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Miniaturization of antenna using metamaterial loaded with CSRR for wireless applications

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ABSTRACT

This paper proposes a compact decagon antenna for wireless applications based on inspired metamaterial (MTM) loaded with a modified complementary split ring resonator (CSRR). A MTM loaded with CSRR is used to achieve a size reduction of 50% when compared to a traditional antenna. The suggested decagon antenna's ground plane has been loaded with CSRR. The antenna was made on an FR4 substrate with a thickness of 1.6 mm and εr=4.4 and has a very small dimension of 0.288 λ_0x0.272 λ_0x0.013 λ_0 (where λ_0 represent center frequency at 2.4 GHz). The given antenna has a 90 MHz bandwidth (2.40-2.50 GHz) with a peak gain of 2.36 dB. The presented design is validated by showing simulated results of the S parameter, VSWR, gain, surface current, and radiation pattern. The proposed antenna is well suited for wireless applications.

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1. INTRODUCTION

Printed antennas are in demand in recent years, this demand attracts global researchers around the world to work on microstrip antenna and produce significant results in the growing demand. Microstrip antenna is not limited to work only in the field of LAN and satellite communication they are now being used in other internet of things (IoT) based application and wearable technologies. In recent years a lot of research was conducted on improving the antenna parameters, including resonating frequency, return loss, bandwidth, voltage standing wave ratio (VSWR), gain, and radiation pattern by applying available techniques. Among them, metamaterial (MTM) seems to be the most promising technique available [1]–[3]. A lot of research is being carried out comprising MTM as the improvement techniques of the antenna parameters. There is no particular definition available, which is universally accepted, but generally, it is defined as a structure that contains some unusual properties which are not found in nature [4]–[6].

Engineering modification of wave characteristics in MTMs may contribute to significant size and weight reductions of antenna that improves antenna parameter. MTM 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 [7], [8]. From recently published studies, it was identified that there are several methods to reduce the size of the antenna by cutting slots in patches [9], varying shape, selecting different substrate materials, using defective ground plane [10], electromagnetic bandgap structure (EBG) [11] using shorting pins and the folded patch feeding method [12] use of multilayer substrate, using MTM structure. The shortcomings of the patch-cutting slots, which have poor radiation characteristics and polarization, also have a complex geometry. The limitations of different substrate materials have limited bandwidth whereas, for the defective ground plane, EBG has low efficiency. The drawback of shorting pins and the folded patch feeding approach is that gain and bandwidth are reduced. Singh *et al.* [13] presented defective ground with an EBG structure to miniaturize the antenna. This antenna's size has decreased compared to a traditional patch antenna by 37.9%. The given antenna has problems, particularly its complex design and unable to reduce the overall size of the antenna.

Using the slotted technique, an octagonal patch antenna with a 10% size reduction was achieved. The reported antenna has problems, particularly given its design and inability to be made smaller [14], [15] has described different approaches for shrinking the size of a patch antenna. Miniaturization is accomplished through the use of MTM structures on the ground plane or above the patch. The second category is MTM substrate change, in which varying thickness can change the outcomes. A lot of articles have been published earlier that show the performance constraints of constructing a compact antenna [16], [17]. It is difficult to reduce the size of a patch antenna. It was observed that by reducing the size of the patch antenna, we may have to sacrifice bandwidth and gain.

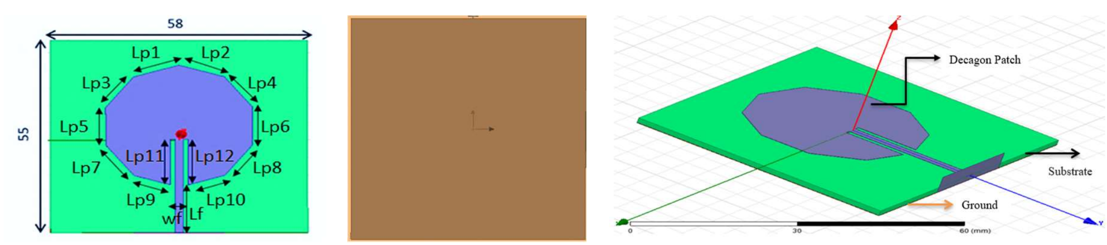
The presented work is novel in terms of constructing a relatively small MTM-loaded antennacompared to previously reported leading-edge antennas. Here, we attempt to find a better solution for achieving improved antenna performance in the proposed antenna by keeping the size compact and the structure simple. A novel MTM structure is proposed in this paper. This proposed work contains the modification of the patch antenna using the novel MTM structure on the ground plane. The patch antenna loaded with MTM helps in miniaturization. The given antenna has a 90 MHz bandwidth (2.40-2.50 GHz) with a peak gain of 2.36 dB. The size of the presented antenna is 50% smaller than the recently published leading edge antennas. The proposed design has double negative properties (2.2-2.78 GHz) in the operating frequency band.

The progression from a conventional design (antenna-I) to a more compact design (antenna-III) is described in section 2. This section also demonstrates how MTMs have helped to reduce the antenna size. Section 3 compares the proposed MTM with traditional MTM antenna-III and also describes the performance of the proposed MTM antenna to that of reference antennas that have already been designed in the literature. The paper is concluded in section 4.

2. ANTENNA DESIGN

2.1. Traditional decagon antenna-I

Figures 1(a) to (c) shows the geometrical view of the traditional decagon antenna-I constructed using HFSS at 2.4 GHz. The structure is composed of FR_4 with a permittivity of 4.4 with an inset feed. The antenna's overall dimensions are 0.46 λ_0 x 0.44 λ_0 x 0.013 λ_0. The effective length of the designed traditional decagon antenna is 104 mm. The decagon shape is selected because it radiates energy in ten corners, resulting in the highest radiation efficiency compared to other antenna shapes. The top side of the antenna has a decagon patch, and the bottom side is a ground plane. The dimensions of the antenna parameter (in mm) as Lp_1 to Lp_8=10.79, Lp_9=8.61, Lp_{10}=8.76, and Lp_{11}=Lp_{12}=13, L_f=13.6, W_f=2.43, W=58, and L=55.



(a) (b) (c)

Figure 1. Geometrical view of traditional decagon patch antenna-I (all dimensions in mm); (a) top view (b) bottom view, and (c) perspective view

In (1) to (4) are used to determine the patch's width and length [18]–[20]:

Width of the patch (W):

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{3X10^8}{2\ X\ 2.4\ X\ 10^9}\sqrt{\frac{2}{4.3+1}} = 38\ mm \tag{1}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}} \ ;\ {}^{W}/_{h} > 1 \tag{2}$$

Fringing length:

$$\Delta L = h(0.412)\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{3}$$

Length of the patch (L):

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L = 28\ mm \tag{4}$$

In (5) and (6) are used to determine the length (Lg) and width (Wg) of a ground plane:

$$\begin{aligned} Lg &= L + 2\times 6h \\ &= 28\ + 19\ =\ 47\ mm \end{aligned} \tag{5}$$

$$\begin{aligned} Wg &= W + 2\times 6h \\ &= 38\ + 19\ = 57\ mm \end{aligned} \tag{6}$$

For optimization, we have selected W=58 mm and L=55 mm.

Figure 2 shows the equivalent circuit of a traditional decagon patch antenna-I. On the patch top side the decagon patch has inductance L_2 is placed parallel with dielectric subtracts C_1 whereas L_1 represents the inductance of the transmission line. A simulation was done in HFSS software and the results were analyzed. At the resonant frequency, Figure 3 represents surface current distribution. It can be seen that there is a significant concentration of current at the edges of the decagon patch.

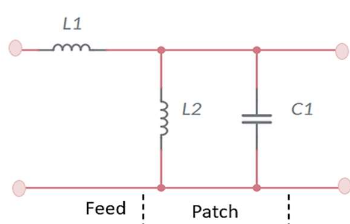


Figure 2. Equivalent circuit of a traditional decagon patch antenna-I

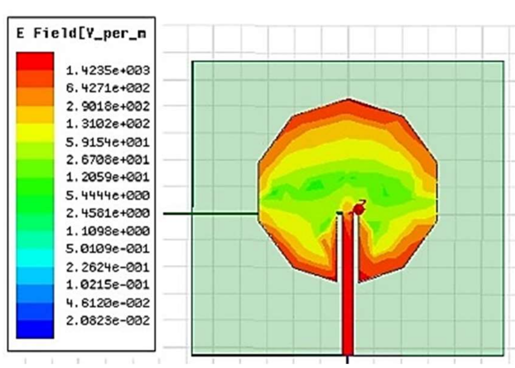


Figure 3. Surface current distribution at 2.4 GHz of traditional decagon antenna-I

2.1.1. Results for traditional decagon antenna-I

Figure 4 shows the radiation pattern of a traditional decagon patch antenna that is similar to those of an omnidirectional antenna. The antenna gain is shown in Figure 5 and the simulated return loss, VSWR shown in Figures 6 and 7. The simulation results show a gain of 4.25 dB, bandwidth of 35 MHz, return loss of 13.79, and VSWR of 1.51 but the antenna has a large size of 58x55 mm^2. The volumetric reduction in area is 925 mm^2. Table 1 shows a comparison of theoretical calculation with the simulation result for traditional decagon antenna-I.

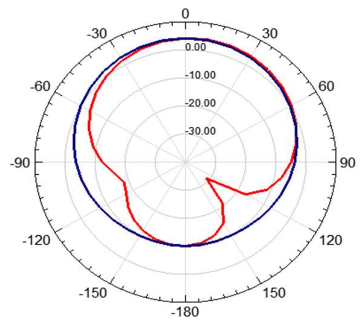


Figure 4. Radiation pattern at 2.48 GHz of the traditional decagon patch antenna

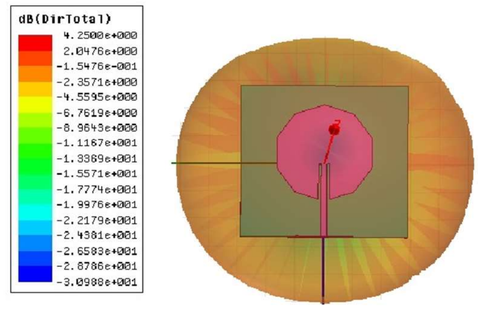


Figure 5. Gain of traditional decagon antenna at 2.4 GHz

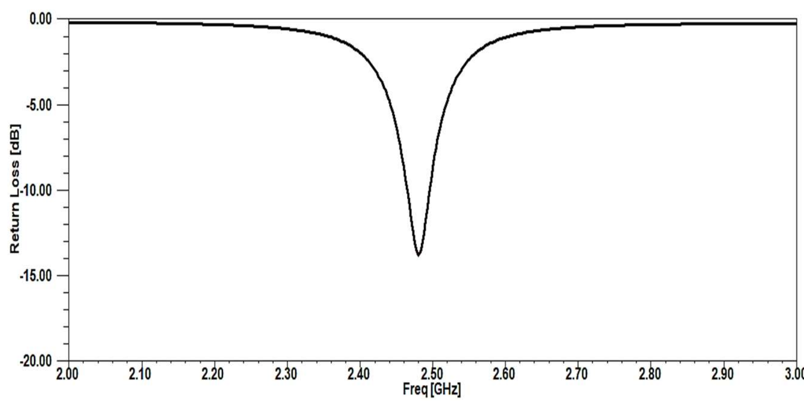


Figure 6. Simulated return loss

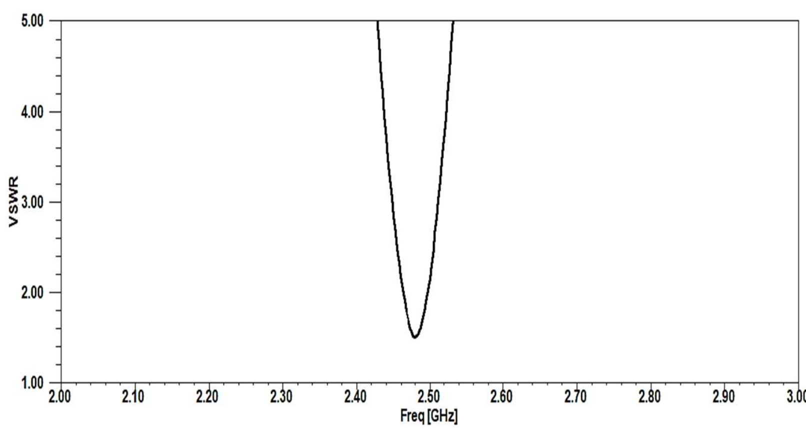


Figure 7. Simulated VSWR

Table 1. Comparison of theoretical calculation with the simulation result

Sr.No.	Results	Return loss (dB)	VSWR	Overall size (mm^2)
1.	Theoretical result	30.45	1.03	
2.	Simulation result	13.79	1.51	58 × 55

Theoretical analysis:

a. Return loss (dB)

As we know return loss=20 $log(\tau)$

$$|\tau| = (Z_L - Z_0)/(Z_L + Z_0) \quad (7)$$

Where Z_L is load impedance and Z_0 is source impedance

$$|\tau| = (47 - 50)/(47 + 50) = 0.030$$

Return loss=20 $log(\tau) = 20\ log(0.030) = 30.45\ dB$

b. VSWR

$$\text{VSWR} = (1 + |\tau|)/(1 - |\tau|\ ) \quad (8)$$

$$\text{VSWR} = (1 + 0.030)/(1 - 0.030) = 1.03$$

2.2. Traditional decagon metamaterial antenna-II

Figures 8(a) to (c) shows the geometrical view of the traditional decagon MTM antenna-II designed at 2.4 GHz using HFSS. The antenna is compact, with measurements of 0.26 λ_0 x 0.28 λ_0 x 0.013 λ_0. The designed traditional decagon MTM antenna-II has an effective length of 75 mm. The antenna has a decagon patch on top and a square split ring resonator on the bottom. In Table 2, all of the antenna parameters are listed.

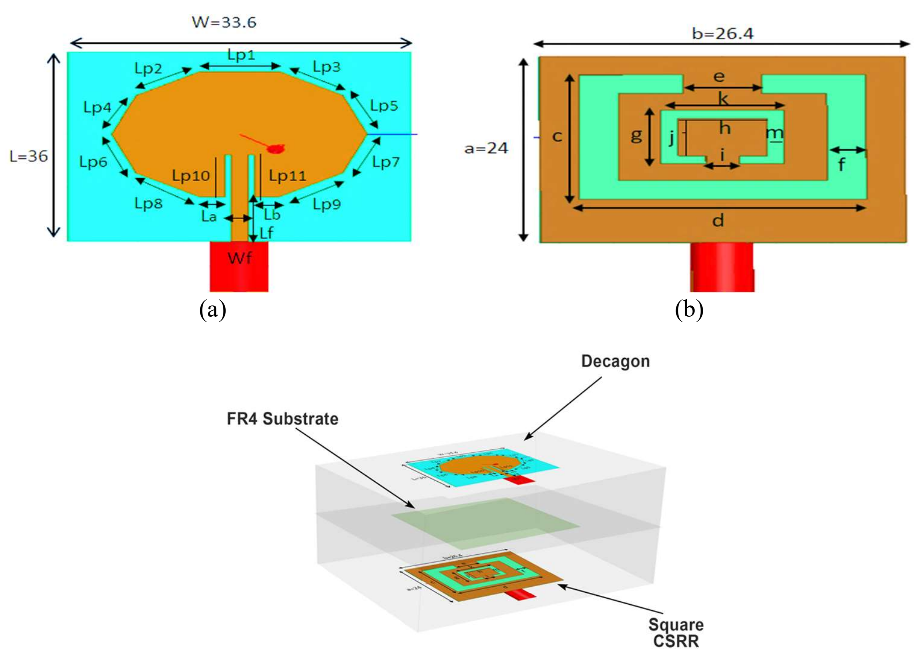


Figure 8. Geometrical view of traditional decagon MTM antenna-II (all dimensions in mm); (a) top view, (b) bottom view, and (c) perspective view

Figure 9 shows the equivalent circuit of a traditional decagon MTM antenna-II. Here outer square ring and the inner square ring slot behaves as a distributed capacitance and the remaining metallic part at the bottom side behaves like inductance. The capacitance C_1 caused by the gap between the outer square ring and capacitance C_2 caused by the split between the inner square ring slot is a parallel way in complementary split ring resonator (CSRR). The bottom side metal has inductance L_1 and is placed in series with C_1. On the patch top side, the decagonal patch has inductance L_2 and is placed parallel with dielectric substrate C_3. In (9) represents the formulas for calculating the amount of volumetric reduction [21]:

$$\text{Overall Volumetric reduction} = (Volume\ 1 - Volume\ 2)/(Volume\ 1) \times 100 \quad (9)$$

where volume 1 is volume of the traditional antenna, volume 2 is volume of the traditional MTM antenna. overall volumetric reduction=$[(925 - 540)/925] \times 100$=41.62%. A volumetric reduction of 41% is achieved in a traditional MTM antenna as compared to a traditional antenna.

Table 2. List of the optimum parameters determined through simulation

Ant. Para.	L	W	Lp_1	Lp_2	Lp_3	Lp_4	Lp_5	Lp_6	Lp_7	Lp_8	Lp_9	L_a
Val.(mm)	36	33.6	7.78	7.78	7.78	7.78	7.78	7.78	7.78	7.78	7.78	2.44
Ant. Para.	L_b	Lp_{10}	Lp_{11}	L_f	W_f	a	b	c	d	e	f	g
Val.(mm)	2.44	8	8	8.4	4.96	24	26.4	16.8	19.2	7.2	3.6	10.32
Ant. Para.	k	i	j	h	m							
Val.(mm)	11.35	3.09	7.22	8.25	1.54							

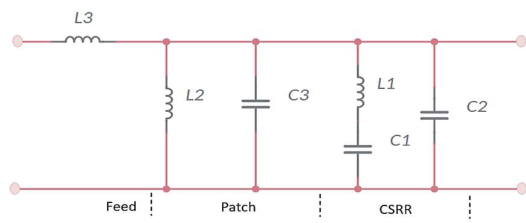


Figure 9. Equivalent circuit of traditional decagon MTM antenna-II

2.2.1. Results for traditional decagon metamaterial antenna-II

To analyze the performance of the antenna, the results are obtained by simulating the design in HFSS software. Figure 10 illustrates the traditional decagon MTM antenna-II radiation pattern at 2.4 GHz closes to an omnidirectional antenna. In Figure 11, the antenna gain is shown. The simulation's results indicate a gain of 1.60 dB. At the resonant frequency of 2.4 GHz, it is noticed that the return loss is obtained at 11.04dB, VSWR as 1.78 as shown in Figures 12 and 13. The simulation shows that the traditional MTM antenna bandwidth is 78 MHz at -10 dB. The traditional decagon MTM has a volumetric reduction of 540 mm^2 (in simulation) as compared to the traditional decagon antenna. A comparison of theoretical calculation with the simulation result for traditional decagon MTM antenna-II is shown in Table 3.

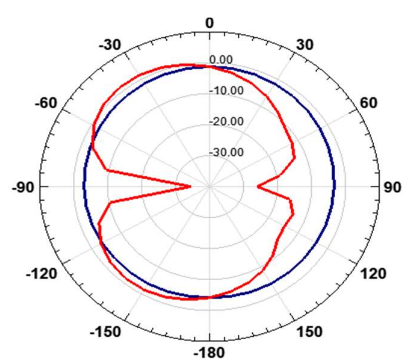


Figure 10. Radiation pattern at 2.48 GHz of traditional decagon MTM antenna-II

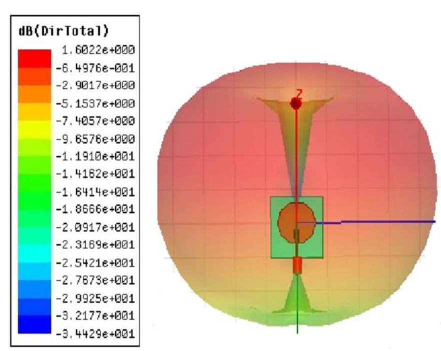


Figure 11. Gain of traditional decagon MTM antenna-II at 2.4 GHz

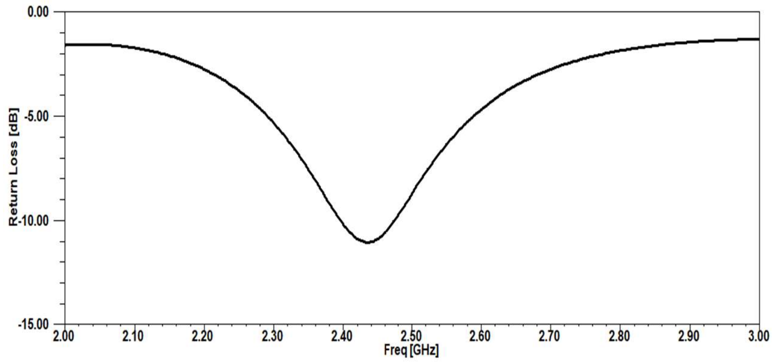


Figure 12. Simulated return loss

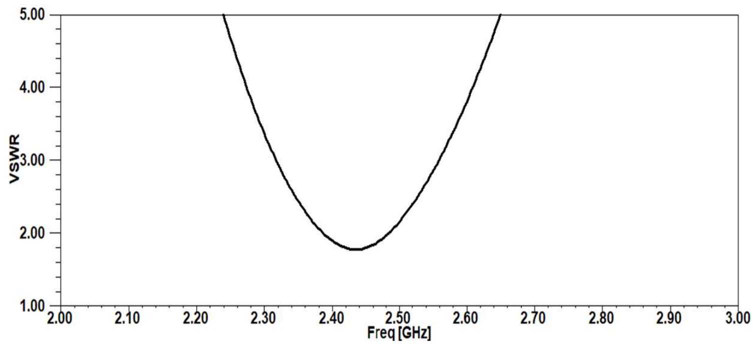


Figure 13. Simulated VSWR

Table 3. Comparison of theoretical calculation with the simulation result

Sr.No.	Results	Return loss (dB)	VSWR	Overall size (mm^2)
1.	Theoretical result	25.67	1.10	33.6×36
2.	Simulation result	11.04	1.78	(41.62 l% volumetric reduction)

2.3. Proposed decagon metamaterial antenna-III

Here, we have attempted size reduction of the decagon antenna using the modified MTM structure. Figures 14(a) to (c) represents the structure of the proposed decagon MTM antenna-III designed at 2.4 GHz using HFSS. The structure is composed of FR_4 with a permittivity of 4.4 with an inset feed. The antenna has small in size with dimensions of 0.26 λ_0 × 0.28 λ_0 × 0.013 λ_0. The effective length of the decagon MTM antenna-III is 74.46 mm. The top side of the antenna has a decagon patch, and the bottom side has been loaded with a modified CSRR structure [15] that helps in miniaturization. Table 4 lists all of the antenna parameters that have been mentioned.

Theoretical analysis:

a. Return loss (dB)

As we know return loss=20 log 20 $log(\tau)$

$$|\tau| = (Z_L - Z_0)/(Z_L + Z_0) \tag{10}$$

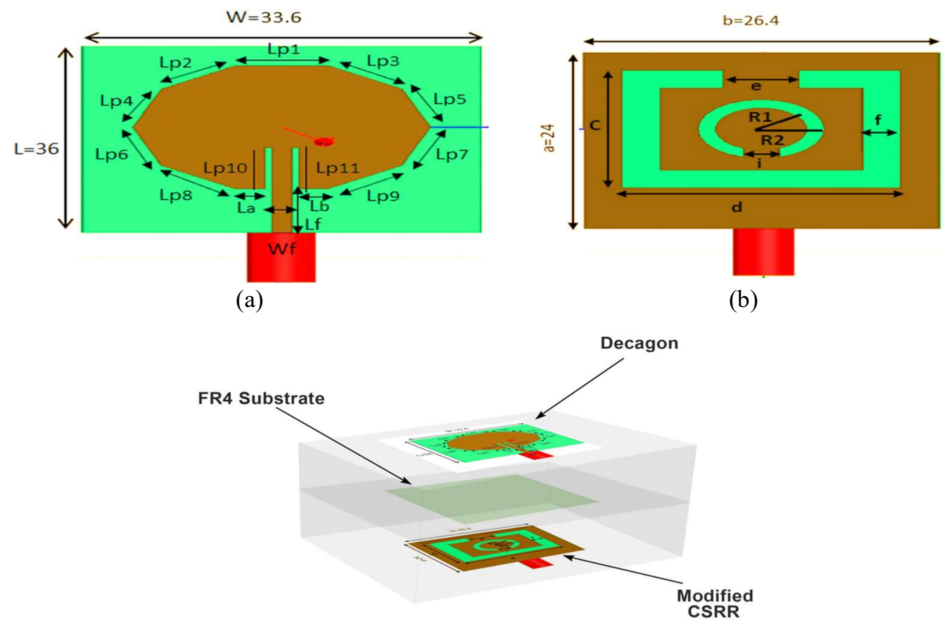
$$|\tau| = (45 - 50)/(45 + 50) = 0.052$$

Return loss=20 $log(\tau) = 20\ log(0.052) = 25.67\ dB$

b. VSWR

$$\text{VSWR} = (1 + |\tau|)/(1 - |\tau|\ ) \tag{11}$$

$$\text{VSWR} = (1 + 0.052)/(1 - 0.052) = 1.10$$



(a) (b)

(c)

Figure 14. Geometrical view of proposed decagon MTM antenna-III (all dimensions in mm); (a) top view, (b) bottom view, and (c) perspective view

Table 4. List of the optimum parameters determined through simulation

Ant.Para.	L	W	Lp_1	Lp_2	Lp_3	Lp_4	Lp_5	Lp_6	Lp_7	Lp_8	Lp_9	L_a
Val.(mm)	36	33.6	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	7.74	2.40
Ant.Para.	L_b	Lp_{10}	Lp_{11}	L_f	W_f	a	b	c	d	e	f	R_1
Val.(mm)	2.40	8.79	8.79	8.4	4.96	24	26.4	16.8	19.2	7.2	3.6	5.1
Ant.Para.	R_2	i	m									
Val.(mm)	3.7	3.3	1.78									

2.3.1. Metamaterial property validation

Figure 15 illustrate boundary conditions for a transmission line with a proposed CSRR unit cell structure. An MTM structure was validated by placing a CSRR unit cell between two waveguide ports (A and B) in HFSS. The faces are defined by a transverse electromagnetic wave (TEM), which is excited by the wave. On the top and bottom faces of the waveguide, the perfect electric conductor (PEC) boundary condition was defined, and on the right and left faces of the waveguide, the perfect magnetic conductor (PMC) boundary condition was defined. Figures 16 and 17 show that the permittivity and permeability of the meta-surface are both negative in the 2.2-2.78 GHz frequency range, verifying the surface's DNG behaviour in this frequency range [22]. At 2.4 GHz the modified decagonal MTM antenna structure on the bottom side causes large current distribution as compared to the traditional decagon antenna-I as shown in Figure 18.

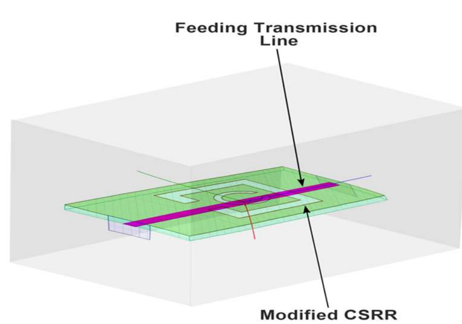


Figure 15. Boundary conditions for a transmission line with a proposed CSRR unit cell structure

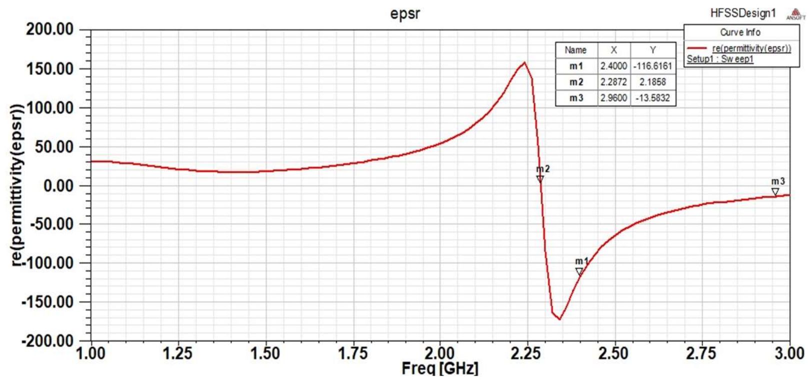


Figure 16. The relative permittivity vs frequency of proposed CSRR unit cell

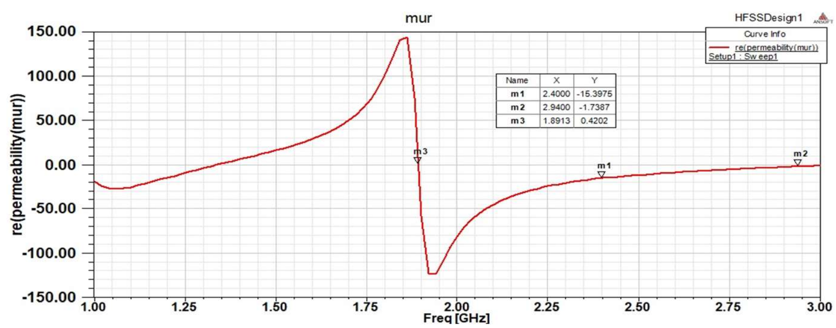


Figure 17. The relative permeability vs frequency of the proposed CSRR unit cell

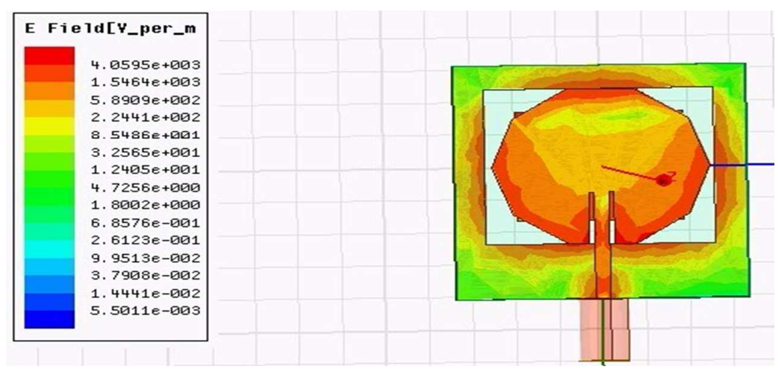


Figure 18. Surface current distribution of proposed decagon MTM antenna-III at 2.4 GHz

The antenna is designed and simulated in HFSS software. The presented MTM area's volumetric reduction is 463 mm^2 (in simulation) as compared to the traditional decagon antenna. In (9) represents the formulas for calculating the amount of volumetric reduction [21]. Using (9) we get overall volumetric reduction=$[(925 - 463)/925] \times 100$=49.94% ~ 50%. A volumetric reduction of 50% is achieved using an MTM structure when compared to a traditional decagon antenna.

2.3.2. Results for proposed decagon metamaterial antenna-III

Figure 19 shows the radiation pattern of the decagon MTM antenna at 2.4 GHz. The antenna gain is shown in Figure 20 and the simulated return loss, VSWR shown in Figures 21 and 22. The simulation results show a gain of 2.36 dB, a bandwidth of 90 MHz, and a return loss of 12.93, with a VSWR of 1.58. The proposed MTM structure improved a gain of 0.7 dBi compared to the traditional MTM structure. Also improved VSWR and return loss of antenna. It was observed that a significant reduction in the size of the antenna was achieved after modified MTM inclusion. The proposed antenna with a novel MTM structure was simulated and analyzed. The conventional antenna did not have parameters that could fulfill the demand. A comparison with the previous results as well as with the conventional patch shows the improvement in the parameter modification. The author would like to mention that if researchers would prefer MTM along with conventional methods then promising results can be achieved. The comparison of theoretical calculation with the simulation result for the proposed decagon MTM antenna-III is shown in Table 5.

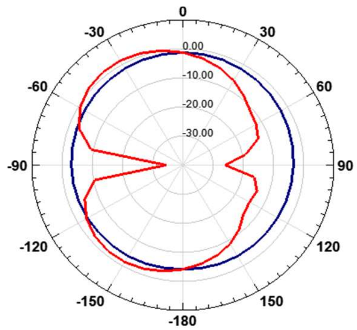


Figure 19. Radiation pattern at 2.48 GHz of decagon MTM antenna-III

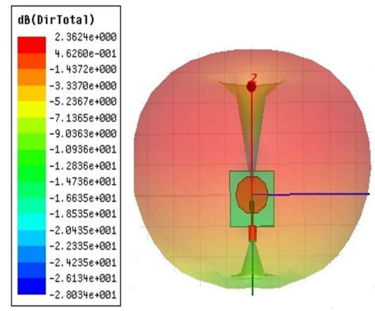


Figure 20. Gain of decagon MTM antenna-III at 2.4 GHz

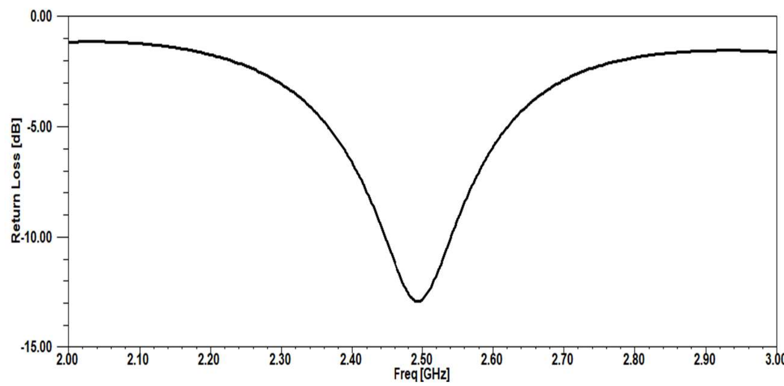


Figure 21. Simulated return loss

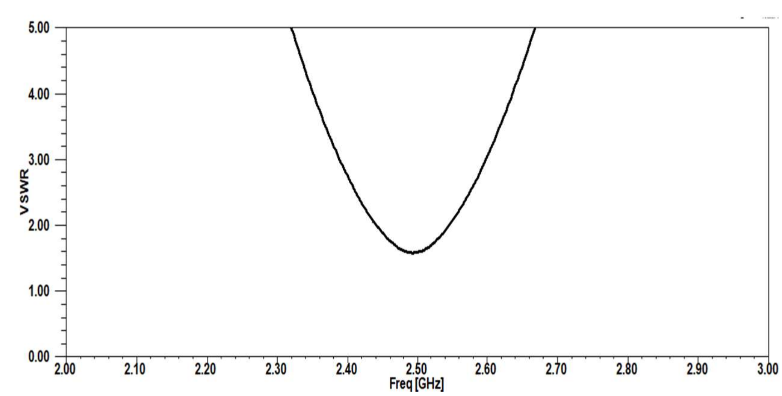


Figure 22. Simulated VSWR

Theoretical analysis:

a. Return loss (dB)

As we know return loss=20 $log(\tau)$

$$|\tau| = (Z_L - Z_0)/(Z_L + Z_0) \quad (13)$$

$$|\tau| = (43 - 50)/(43 + 50) = 0.075$$

Return loss=20 $log(\tau) = 20\ log(0.075) = 22.49\ dB$

b. VSWR

$$VSWR = (1 + |\tau|)/(1 - |\tau|\ ) \quad (14)$$

$$VSWR = (1 + 0.075)/(1 - 0.075) = 1.16$$

Table 5. Comparison of theoretical calculation with the simulation result

Sr.No.	Results	Return loss (dB)	VSWR	Overall size (mm^2)
1.	Theoretical result	22.49	1.16	33.6×36
2.	Simulation result	12.93	1.58	(50% volumetric reduction)

3. COMPARISON TABLE

Table 6 compares the proposed MTM decagon antenna with the traditional MTM antenna. The proposed MTM structure improved a gain of 0.7dBi compared to the traditional MTM structure. Also improved VSWR and return loss, bandwidth. The proposed MTM-loaded antenna has a bandwidth of 90 MHz (2.40-2.50 GHz), which is up to 2.75 times more than the reference antenna's bandwidth of 35 MHz. Also, a volumetric reduction of 50% is achieved using an MTM structure when compared to a traditional decagon antenna. Table 7 compares the performance of the proposed MTM antenna to that of reference antennas that have already been designed in the literature. The overall size of the proposed MTM antenna is less and it has higher gain characteristics than that of state-of-the-art designs [13], [18], [23]–[32] mentioned in literature.

Table 6. Comparison of proposed design performance with traditional antenna

Antenna design	Size (mm^2)	Freq (GHz)	Reflection coefficient (dB)	VSWR	BW (MHz)	Gain (dB)	Volumetric area (mm^2)
Traditional decagon antenna-I	58x55	2.45	13.79	1.51	35	4.25	925
Traditional MTM decagon antenna-II	33.6x36	2.43	11.04	1.78	78	1.60	540
Proposed MTM decagon antenna-III	33.6x36	2.49	12.93	1.58	90	2.36	463

Table 7. Comparison of the presented antenna with leading-edge antennas

Ref.	Antenna dimensions	Freq (GHz)	% of miniaturized	Gain (dB)	Technique used
[13]	67x64	2.45	-	2.12	Conventional patch antenna
	35x28.88	2.45	37.90	3.77	Mushroom-type EBG structure
[18]	60x46	2.45	10.44	2.9	Octagon ring shape structure
[23]	80×80	2.40	-	-2.33	Slotted
[24]	50×50	2.40	47	1.42	SRR EBG structure
[25]	30x24.8	2.54	46.8	2.3	MTM rectangular CSRR
[26]	48×48	2.53	-	1.9	Slotted patch
[27]	33x22	2.4	-	1.43	Square split ring
[28]	40x40	2.66	-	1.5	ENG TL with CPS stripline structure
[29]	32.2×20	2.40	-	1.62	Zeroth ordered resonant antenna
[30]	30x50	1.9 3.5	38	1 2.4	Shorting pins, offset pins, and centered pins help to improve antenna parameters
[31]	40x36	2.45, 3.5 5.5.	-	2.1, 2, 2.98	Triangular-shaped CPW-fed monopole antenna
[32]	25x16	2.72	-	0.72,2	Dual-band MTM antenna
Proposed antenna	33.6x36	2.40	50	2.36	Modified CSRR MTM structure

4. CONCLUSION

A compact decagonal antenna using inspired MTM loaded with a CSRR is presented at 2.4 GHz for wireless applications. It has an overall dimension of 0.288 λ_0x0.272 λ_0x0.013 λ_0. The MTM-loaded CSRR structure is used to achieve miniaturization. In comparison to the standard traditional antenna, a 50% size reduction is achieved. The presented MTM-loaded antenna exhibits a bandwidth of 90 MHz (2.40-2.50 GHz), which is up to 2.75 times greater than the 35 MHz bandwidth of the reference antenna. Because of its small size, the suggested antenna is appropriate for wireless applications. Future work will concentrate on designing a compact high gain frequency reconfigurable metasurface reflector (MSR) loaded decagon antenna using a varactor diode. Changing the varactor's DC reverse bias voltage causes its resonance frequency to shift which makes the antenna tunable.

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