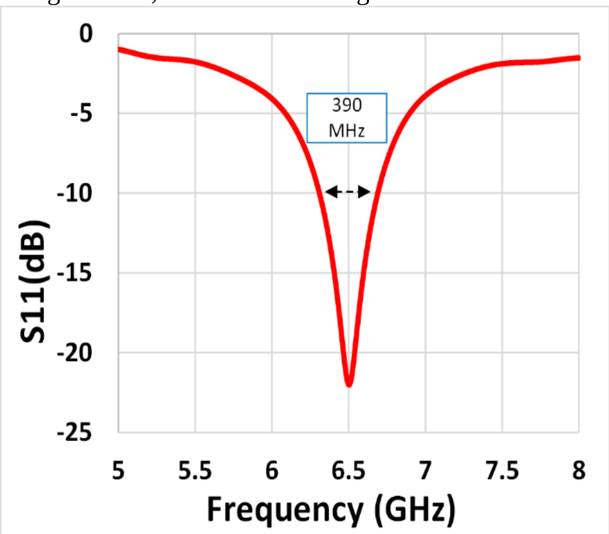

Figure 4. Return loss graph of the antenna (S11)

When the graph in Figure 4 is examined, it is noted that the antenna operates at a resonant frequency of 6.5 GHz within the 5-8 GHz range, and a return loss of 22.01 dB and bandwidth as 390 MHz are obtained at this value. Furthermore, the simulation conducted with the CST program produced the antenna's gain graph, which is displayed in Figure 5. According to this graph, the maximum gain was obtained as 2.8 dBi at an angle of -4 degrees.

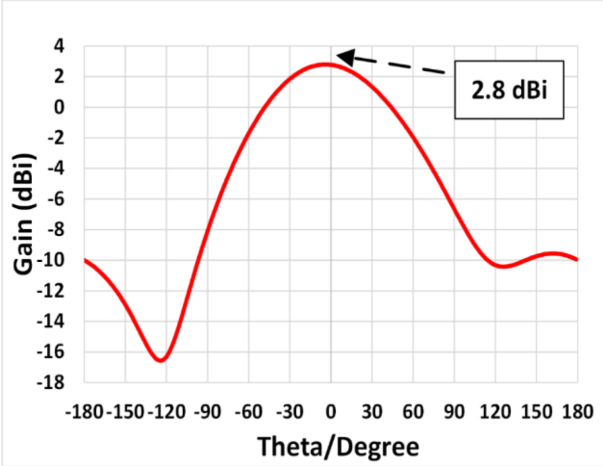

Figure 5. Gain graph of the CPA

3. RESULTS AND DISCUSSION

3.1. Application of The FASM Cell on The CPA

Metamaterial applications with electromagnetic antennas offer an innovative solution to improve antenna performance. The negative refractive index and unique electromagnetic properties of metamaterials can enhance antenna efficiency, reduce their size, and improve undesired radiation patterns. By placing metamaterials on or around circular patch antennas, they provide advantages such as lowering the operating frequency, increasing gain, and improving directivity. Especially in narrow-space applications, metamaterials can elevate the performance parameters of the antenna to levels that cannot be achieved through traditional methods. Such integration paves the way for more efficient and compact antenna designs in wireless communications, radar systems, and satellite communication [19, 20]. In this section, the impact of using FASM unit cells in conjunction with a circular patch antenna on the antenna's performance has been examined. To achieve this, a lens layer consisting of 9 unit cells (3x3), as shown in Figure 6, was created using FASM unit cells, with identical front and back layers.

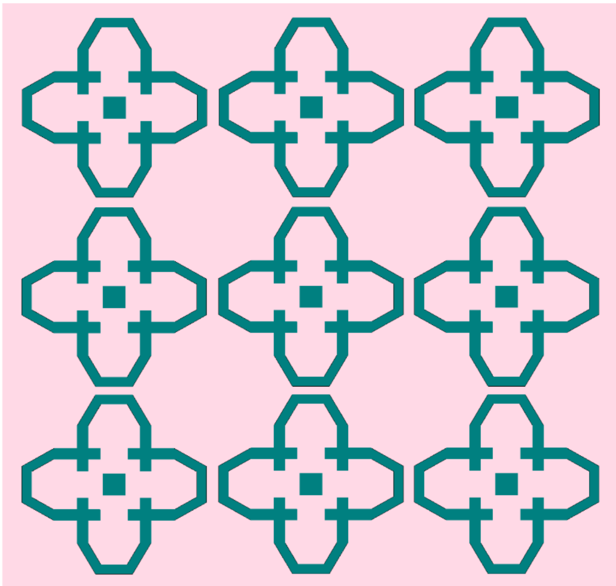
Figure 6. View of the FASM lens layer

In the next step, a lens layer composed of FASM unit cells was placed in front of the CPA as a single layer, as shown in Figure 7. The resulting structure was simulated at various distances between the antenna and the lens layer by utilizing the parameter sweep function of the CST program, and the results were given in Table 3. When Table 3 is examined, it is observed that the best gain value was obtained as 3.77 dBi for a distance of 15 cm, which is 34.64% higher than the gain of the reference antenna.

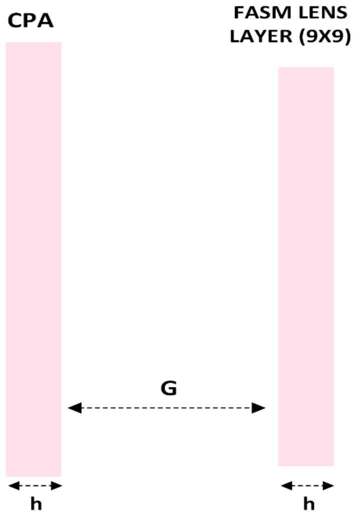

Figure 7. Usage of the CPA together with the FASM lens layer

Table 3. Antenna gain values according to the distance between single layer FASM lens-CPA

Gap (G)(mm)	Gain(dBi)	Gain Increase (%)
5	1.76	-37.14%
7.5	2.93	4.64%
10	3.51	25.36%
12.5	3.7	32.14%
15	3.77	34.64%
17.5	3.71	32.50%
20	3.73	33.21%

In the next step, as shown in Figure 8 and Figure 9, another lens layer made with FASM was added in front of the CPA, and the resulting structure was re-simulated by varying the distances between the antenna and the lens layers. The gap between the antenna and the first lens layer was fixed at 15 mm (G), while the simulation was conducted by varying the distance (T) between the two lens layers. The gain values obtained according to the changes in the intermediate distances are given in Table 4. Additionally, to allow for comparison on the graph, the gain graph (maximum value taken) for the reference antenna and the proposed antenna's single-layer and double-layer usage is provided in Figure 10. Additionally, the S11 graph of the reference antenna and the proposed structure is given in Figure 11.

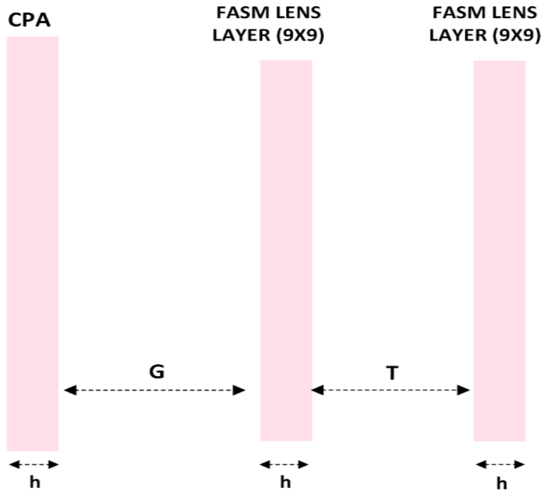

Figure 8. Usage of the CPA together with the double layers FASM lens

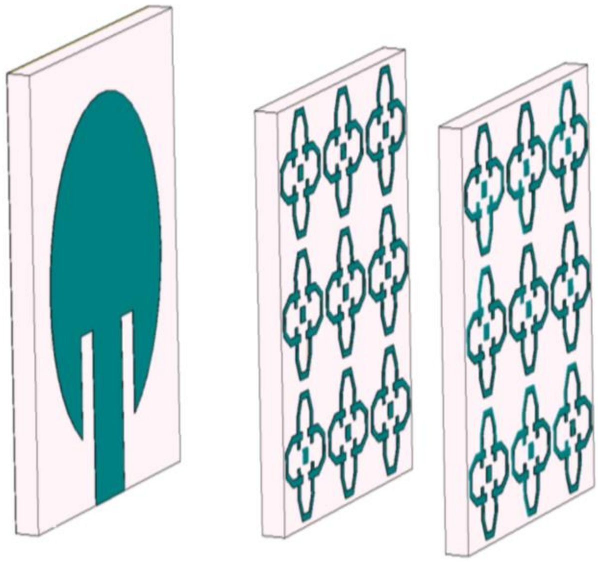

Figure 9. 3D view of the CPA together with the double layers FASM lens

Table 4. Antenna gain values according to the distance between FASM lens layers

Gap (T)(mm)	Gain(dBi)	Gain Increase (%)
5	4.25	51.79%
7.5	4.57	63.21%
10	4.95	76.79%
12.5	5.14	83.57%
15	5.07	81.07%
17.5	4.98	77.86%
20	4.7	67.86%

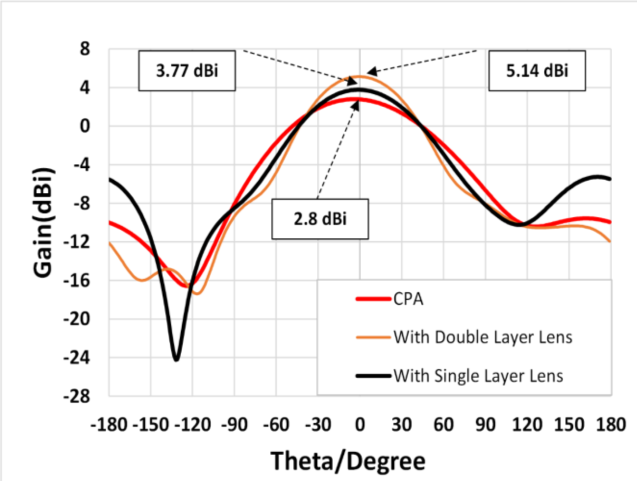

Figure 10. Comparison of the gain graphs between reference antenna and proposed antenna.

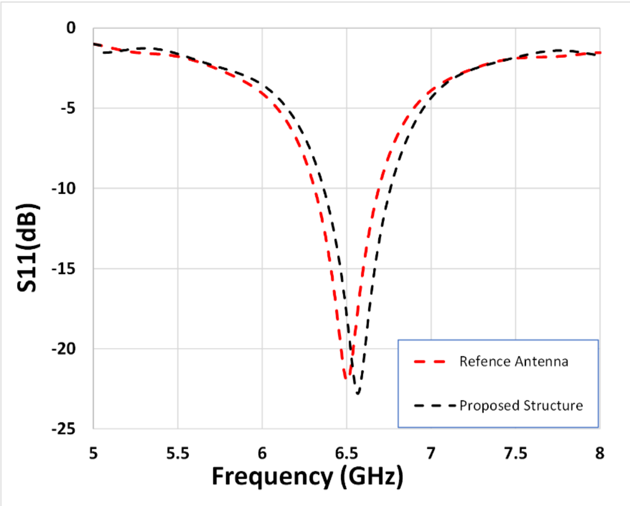

Figure 11. S11 graphs of reference antenna and proposed antenna.

When Table 4 and Figure 10 is examined, it is observed that the highest gain value, 5.14 dBi, is obtained when the distance (T) between the lens layers is 12.5 mm (with G=15 mm). This gain value is 83.57% higher than the gain of the reference antenna. In light of these results, it has been demonstrated that the use of lens layers made with FASM unit cells together with the CPA results in a significant increase in the antenna's gain. In addition, as seen in Figure 11, the resonant frequency of the proposed antenna shifted slightly to 6.7 GHz and its bandwidth was obtained as 527 MHz. This value is 137 MHz more than the bandwidth of the reference antenna.

4. CONCLUSION

In conclusion, this study successfully designed and demonstrated the effectiveness of a novel four-armed symmetric metamaterial (FASM) in improving the performance of a circular patch antenna (CPA). The FASM, when applied as a lens layer in both single and double configurations, yielded substantial gains in antenna performance. The maximum gain increase observed was 83.57%, which was achieved with a double-layer FASM configuration. These results confirm that metamaterials can provide significant enhancements in antenna gain and directivity, making them valuable for a wide range of applications in wireless communications, radar, and satellite technologies. The integration of metamaterials into antenna designs presents a promising approach to achieving more compact, efficient, and high-performing antennas. Future research may focus on further optimizing these structures for different frequency bands and exploring their potential for other applications in advanced technologies.

REFERENCES

[1] Veselago VG. The electrodynamics of substances with simultaneously negative values of ε and μ. Soviet Physics Uspekhi. 1968, 10(4), 509-514. https://doi.org/10.1070/PU1968v010n04ABEH003699

[2] Smith DR, Padilla WJ, Vier DC, Nemat-Nasser SC, Schultz S. Composite medium with simultaneously negative permeability and permittivity. Physical Review Letters. 2000; 84(18):4184-4187. https://doi.org/10.1103/PhysRevLett.84.4184

[3] Pendry JB. Negative refraction makes a perfect lens. Physical Review Letters. 2000; 85(18):3966-3969. https://doi.org/10.1103/PhysRevLett.85.3966

[4] Shalaev VM. Optical negative-index metamaterials. Nature Photonics. 2007; 1(1): 41-48. https://doi.org/10.1038/nphoton.2006.50

[5] Valentine J, Zhang S, Zentgraf T, Ulin-Avila E, Genov DA, Bartal G, Zhang X. Three-dimensional optical metamaterial with a negative refractive index. Nature. 2008; 455(7211): 376-379. https://doi.org/10.1038/nature07238

[6] Fang N, Zhang X. Imaging properties of a metamaterial superlens. Applied Physics Letter.2003; 82(2): 161-163. https://doi.org/10.1063/1.1539261

[7] Liu Z, Lee H, Xiong Y, Sun C, Zhang X. Far-field optical hyperlens magnifying sub-diffraction-limited objects. Science. 2007; 315(5819):1686-1686. https://doi.org/10.1126/science.1139890

[8] Cui TJ, Smith DR, Liu R. Metamaterials: Theory, Design, and Applications. Springer; 2010. https://doi.org/10.1007/978-3-642-03453-2

[9] Zheludev NI, Kivshar YS. From metamaterials to metadevices. Nature Materials. 2012; 11(11), 917-924. https://doi.org/10.1038/nmat3341

[10] Khanikaev AB, Mousavi SH, Tse WK, Kargarian M, MacDonald AH, Shvets G. Photonic topological insulators. Nature Materials. 2013; 12: 233-239. https://doi.org/10.1038/nmat3520

[11] Lu L, Joannopoulos JD, Soljačić M. Topological photonics. Nature Photonics. 2014; 8 (11): 821-829. https://doi.org/10.1038/nphoton.2014.227

[12] Urul B. Dielektrik alt tabaka parametrelerinin metamateryal ile mikroşerit anten kazancının artırılmasına etkisi. Igdir University Journal of the Institute of Science and Technology. 2020; 10(2): 944-955. https://doi.org/10.21597/igusbd.751301

[13] Urul B. High-gain UWB antenna optimized with particle swarm optimization using metamaterial lens layer for satellite communication applications. International Journal of RF and Microwave

Computer-Aided Engineering. 2022; 32(9): e23280. https://doi.org/10.1002/mmce.23038
[14] Urul B. The effect of etched FSMM on the circular patch antenna using DGS method. International Congress on Human-Computer Interaction, Optimization and Robotic Applications (HORA). IEEE, 2020; p. 1-4. https://doi.org/10.1109/IMS.2020.9149721
[15] Li X, Wu SB, Wang Y, Hu Y. Design of broadband metamaterial absorbers in the near-infrared region. Advanced Theory and Simulations. 2024; 7(1), Article 2400839. https://doi.org/10.1002/adts.202400839
[16] Yixin L, Chenxia L, Bo F, Liang C, Jianfeng X, Fuhai L, Lizhen X, Xiao L, Ying T, Zhi H, Xufeng J. Research Progress in Tunable Metamaterial Absorbers. Advanced Photonics Research. 2024; Vol. 5, no. 2.
[17] Shi Y, Hao T, Li L, Liang CH. An improved NRW method to extract electromagnetic parameters of metamaterials. Microwave Optical Technology Letters, 2016; Vol. 58, Issue 3, Pages 647-652, 2016.
[18] Shi Y, Li ZY, Li L, Liang CH. An electromagnetic parameters extraction method for metamaterials based on phase unwrapping technique. Waves Random Complex Medium, 2016, Vol. 26, Issue 4, Pages 417-433.
[19] Chen X, Grzegorczyk TM, Wu BI, Kong JA. Robust method to retrieve the constitutive effective parameters of metamaterials. Physical Review E. 2004; 70(1): 016608. https://doi.org/10.1103/PhysRevE.70.016608
[20] Barroso JJ, Hasar UC. Resolving phase ambiguity in the inverse problem of transmission/reflection measurement methods. Journal of Infrared, Millimeter, and Terahertz Wave.2011; 32(7): 857-866. https://doi.org/10.1007/s10762-011-9800-1