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Analysis and Implementation of Metamaterial-Inspired Microstrip Antenna for Wireless Applications

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Abstract. In this paper, a novel metamaterial-inspired microstrip antenna for wireless applications is proposed. The proposed design consists of a radiating path on top and a uniformly distributed split ring-shaped metamaterial structure on the ground. The presented antenna of 50×38 mm with a thickness of 1.6 mm is printed on FR_4 substrate and resonates at 1.80 GHz. The design was fabricated and the measured results were found to be in accordance with the simulations. The goal is accomplished by loading uniformly distributed split ring-shaped metamaterial structures on the ground plane of this antenna. The results of the experiments show that using the metamaterial structure on the ground plane improved gain from 4.34 to 7.3 dB, efficiency from 5.94 to 7.8 dB compared to the conventional patch antenna. This introduction in the ground plane exhibits return loss up to –38 dB and modified the gain and directivity to 7.3 and 7.8 dB respectively. The presented antenna has 45 MHz bandwidth. The presented design is proven by simulated surface current, S parameter, VSWR, radiation pattern. We have also investigated the effect of substrate permittivity, split width, and inter-element spacing in a split ring-shaped metamaterial structure on return loss. This directive antenna is designed for the applications of wireless local area networks and other Internet of things-based applications.

Keywords: metamaterial, directivity, gain, split ring

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Анализ и использование микрополосковой антенны на основе метаматериала для беспроводной связи

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Реферат. В данной статье предлагается новая микрополосковая антенна на основе метаматериалов, обеспечивающая беспроводную связь. Предлагаемая конструкция состоит из трассы распространения излученной волны, располагающейся сверху, и равномерно распределенной структуры метаматериала в форме расщепленного кольца, которая располагается на земле. Представленная антенна размером 50×38 мм, толщиной 1,6 мм напечатана на FR_4-подложке

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и резонирует на частоте 1,80 ГГц. Антенна данной конструкции была изготовлена, а полученные результаты измерений соответствуют ранее смоделированным. Цель достигается за счет загрузки равномерно распределенных структур метаматериала в форме разрезных колец на заземленную плоскость этой антенны. Результаты экспериментов показывают, что использование конструкции из метаматериала на заземленной плоскости позволило улучшить усиление сигнала с 4,34 до 7,3 дБ, эффективность с 5,94 до 7,8 дБ по сравнению с обычной патч-антенной. Предложенное нововведение в экран антенны позволяет свести обратные потери до –38 дБ, а также улучшить значения коэффициента усиления антенны и коэффициента ее направленности до 7,8 и 7,8 дБ соответственно. Представленная антенна имеет полосу пропускания 45 МГц. Предлагаемая конструкция апробирована с помощью смоделированного поверхностного тока, параметра S, VSWR (коэффициент стоячей волны напряжения), диаграммы направленности антенны. Авторы также исследовали влияние диэлектрической проницаемости подложки, ширины разделения и межэлементного расстояния в структуре метаматериала в форме расщепленного кольца на обратные потери. Предлагаемая направленная антенна предназначена для приложений беспроводных локальных сетей, а также других приложений в Интернете.

Ключевые слова: метаматериал, коэффициент направленности, коэффициент направленного действия, разъемное кольцо

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Introduction

Printed antennas have been in demand in recent years, and this demand attracts global researchers around the world to work on microstrip antennas and produce significant results in response to the growing demand. Other Internet of Things (IoT)-based applications and wearable technologies are now using microstrip antennas, expanding their use beyond WLAN and satellite communication.

Researchers have applied available techniques to improve antenna parameters such as resonating frequency, return loss, bandwidth, VSWR, gain, and radiation pattern in recent years. Among them, metamaterial seems to be the most promising technique available.

In recent years, metamaterial has emerged as the most promising technique, prompting extensive research on its potential to improve antenna parameters. Stu Wolf and Valerie Browning from the DARPA Defense Advanced Research Projects Agency highlight that Metamaterial Technology (MTM) represents an innovative category of anticipated combinations that exhibit exceptional features not observed in the environment. These features come from qualitatively novel response tasks that are not found in element materials and are the result of extrinsic, short, artificial homogeneities.

There is no particular definition available, that is universally accepted, but generally, it is defined as a structure that contains some unusual properties that are not found in nature [1, 2].

Metamaterials have properties that don't come from the materials themselves, but rather from the structures they are made of. Their shape, size, orientation, and arrangement make them smart enough to manipulate electromagnetic waves in ways that go beyond what is not possible with regular materials. To get benefits, they can enhance, block, or even absorb bending waves.

Recently reduction in radar cross-section was achieved by implementing polarization conversion metamaterial [3], metamaterial could be the combination of variously shaped structures, it may contain only a split and a thin wire as a combination or it can be a group of SRRs [4–6].

Printed antenna with slots on the ground plane has also been trending along with the metamaterial [7–10], as this is also the effortless technique available to modify the antenna parameters.

Ref [11] presents an MTM-based magneto dielectric structure that helps in miniaturization. The given antenna has problems, particularly its complex construction and its inability to improve antenna parameters. This presented work includes a modification of the patch antenna utilizing the SRR metamaterial structure on the ground plane, which significantly enhances antenna parameters.

Due to the compact design of MPA, it attracts researchers to match the requirements of communication equipment [12]. The authors have proposed a wide range of metamaterial structures so far. Parameter enhancement after implementing metamaterial is achieved [13].

Ref [14] describes RMPA resonating at 1.8 GHz. The antenna's electrical dimension is 51×73 mm. The presented antenna in this paper is smaller than the stated antenna. Incorporating a metamaterial on the ground plane offers higher gain enhancement and compactness in comparison to previously published antennas.

In Ref [15], it has been demonstrated that patch antennas can be reduced in size by incorporating metamaterial structure on the ground plane. Using metamaterial, return loss, size reduction are achieved.

A lower dielectric constant and a thicker substrate improve the antenna's performance by providing a larger bandwidth, improved radiation, and increased efficiency. If the substrate is thin, then it increases the size of the antenna [16]. We use a substrate with a higher dielectric constant, which consequently reduces bandwidth and efficiency. Hence, there is a tradeoff between antenna dimensions and antenna performance.

Ref [17] tried to reduce the antenna size. Despite achieving some miniaturization, the reported antenna gain remains extremely low. It may be challenging to decrease the size of the antenna in an existing system while maintaining a high gain.

There have been numerous reports of microstrip patch antennas with reduced sizes. Various techniques such as Metamaterial loaded patch [18–19], Minkowski and Koch Fractal [20], Shorting pin [21], CLRH transmission line [22], and Defected Ground Structure [23–26] were used to miniaturize the antenna.

For WLAN applications, a small patch that incorporates the λ/4 resonator has been presented in [27] for improving the bandwidth and gain of the antenna. The antenna's electrical dimensions are 40×30 mm^2. This method did not significantly enhance the gain compared to the proposed antenna in this paper.

Over the past few years, demand for highly efficient and compact antennas has steadily increased. A small and cheap antenna has always been favorable. The proposed study will implement SRR metamaterial on the ground plane to minimize the size of patch antennas. This implementation reduces the antenna size while improving gain and return loss.

The design process includes geometrical design, calculation, simulation, and comparison of results with or without MTM. The CST 2018 Microwave Studio serves as a tool for design and simulation. The first step in the modeling process is to determine its dimensions based on the operating frequency. After designing and comparing it with the measured demand, we will determine whether the proposed antenna fulfills all the desired characteristics or not. If not, we will proceed with further modifications. The focus will be on providing a small, tunable antenna.

This paper proposes the use of a novel metamaterial structure. This proposed work involves a modification of the patch antenna using the metamaterial structure on the antenna's ground plane. This introduction not only improved the antenna's return loss but also increased the BW, gain, and directivity. This paper presents a directive antenna with improved return loss, increasing a return loss of –38 dB and modifying gain and directivity to 7.3 and 7.8 dBi, respectively. This antenna is suitable for wireless applications.

We have divided this paper into the following sections: The second section discusses motivation. Section 3 introduces antenna geometry and construction. Section 4 presents a parametric analysis. Section 5 presents the simulation and measurement results, along with a comparison of other published literature. In Section 6, we present the conclusion.

Motivation

Motivations come from the in-depth literature review, which shows that the need for smaller, smarter, and cheaper products has emerged, and the demand has been on the rise for several years. At microwave frequencies, MPA is very attractive because of its various advantages, such as its low profile, low weight, and low cost.

There is a lot of research being done on antennas for radio amateur communication and other portable applications. As a result, it proves that MPA generates good-quality radiation, but patch elements have the disadvantage of low gain. In recent years, researchers have applied available techniques to improve antenna parameters such as resonating frequency, return loss, bandwidth, VSWR, gain, and radiation pattern. Microstrip antennas are the most cost-effective option for meeting such demands due to their fabrication process, which is largely dependent on printed circuit technology. Additionally, they are smaller than other antennas. Furthermore, they are very thin, making them compatible with integrated circuit technology. In recent years, metamaterial has emerged as the most promising technique, attracting research to enhance antenna parameters.

Design of Patch antenna loaded with MTM

We designed a microstrip patch using an FR4 (lossy) substrate with a dielectric constant of and a width of 1.6 mm. We designed this antenna for a wide range of WLAN applications. Strip fed was used in the design of this proposed antenna. The simulation was done on CST Version 2018 and then results were analyzed.

The following Mathematical equations are used to approximate patch antenna design [28–30], unit cell SRR:

$$W=\frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}}; \qquad (1)$$

$$L_{eff}=\frac{c}{2f_{r\sqrt{\epsilon_r}}}; \qquad (2)$$

$$L=L_{eff}-2\Delta L; \qquad (3)$$

$$\Delta L=h(0.412)\frac{\left(\varepsilon_{reff}+0.3\right)\left(\frac{h}{W}+0.264\right)}{\left(\varepsilon_{reff}-0.258\right)\left(\frac{h}{W}+0.8\right)}; \qquad (4)$$

$$\varepsilon_{reff}=\frac{\varepsilon_r+1}{2}=\frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2}. \qquad (5)$$

Based on the above calculations, using a permittivity of 4.4 & thickness of 1.6 mm, the presented antenna design on frequency 1.8 GHz requires a size of 50 mm width, 38 mm length. In this paper, we present an antenna that resonates at 1.8 GHz. Fig. 1 shows the proposed patch, all the dimensions are in mm.

The proposed rectangular patch consists of a 50×38 mm. After designing this patch, a simulation was done and the results were analyzed. The optimized dimensions of the designed rectangular patch (Patch I) are as follows (in mm) as shown in Table 1.

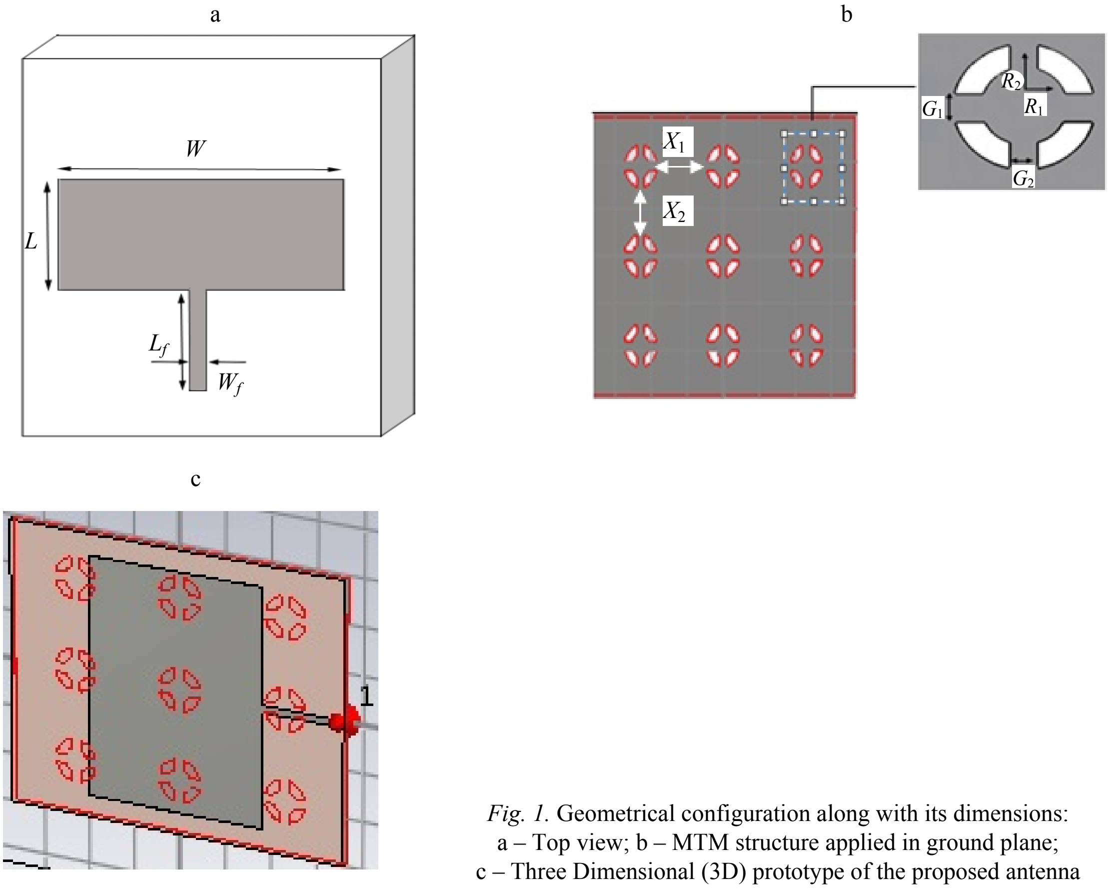


Fig. 1. Geometrical configuration along with its dimensions:
a – Top view; b – MTM structure applied in ground plane;
c – Three Dimensional (3D) prototype of the proposed antenna

Table 1

Dimensions of designed RMPA

Parameter	Value (mm)
Patch's Width (W)	50
Patch's Length (L)	38
Substrate thickness (t_s)	1.6
ground plane thickness (t_g)	0.036
Width of Feed line (W_f)	1.5
Dielectric constant of substrate	4.3
Length of Feed line (L_f)	16.5

After designing the conventional rectangular patch antenna, the metamaterial structure complies with SRRs [31–33] was implemented in the ground plane.

The Proposed SRR used in the MTM structure is shown in Fig. 1 (b).

$$\lambda = \frac{c}{f} = \frac{3x \cdot 10^8}{1.8x \cdot 10^9} = 0.1666 \text{ m}; \qquad (6)$$

$$\frac{\lambda}{4} = \frac{0.1666}{4} = 0.04165 \text{ m} = 41.65 \text{ mm}.$$

- Outer ring radius (R_2): 4.5 mm.
- Inner ring radius (R_1): 2.5 mm.
- Area of outer ring radius: $\pi R_2^2 = 63.58$ mm^2.
- Area of Inner ring radius: $\pi R_1^2 = 19.62$ mm^2.
- Area of the ring = (63.58–19.62) = 43.98 mm^2.

Taking square root (in meter) = 6.63 mm.

So the design unit cell-driven MTM has size < λ / 4.

The dimensions of the proposed SRR used in the MTM structure as (in mm) shown in Table 2.

Table 2

Dimensions of proposed SRR

Parameter	Value (mm)
Ring's inner radius (R_1)	2.5
Ring's outer radius (R_2)	4.5
Horizontal split gap (G_1)	1.6
Vertical split gap (G_2)	0.036
Distance of horizontal separation Between two SRR (X_1)	23
Distance of Vertical separation Between two SRR (X_2)	19

After creating the initial SRR, a combination of these prototypes was combined and implemented. The proposed metamaterial structure, implemented in the ground plane of the antenna is presented in Fig. 1c. This proposed structure is the combination of 9 SRR separated with the distance of $X_1 = 23$ mm and $X_2 = 19$ mm.

A 3D model and geometry of the proposed antenna can be seen in Fig. 1a, b, and c. Fig. 2a–b shows the fabricated prototype on the FR$_4$ substrate. Fig. 2c–e illustrates the design procedure during the development stages of Metamaterial Structures.

Parametric Study

A) Effect of split width G$_1$ and G$_2$ on S parameter

This section explains the impact on S11 characteristics of the Antenna by varying various parameters of the unit cell on the ground plane.

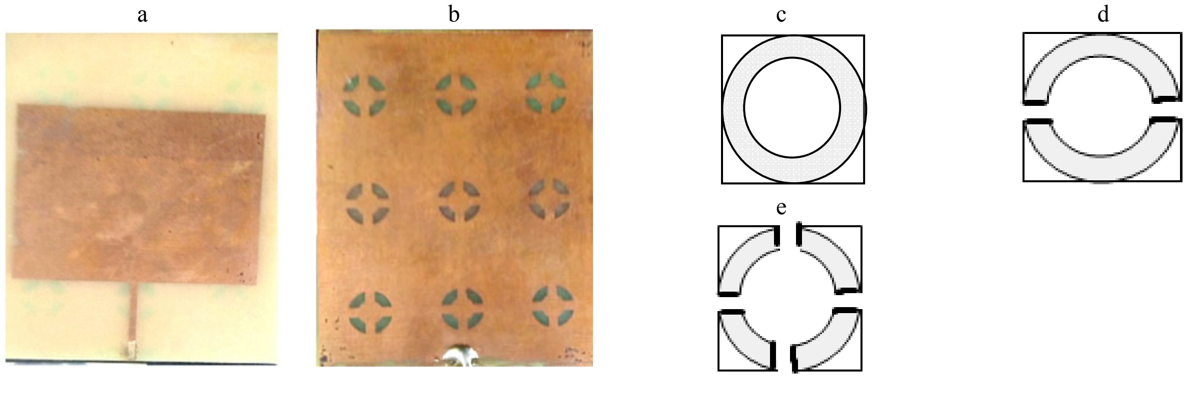


Fig. 2. a, b – Top and bottom view of the proposed fabricated antenna; c–e – Development stages of the proposed MTM Unit Cell

Fig. 3 shows a parametric study of the Width "G_1" of the periodical split ring resonator designed on the ground plane and their impact on the S11 characteristics of the proposed antenna. Width is changed from 1 to 3 mm in a step of 1 mm. The effect of increasing the split width G_1 decreases the capacitance which in turn increases the resonant frequency [G_1 = 1 mm, F_r =1.79 GHz, G_1 = 2 mm, F_r = 1.805 GHz, G_1 = 3 mm, F_r = 1.82 GHz].

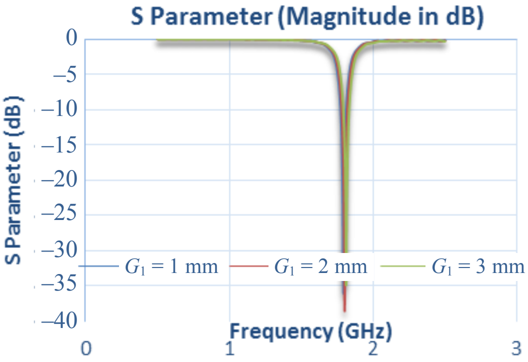


Fig 3. S Parameter for different values of parameter "G_1"

Fig. 4 shows the impact on the S11 characteristics of the antenna by varying the width "G_2" of the periodical split ring resonator designed on the ground plan. We change the width from 1 to 3 mm in steps of 1 mm. In the proposed design, the introduction of the second split G_2 connects the capacitance in series, leading to a decrease in the overall capacitance and an increase in the resonant frequency [G_2 = 1 mm, F_r = 1.77 GHz, G_2 = 2 mm, F_r = 1.805 GHz, G_2 = 3 mm, F_r = 1.82 GHz].

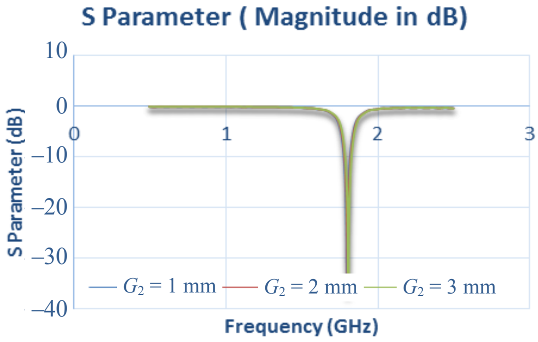


Fig. 4. S Parameter for different values of parameter "G_2"

B) Effect of inter-element spacing on S parameter

This section explains the impact of changing the metal width of the inner and outer ring on the S parameter. Increasing the metal width of the rings decreases the mutual inductance as well as capacitance. Therefore SRR with narrow rings as shown in the Fig. 5 have smaller resonant frequencies.

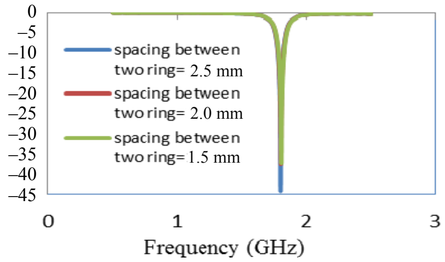


Fig. 5. Impact on S Parameter by changing Inter element spacing

C) Effect of Substrate Permittivity on S Parameter

The impact on the S11 parameter by changing the substrate permittivity is shown in Fig 6. S11 parameter considering different permittivity's as Rogers RO3003 ($\varepsilon_r = 3$), FR4 ($\varepsilon_r = 4.3$), Rogers RT6006 ($\varepsilon_r = 6.45$).

By increasing the substrate permittivity the resonant frequency shifts toward the lower side because it has an inverse relationship with permittivity (ε_r).

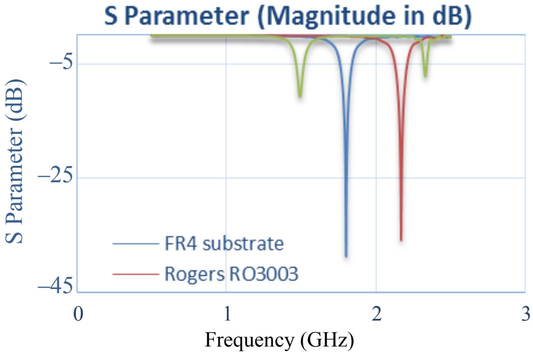


Fig. 6. The impact on the S11 parameter by changing the substrate permittivity

Result and Discussion

We simulated the antenna design in CST version 18 to get the antenna performance analysis. The results are as follows.

A. Frequency characteristics

Below, we present the surface current distribution and return loss, which aid in understanding the frequency characteristics of the proposed design antenna.

I. Return loss

Fig. 7 shows the comparison of the reflection coefficient before metamaterial implementation and after metamaterial incorporation. After metamaterial inclusion, significant improvement was observed. We simulated and analyzed the proposed antenna with a novel metamaterial structure; the conventional antenna did not have parameters that could meet the demand.

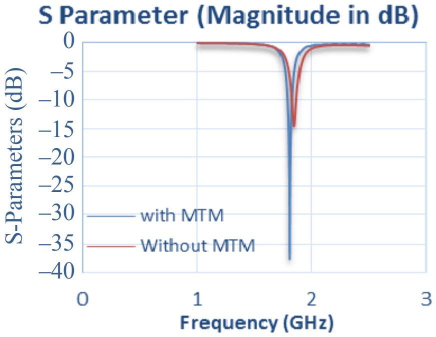


Fig. 7. Comparison of the reflection coefficient with and without MTM

To make it usable, amendments were required. After SRR implementation in the ground plane, the following Fig. 8 shows S11 variation during the development stages of MTM, focusing on three configuration ring with no cut, with one cut and double cut.

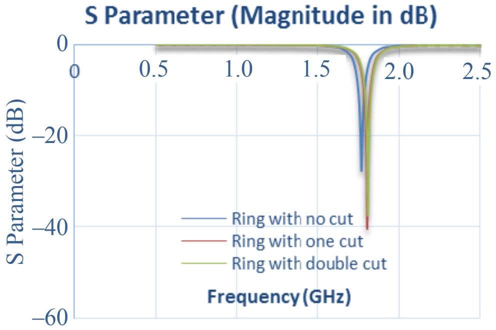


Fig. 8. S11 during the development stages of MTM

It can be observed that the Conventional proposed antenna has a return loss of –11 dB whereas after metamaterial implementation having a return loss of –38 dB shown in Fig. 7.

II. Current distribution

Fig. 9 (a–b) shows the surface current distribution of the proposed antenna at 1.8 GHz.

III. Radiation pattern

Fig. 10 shows the simulated radiation pattern of the presented antenna at different cut angles. Fig. 11a, b illustrates the 3D radiation pattern of a conventional patch antenna, showing gain and directivity, and Fig. 11c, d after metamaterial implementation at 1.8 GHz, showing gain and directivity.

Fig. 9. Distribution of surface current in the proposed antenna (a) front (b) back

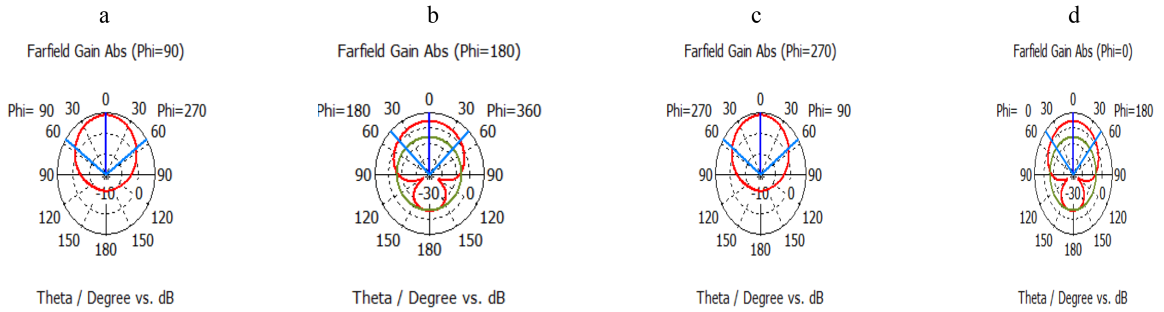
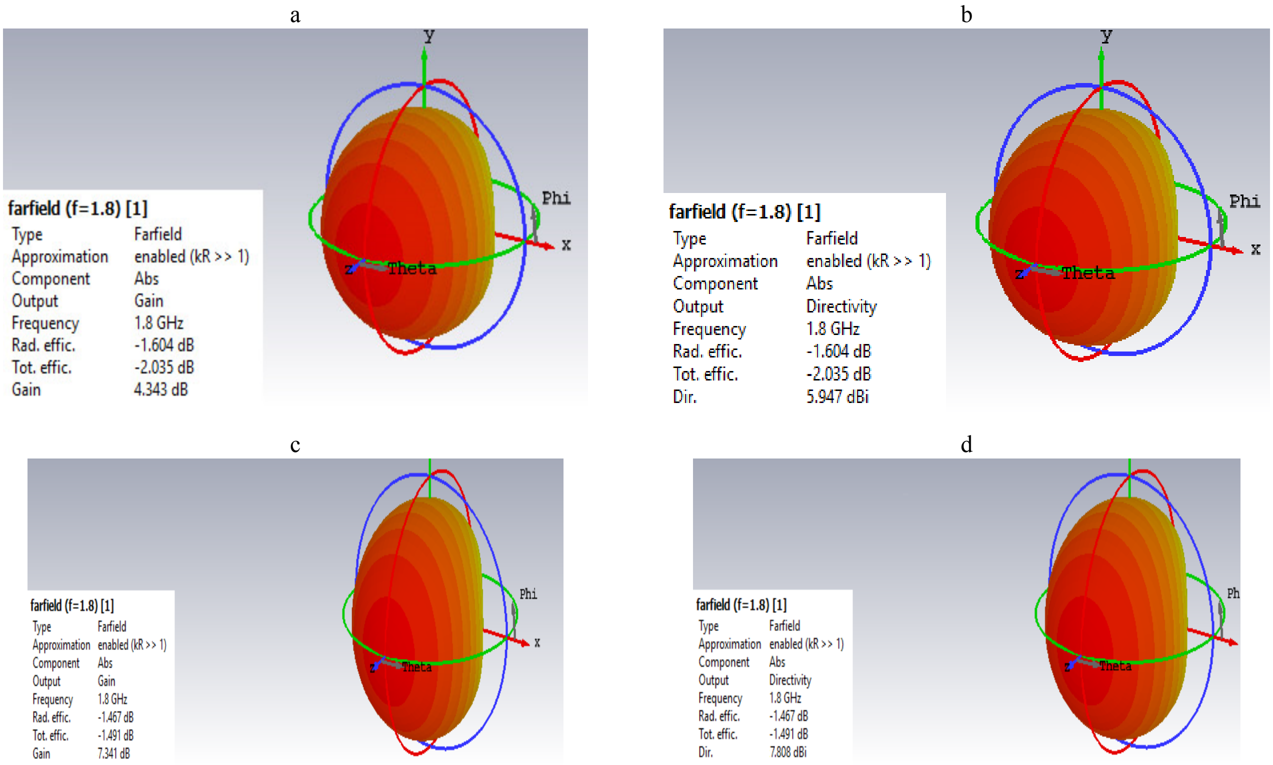


Fig. 10. Radiation pattern of the presented antenna at different cut angles:
a – 90 degree; b – 180; c – 270; d – 0/360 degree



a

farfield (f=1.8) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	1.8 GHz
Rad. effic.	-1.604 dB
Tot. effic.	-2.035 dB
Gain	4.343 dB

b

farfield (f=1.8) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Directivity
Frequency	1.8 GHz
Rad. effic.	-1.604 dB
Tot. effic.	-2.035 dB
Dir.	5.947 dBi

c

farfield (f=1.8) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	1.8 GHz
Rad. effic.	-1.467 dB
Tot. effic.	-1.491 dB
Gain	7.341 dB

d

farfield (f=1.8) [1]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Directivity
Frequency	1.8 GHz
Rad. effic.	-1.467 dB
Tot. effic.	-1.491 dB
Dir.	7.808 dBi

Fig. 11. Radiation pattern of conventional patch antenna showing gain and directivity (left side) and after Metamaterial Implementation (right side) at 1.8 GHz showing Gain & Directivity (c–d)

B. Measured result

We have developed an antenna by loading a uniformly distributed split ring-shaped metamaterial on the ground plane resonating at 1.8 GHz for WLAN applications. We perform the measurement using the Portable Spectrum Analyzer Model TW4950. Fig. 12 shows a comparison of the simulated and measured return losses. The simulated and measured values of the gain are fairly close to each other.

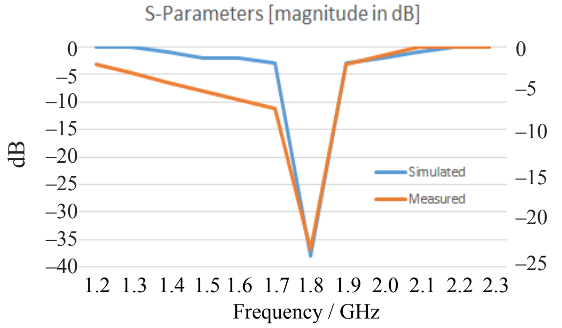


Fig. 12. Comparison of the simulated & measured return loss

Table 3

Illustrates the comparison between the performance of the presented MTM antenna to that of reference antennas [12, 16, 21–23, 25–27]. Compared with existing design, the presented antenna has better return loss, gain, directivity

Ref.	Antenna Dimensions (mm)	Frequency (GHz)	Antenna Parameter				Technique
			Return Loss (dB)	BW (MHz)	Gain (dB)	Directivity (dB)	
1	2	3	4	5	6	7	8
[11]	80×80 60×60	1.8	–17.5 –24	– 39	– 3.54	– –	Conventional FR$_4$ antenna Metamaterial based Magneto dielectric antenna
[14]	51×73	1.8	–15.61	43	4.39	–	Conventional Rectangular patch antenna

Ending of Table 3

1	2	3	4	5	6	7	8
[15]	51×38 41×28	1.8	–22.5 –25	– –	– –	– 5.45	Traditional microstrip patch antenna Array of 5 split ring resonators (SRRs) unit cells
[17]	30×30 24×24	1.76		25 50	2.11 –12	– –	First Design – 2 parallel Interdigital capacitors. Second design-interdigital capacitor and a spiral inductor
[34]	49×12	1.8	–23	–	–0.67	–	Electrically small antenna
[35]	50×40 32×18	1.8	–12 –34	– –	– –	– 6.14	Traditional RMPA Substrate with left hand metamaterial
[36]	40×40	1.76	–14	35	5.4	–	antenna with CRLH loading
[37]	23×58	1.76	–19	27	6.4	–	MTM transmission line
Proposed Antenna	50×38	1.8	–11 –38	42.6 45	4.34 7.3	5.94 7.8	Conventional patch alone Array of 9 Split Ring Shaped Meta material Structure

CONCLUSION

The proposed metamaterial structure, which has nine split-ring resonators on the ground plane of the conventional patch, implies that a metamaterial structure can significantly improve antenna characteristics. Modifications to the antenna structure's geometry alter the antenna's performance parameters, including resonating frequency, return loss, bandwidth, VSWR, gain, and radiation pattern. A comparison with the existing results and the conventional patch reveals an improvement in the parameter modification. The author noted that researchers could achieve promising results if they preferred metamaterials along with conventional methods.

REFERENCES

1. Cao W., Zhang B., Liu A., Yu T., Guo D., Pan X. (2012) Multi- Frequency and Dual-Mode Patch Antenna Based on Electromagnetic Band-gap (EBG) Structure. *IEEE Transactions on Antennas and Propagation,* 60 (12), 6007–6012. https://doi.org/10.1109/tap.2012.2211554.
2. Metamaterials: The Complete Definition, History & Applications, 2016.
3. Liu Y., Hao Y., Li K., Gong S. (2016) Radar Cross Section Reduction of a Microstrip Antenna Based on Polarization Conversion Metamaterial. *IEEE Antennas and Wireless Propagation Letters*, 15, 80–83. https://doi.org/10.1109/lawp.2015.2430363.
4. Pandeeswari R., Raghavan S. (2015) Microstrip Antenna with CSRR Loaded Ground Plane for Gain Enhancement. *Micro-wave and Optical Technology Letters*, 57 (2), 292–296. https://doi.org/10.1002/mop.28835.
5. Hu J. R., Li J. S. (2014) Compact Microstrip Antennas using CSRR Structure Ground Plane. *Microwave and Optical Technology Letters*, 56, 117–120. https://doi.org/10.1002/mop.28023.
6. Wang N., Zhang C., Zeng Q., Wang N., Xu J. (2013) New Dielectric 1D EBG Structure for the Design of Wideband Dielectric Resonator Antennas. *Process in Electromagnetic Research*, 141, 233–248. https://doi.org/10.2528/pier13061207.
7. Dastranj A., Imani A., Naser-Moghaddasi M. (2008) Printed Wide-slot Antenna for Wideband Application. *IEEE Transactions on Antennas and Propagation*, 56 (10), 3097–3102. https://doi.org/10.1109/tap.2008.929459.
8. Jan J.-Y., Su J.-W. (2005) Bandwidth Enhancement of a Printed Wide-Slot Antenna with a Rotated Slot. *IEEE Transactions on Antennas and Propagation*, 53 (6), 2111–2114. https://doi.org/10.1109/tap.2005.848518.
9. Chen W.-L., Wang G.-M., Zhang C.-X. (2009) Bandwidth Enhancement of a Microstrip-line Fed Printed Wide-slot Antenna with a Fractal-Shaped Slot. *IEEE Transactions on Antennas and Propagation*, 57 (7), 2176–2179. https://doi.org/10.1109/tap.2009.2021974.
10. See C. H., Abd-Alhameed R. A., Zhou D., Lee T. H., Excell P. S. (2010). A Crescent- Shaped Multiband Planar Monopole Antenna for Mobile Wireless Applications. *IEEE antennas and wireless propagation letters,* 9, 152–155. https://doi.org/10.1109/lawp.2010.2044741.
11. Goswami C., Pal M., Ghatak R., Poddar D. R. (2014) Metamaterial Based Miniaturized Dual Band Antenna. 2nd International Conference on Emerging Technology Trends in Electronics, Communication and Networking, 51, 1–4. https://doi.org/10.1109/et2ecn.2014.7044956.

12. Bhattacharya A. (2014) Modeling & Simulation of Meta material Based Devices for Industrial Applications. *Elektronika – Konstrukcje, Technologie, Zastosowania*, 1 (10), 68–71. https://doi.org/10.15199/13.2016.10.17.
13. Radavaram S., Pour M. (2019) Wideband Radiation Reconfigurable Microstrip Patch Antenna Loaded with Two Inverted U-Slots. *IEEE Transactions on Antennas and Propagation*, 67 (3), 1501–1508. https://doi.org/10.1109/tap.2018.2885433.
14. Rambe A., Suherman S., Erwin E. (2019) Design of Rectangular Microstrip Patch Antenna for 1.8 GHz Applications. *Proceedings of the Proceedings of The 2nd International Conference On Advance And Scientific Innovation, ICASI 2019*, 18 July, Banda Aceh, Indonesia. https://doi.org/10.4108/eai.18-7-2019.2288555.
15. Islam M. R., Adel A. A. A., Mimi A. W. N., Yasmin M. S., Norun F. A. M. (2017) Design of Dual Band Microstrip Patch Antenna using Metamaterial. *IOP Conference Series: Materials Science and Engineering*, 260, 012037. https://doi.org/10.1088/1757-899x/260/1/012037.
16. Rop K. V., Konditi D. B. O. (2012) Performance Analysis of a Rectangular Microstrip Patch Antenna on Different Dielectric Substrates. *Innovative Systems Design and Engineering,* 3 (8), 1–14.
17. Rahimi M., Zarrabi F. B., Ahmadian R., Mansouri Z., Keshtkar A. (2014) Miniaturization of Antenna for Wireless Application with Difference Metamaterial Structures. *Progress in Electromagnetics Research*, 145, 19–29. https://doi. org/10.2528/pier13120902.
18. Jain S. K., Shrivastava A., Shrivas G. (2015) Miniaturization of Microstrip Patch Antenna using Metamaterial Loaded with SRR. *2015 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, a 87, 1224–1227. https://doi.org/10.1109/iceaa. 2015. 729 7313.
19. Singh H. P. (2017) Design and Simulation of Rectangular Microstrip Patch Antenna Loaded with Metamaterial Structure. *Electrical & Electronic Technology Open Access Journal*, 1 (1), 58–62. Available at: https://medcraveonline.com/EETOAJ/EETOAJ-01-00012.pdf
20. Mishra G. P., Mangaraj B. B. (2020). Highly Compact Microstrip Patch Design based on Improved Capacitive Minkowski Fractal Defected Ground Structure. *AEU – International Journal of Electronics and Communications*, 115, 153049. https://doi.org/10.1016/j.aeue.2019.153049.
21. Yang M., Chen Z. N., Lau P. Y., Qing X., Yin X. (2015). Miniaturized Patch Antenna with Grounded Strips. *IEEE Transactions on Antennas and Propagation*, 63 (2), 843–848. https://doi.org/10.1109/tap.2014.2382668.
22. Wqrner D. H., Ganguly S. (2003). An Overview of Fractal Antenna Engineering Research. *IEEE Antennas and Propagation Magazine*, 45 (1), 38–57. https://doi.org/10.1109/map.2003.1189650.
23. Suvarna K., Murty N. R., Vardhan D. V. (2019) A Miniature Rectangular Patch Antenna using Defected Ground Structure for Wlan Applications. Progress In Electromagnetics Research C, 95, 131–140. https://doi.org/10.2528/pierc19061602.
24. Er-rebyiy R., Zbitou J., Latrach M., Tajmouati A., Errkik A., El Abdellaoui L. (2017). A Novel Design of a Miniature Low Cost Planar Antenna for ISM Band Applications. *Proceedings of the 2nd International Conference on Computing and Wireless Communication Systems*, 99, 1–5. https://doi.org/10.1145/3167486.3167492.
25. Ghaloua A., Zbitou J., El Abdellaoui L., Errkik A., Tajmouati A., Latrach M. (2017). A Miniature Circular Patch Antenna Using Defected Ground Structure for ISM Band Applications. *Proceedings of the 2nd International Conference on Computing and Wireless Communication Systems*, 4, 1–5. https://doi.org/10.1145/3167486.3167571.
26. Er-rebyiy R., Zbitou J., Latrach M., Tajmouati A., Errkik A., Abdellaoui L. E. (2017). New Miniature Planar Microstrip Antenna Using DGS for ISM Applications. *TELKOMNIKA* (Telecommunication Computing Electronics and Control), 15 (3), 1149. https://doi.org/10.12928/telkomnika.v15i3.6864.
27. Zhang H., Chen D., Yu Y., Zhao C., Tian G. (2019) A Novel Compact Microstrip Antenna with an Embedded $\lambda/4$ Resonator. *International Journal of Antennas and Propagation*, 2019, 1–7. https://doi.org/10.1155/2019/2431760.
28. Balanis C. A. *Antenna Theory & Design*. John Wiley & Sons, Inc., 1997.
29. Pozar D. M. (2004) *Microwave Engineering*. 3rd ed. John Wiley & Sons.
30. Stutzman W. L., Thiele G. A. (1998) *Antenna Theory & Design*. 2nd ed. John Wiley & Sons, New York.
31. Haupt R. L. (1995) An Introduction to Genetic Algorithms for Electromagnetic. *IEEE Antennas and Propagation Magazine*, 37 (2), 7–15. https://doi.org/10.1109/74.382334.
32. Hamzidah N. K., Setijadi E. (2015) Design of Microstrip Patch Antenna Based on Complementary Split Ring Resonator Metamaterial for Wi-MAX Application. 2015 International Seminar on Intelligent Technology and Its Applications (ISITIA), 56, 413–418. https://doi.org/10.1109/isitia.2015.7220016.
33. Nutan R. A., Raghavan S. (2013) Split Ring Resonator and Its Evolved Structures over the Past Decade: This paper discusses the nuances of the most celebrated composite particle (split-ring resonator) with which novel artificial structured materials (called metamaterials) are built. *2013 IEEE International Conference ON Emerging Trends in Computing, Communication and Nanotechnology (ICECCN)*. https://doi. org/10. 1109/ice-ccn.2013.6528575.
34. Sharma S. K., Abdalla M. A., Hu Z. (2018) Miniaturisation of an Electrically Small Metamaterial Inspired Antenna using Additional Conducting Layer. *IET Microwaves, Antennas & Propagation*, 12 (8), 1444–1449. https://doi.org/10.1049/iet-map.2017.0927.
35. Sharma R., Singh H. (2015) Left Handed Metamaterial Antenna Design for GSM 1.8 GHz Applications. *2015 2nd International Conference on Recent Advances in Engineering & Computational Sciences (RAECS)*, 2, 1–5. https://doi.org/10.1109/raecs.2015.7453276.
36. Segovia-Vargas D., Herraiz-Martinez F. J., Ugarte-Munoz E., Garcia-Munoz L. E., Gonzalez-Posadas V. (2013) Quad-Frequency Linearly-Polarized and Dual-Frequency Circularly-Polarized Microstrip Patch Antennas with CRLH Loading. *Progress In Electromagnetics Research*, 133, 91–115. https://doi.org/10.2528/pier12072413.
37. Niu J.-X. (2010). Dual-Band Dual-Mode Patch Antenna based on Resonant-Type Metamaterial Transmission Line. *Electronics Letters*, 46 (4), 266. https://doi.org/10.1049/el.2010.3142.

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