Enhancement of gain using a multilayer superstrate metasurface cell array with a microstrip patch antenna

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ABSTRACT

This research presents a new idea in the use of wireless communication antennas: it uses a multi-layered array of cells called a superstrate multi-layer metasurface (MTM) and is placed in front of a patch of microstrip antenna to absorb surface waves and prevent them from passing through the insulating material, which reduces the permeability of the insulator and thus improves the Antenna properties, The proposed hexagonal cell with resonators is placed on the flame resistant (FR4) substrate, with a relative permittivity of 4.3 and an area (14×14) mm^2. It was tested when the metasurface layer is 4 mm in front of the patch and the distance between the metasurface layers is 2 mm. The optimum distances were calculated by the sweep parameter, and the improved antenna gain and the input reflection coefficient were obtained together. (S11) has been improved from -31.217 to -38.338 dB and, the gain from 3.28 dB to 6.554 dB.

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1. INTRODUCTION

Small planar antennas have a low gain, which must be resolved in order to meet the maximum energy budget of transceiver systems. A metamaterial is a material that has been employed in the design of antennas in addition to using an array antenna. Artificial magnetic materials (AMMs) could be used in this situation. They are used in the antenna's environment by arranging the metamaterials unit cells about the antenna's radiated elements [1]-[3], or by creating a superstructure above or below the radiated parts [4]-[6], or by using metamaterials as the antenna's loading [7]-[10]. Figure 1 depicts how metamaterials have been used as a superstrate to improve antenna gain.

Each of these techniques has its own set of benefits and drawbacks. The number of metasurface layers, the distance between them, the shape of the single cell, the distance between the cell parts that form resonance, and the radiation elements significantly affect the antenna power gain [11]-[14]. The position of the metasurface layer and the number of cells forming the array in front of or behind the bag also has a great effect on the antenna properties, especially the gain, and the number of single cells and the resonant frequency of the built-in antenna affect the gain value [15]-[17]. Artificial magnetic conductors (AMCs) or AMMs are generated by these array unit cells, and they can be loaded on one or both sides of the superstrate. The number of superstrates, unit cells, and distance between the radiation element and the superstrate decide the antenna's power gain [18], [19].

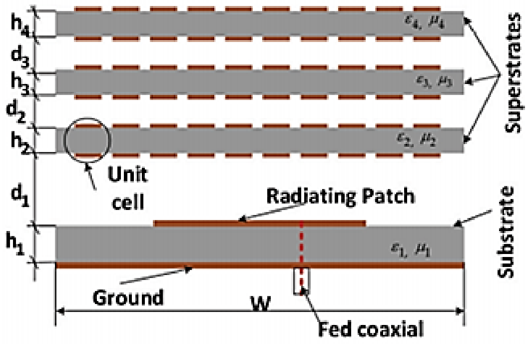
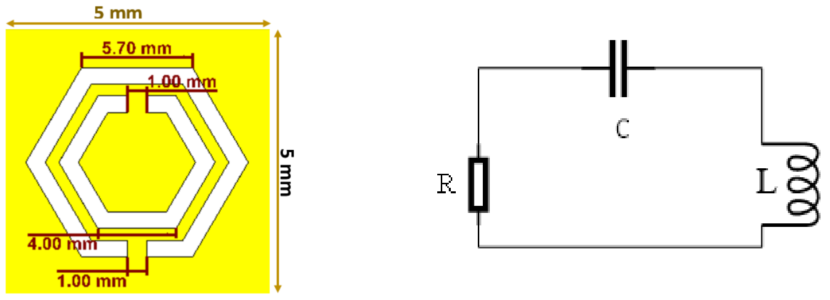


Figure. 1. Metamaterials used as a superstrate to increase the antenna gain

2. DESIGN OF THE METASURFACE UNIT CELL

Two symmetrically arranged hexagonal shaped split ring resonators make up the proposed metamaterial unit cell pentagonal short-range reconnaissance (SRR). The proposed pentagonal SRR's comprehensive dimension structure is shown in Figure 2. A capacitor can be used to depict the separation distance in hexagonal shape patches. The capacitor, on the other hand, fills the gap in the hexagonal shape sides. An inductor provides the conductor bar in the hexagonal shape section. The free space impedance (377) is used to calculate the load resistance [20]-[26]. Figure 3 shows (s_{11}) for the unit cell of metasurface proposed.



(a) (b)

Figure 2. The hexagonal of (a) cell proposed and (b) cell proposed of equivalent circuit

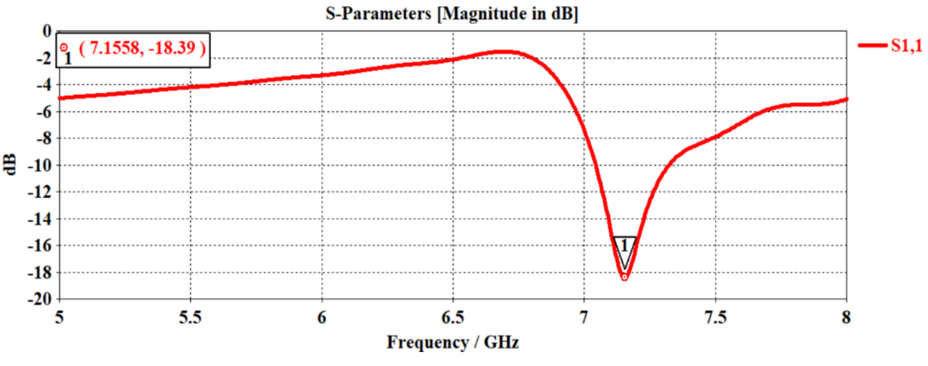


Figure 3. (S_{11}) of unit cell metasurface

3. MICROSTRIP ANTENNA DESIGN

This antenna consists of three layers, a patch, operates at a frequency of 7.26 GHz, flame resistant (FR4) dielectric substrate with a relative permittivity of 4.3 and a thickness of 1.6 mm, and ground plane. Figure 4 shows the antenna's design parameters. The dimensions that are mentioned in Figure 4 is shown in Table 1. When the microstrip antenna was measured at 7.26 GHz the input reflection coefficient (S11) of the -31.217 dB, and the microstrip antenna gain at the same frequency is 3.28 dB as shown in Figures 5 and 6.

Figure 4. The proposed of (a) front patch antenna and (b) ground plane for antenna

Table 1. The designed microstrip antenna's dimensions

Symbol	Quantity	Value (mm)
L_g	Ground plane length	3
W_g	Ground plane width	12
h_t	Copper thickness	0.035
L_s	Substrate length	28.51
h_s	Substrate height	1.6
W_s	Substrate width	33.79
L_f	Feed line length	4.13
W_f	Feed line width	2
Wp	Patch plan width	12

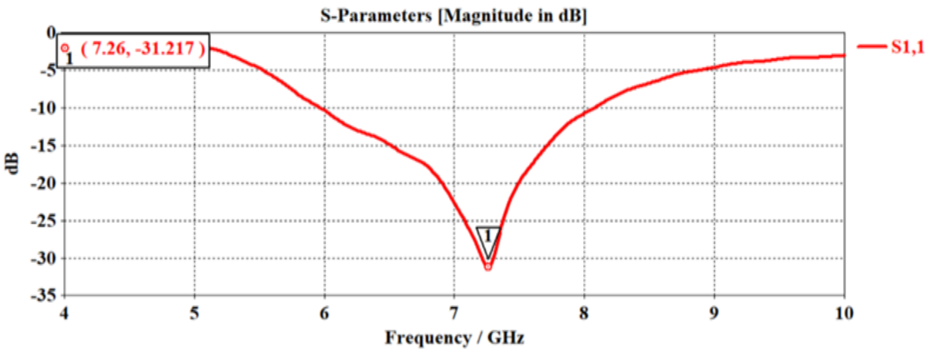


Figure 5. S_{11} of proposed antenna

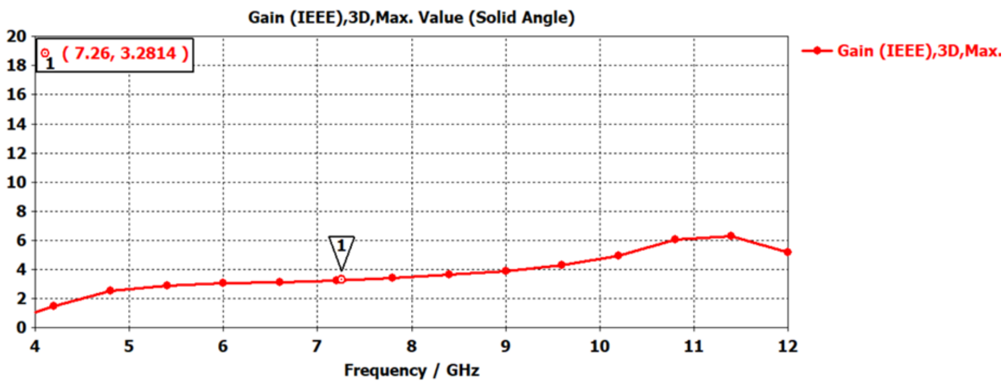
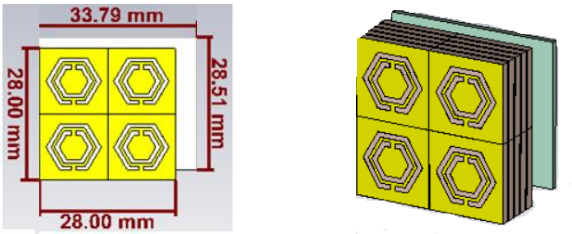


Figure 6. Proposed microstrip antenna gain

4. SUPERSTRATE ANALYSIS OF MULTI-LAYER METAMATERIALS

This section introduces a new idea for using a metasurface as a multilayer superstrate and found it in a positive and effective manner. The metasurface of superstrate is composed of a (2×2) cells of hexagonal shape unit cells and has a total area of (28×28) mm^2. This number of unit cells was chosen because the area of a loaded antenna must be the same or smaller than the patch area, as shown in Figure 7(a). A multi-layer superstrate with the suggested antenna is displayed in Figure 7(b). The suggested antenna was analyzed using the CST microwave studio package.



(a) (b)

Figure 7. The unit cell array (a) geometrical structure of the multi-layer metasurface (MTM) superstrate and (b) side view

5. PARAMETRIC STUDY

The sweep parameter features in the CST software, which selects the ideal values for the antenna elements, is used to generate the best designs that give the highest improvement in the matching impedance resonance and the gain of the microstrip antenna. Figure 8 show the S_{11} of the proposed patch antenna at a different space between the layers and a patch. The distance to reach the optimal result after examining the parametric study results for the maximum input reflection coefficient and the gain is d=4 and the distance between layers is 2 mm as shown in Figures 9 and 10. The position of the metasurface layers is optimized to enhanced the input reflection coefficient as shown in Figure 9, (S11) parameter was equal to -38.338 dB, it validated to be more than (10 dB) indicating good antenna matching.

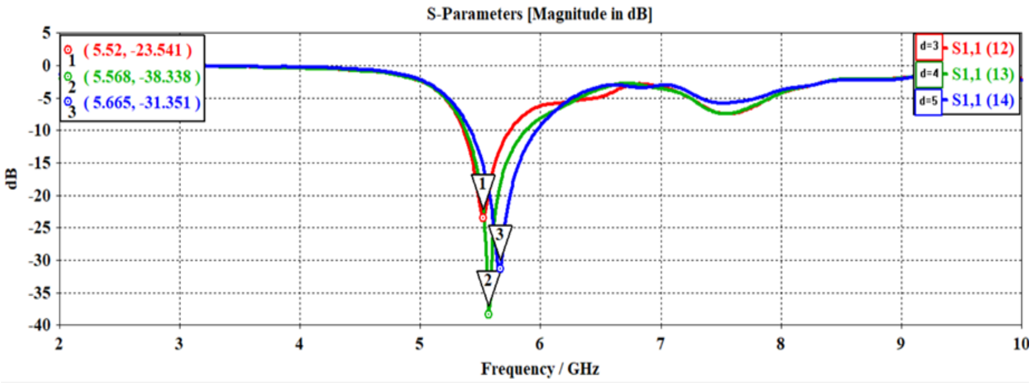


Figure 8. Input reflection coefficient parametric analysis for various distances

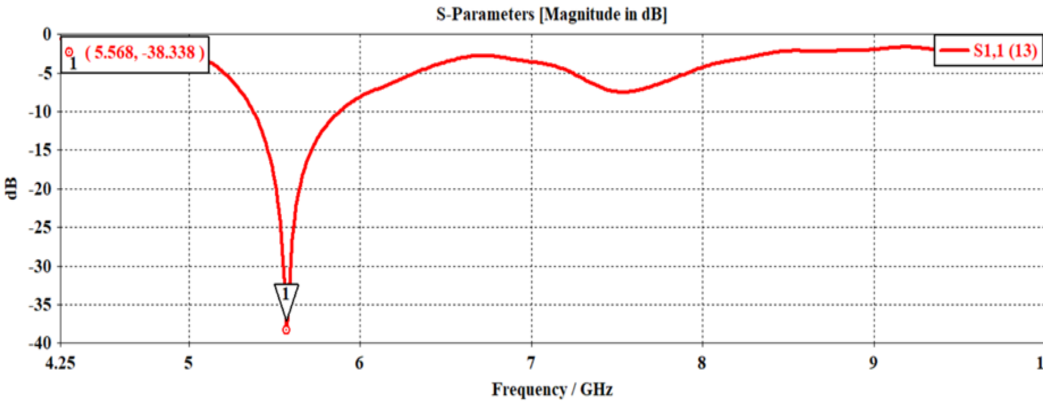


Figure 9. (s_{11}) at a distance of 4 mm

The proposed antenna gain enhancement can be described using Snell's law of refraction, whereby electromagnetic waves are transmitted in the direction of the surface standard by and away from the source where it is a material with a low refractive index. The field distribution of the antenna is also affected by the presence of an MTM superstrate. One of the most important features is to improve the gain of the microstrip antenna, in this case, is enhanced as shown in Figure 10. Figure 11 is shown voltage standing wave ratio (VSWR) was calculated and validated to be less than 2, indicating that the antenna matching was satisfactory because VSWR is a measurement of the mismatch between the antenna and the feeding system. Larger the mismatch, the higher the VSWR. The smallest value of VSWR is unity, which results in a perfect match. The proportion of maximum to minimum voltages is referred to as VSWR.

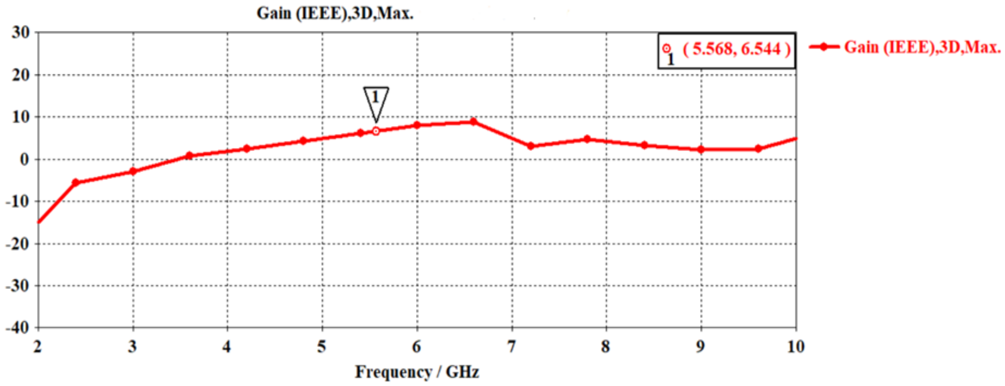


Figure 10. The gain for proposed antenna with multi-layer superstrate

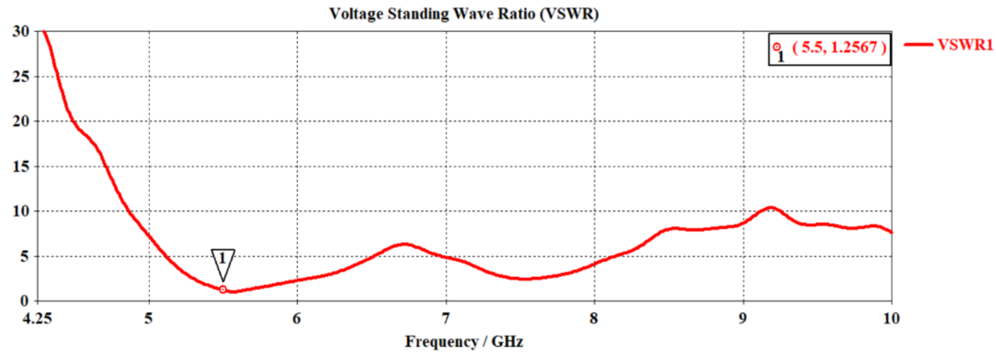


Figure.11. VSWR at the distance 4 mm

When the metasurface is applied over the microstrip antenna patch, we observe a frequency shift when the dielectric property of the substrate is changed as shown in the (1),

$$f_r = \frac{f_o}{\sqrt{\varepsilon_r}} \tag{1}$$

where, f_0 is operating of frequency (GHz), f_r is resonant of frequency (GHz), and ε_r is relative of permittivity Table 2 compares the proposed antenna without a metasurface to the proposed one with a multi-layer metasurface.

Table 2. Comparison between characteristics antennas

Case of antenna	Frequency (GHz)	Input reflection coefficient value (dB)	Gain value(dB)
Without metasurface	7.26	-31.217	3.28
With a multi-layer metasurface	5.5	-38.338	6.544

6. CONCLUSION

One of the most important conclusions that have been reached when using a metasurface with the antenna is the significant improvement in the antenna properties, including the growth of reflection coefficient and the gain, as well as the number and shape of the metasurface cells, the distance between the components of the unit cell and the distance between the cells forming the array has a significant impact on the properties of the antenna and the location of the metasurface in front of the patch or ground also has an effect on the gain as a multi-layer MTM superstrate layer has been developed on the microstrip antenna patch. For the purpose of wireless communication, the hexagonal cells are placed on a FR-4 substrate with a total area of (14x14) mm^2. The MTM substrate layers are in front of the patch and the metasurface layer is 4 mm apart and the distance between the super layers is 2 mm. The antenna gain and reflection coefficient are increased together. (S_{11}) was improved from -31.217 dB to -38.338 dB and the gain was improved to 6.544 dB.

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REFERENCES

[1] X. Gao, T. Cai, and L. Zhu, "Enhancement of gain and directivity for microstrip antenna using negative permeability metamaterial," *Int. J. Math. Comp. Sci.*, vol. 70, no. 7, pp. 880-885, 2016, doi: 10.1016/j.aeue.2016.03.019.

[2] D. Kim and J. Choi, "Analysis of antenna gain enhancement with a new planar metamaterial superstrate: An effective medium and a fabry-pérot resonance approach," *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 31, no. 11, pp. 1289-1303, 2010, doi: 10.1007/s10762-010-9712-2.

[3] P. J. F. Gonzalez, "Multifunctional metamaterial designs for antenna applications," PhD Thesis, Department of Signal Theory and Communications, Universitat Politecnica de Catalunya, Barcelona, Spain, 2015.

[4] H. Mosallaei and K. Sarabandi, "Design and Modeling of Patch Antenna Printed on Magneto-Dielectric Embedded-Circuit Metasubstrate," *IEEE Tran. Ant. Pro.*, vol. 55, no. 1, pp. 45-52, 2007, doi: 10.1109/TAP.2006.886566.

[5] R. Grimberg, "Electromagnetic metamaterials," *Materials Science and Engineering: B*, vol. 178, no. 19, pp. 1285-1295, 2013, doi: 10.1016/j.mseb.2013.03.022.

[6] C. Caloz, A. Sanada, and T. Itoh, "A novel composite right-/left-handed coupled-line directional coupler with arbitrary coupling level and broad bandwidth," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 3, pp. 980-992, March 2004, doi: 10.1109/TMTT.2004.823579.

[7] Y. Liu, X. Guo, S. Gu, and X. Zhao, "Zero index metamaterial for designing high-gain patch antenna," *International Journal of Antennas and Propagation*, 2013, doi: 10.1155/ 2013/215681.

[8] T. N. Cao and W. J. Krzysztofik, "Multiband fractal antenna for C-band ground station of satellite TV in ITU region-3," *21st Int. Conf. Micro., Rad. Wir. Comm.*, 2016, pp. 1-4, doi: 10.1109/MIKON.2016.7491946.

[9] F. Raval, Y. P. Kosta, and H. Joshi, "Reduced size patch antenna using complementary split ring resonator as defected ground plane," *Int. J. Elec. Comm.*, vol. 69, no. 8, pp. 126-1133, 2015, doi: 10.1016/j.aeue.2015.04.013.

[10] R. Rajkumar and K. U. Kiran, "A compact metamaterial multiband antenna for WLAN/WiMAX/ ITU band applications," *AEU – Int. J. Elec. Comm.*, vol. 70, no. 5, pp. 599-604, 2016, doi: 10.1016/j.aeue.2016.01.025.

[11] A. A. Jabber, A. K. Jassim, and R. H. Thaher, "Compact reconfigurable PIFA antenna for wireless applications," *TELKOMNIKA Telecommunication Computing Electronics and Control*, vol. 18, no. 2, pp. 595-602, 2020, doi: 10.12928/telkomnika.v18i2.13427.

[12] Z. Szabó, G. Park, R. Hedge, and E. Li, "A Unique Extraction of Metamaterial Parameters Based on Kramers–Kronig Relationship," *IEEE Tran. Micro. The. Tech.*, vol. 58, no. 10, pp. 2646-2653, 2010, doi: 10.1109/TMTT.2010.2065310.

[13] A. Benedetti, C. Sibilia, and M. Bertolotti, "Wideband negative magnetic permeability materials (NMPM) with composite metal-semiconductor structures based on the Drude model, and applications to negative-refractive index (NIM)," *Opt. Express*, vol. 15, no. 11, pp. 6534-6545, 2007, doi: 10.1364/OE.15.006534.

[14] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Low-frequency plasmons in thin-wire structures," *J. Phys. Condens. Matter*, vol. 10, no. 22, 1998, doi: 10.1088/0953-8984/10/22/007.

[15] J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, "Extremely low-frequency plasmons in metallic mesostructures," *Phys. Rev. Lett.*, vol. 76, no. 25, pp. 4773-4776, 1996, doi: 10.1103/PhysRevLett.76.4773.

[16] A. Alu and N. Engheta, "Pairing an epsilon-negative slab with a mu-negative slab: resonance, tunneling and transparency," *IEEE Tran. Ant. Pro.*, vol. 51, no. 10, pp. 2558-2571, 2003, doi: 10.1109/TAP.2003.817553.

[17] D. R. Smith, D. C. Vier, T. Koschny, and C. M. Soukoulis, "Electromagnetic parameter retrieval from inhomogeneous metamaterials," *Phys. Rev. E*, vol. 71, no. 3, 2005, doi: 10.1103/PhysRevE.71.036617.

[18] A. K. Jassim, M. J. Farhan, and A. F. Fahad, "Design selective band antenna using coupling sidewall and multi resonator for wireless communications," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 5, pp. 2206-2212, 2020, doi: 10.11591/eei.v9i5.2247.

[19] J. Baker-Jarvis, E. J. Vanzura, and W. A. Kissick, "Improved technique for determining complex permittivity with the transmission/reflection method," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 38, no. 8, pp. 1096-1103, Aug. 1990, doi: 10.1109/22.57336.

[20] X. Chen, T. M. Grzegorczyk, B-I. Wu, J. Pacheco, and J. A. Kong, "Robust method to retrieve the constitutive effective parameters of metamaterials," *Phys. Rev. E*, vol. 70, no. 1, 2004, doi: 10.1103/PhysRevE.70.016608.

[21] H. A. Majid, M. K. A. Rahim, and T. Masri, "Left handed metamaterial design for microstrip antenna application," *2008 IEEE International RF and Microwave Conference*, 2008, pp. 218-221, doi: 10.1109/RFM.2008.4897426.

[22] G. Kiziltas and J. L. Volakis, "Miniature antenna designs on metamaterial substrates," *8th Int. Conference on Electromagnetics in Advanced Appl. (ICEAA), Conf. Proceedings*, 2003, pp. 431-434.

[23] Y. Dong and T. Itoh, “Metamaterial-Based Antennas,” in *Proceedings of the IEEE*, vol. 100, no. 7, pp. 2271-2285, July 2012, doi: 10.1109/JPROC.2012.2187631.

[24] A. K. Jassim and R. H. Thaher, “Design and analysis microstrip antenna with a reflector to enhancement gain for wireless communication,” *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 2, pp. 652–660, 2020, doi: 10.11591/eei.v9i2.1696.

[25] K. Aydin and E. Ozbay, “Left-handed metamaterial-based superlens for subwavelength imaging of electromagnetic waves,” *Appl. Phys. A*, vol. 87, no. 2, pp. 137–141, 2007, doi: 10.1007/s00339-006-3817-4.

[26] R. M. Salih and A. K. Jassim, “Microstrip patch antenna with metamaterial using superstrate technique for wireless communication,” *Bulletin of Electrical Engineering and Informatics*, vol. 10, no. 4, pp. 2055-2061, 2021, doi: 10.11591/eei.v10i4.2722.

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