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Gain Enhancement of Cross Shaped Patch Antenna for IEEE 802.11ax Wi-Fi Applications

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Abstract—In this paper, a dual band high gain miniaturized cross shaped patch antenna is proposed for IEEE 802.11ax applications. The radiating patch size is $0.330\lambda_0 \times 0.417\lambda_0$ on a low cost Flame Retardant 4 substrate. A cross shaped radiating element is designed to cover the upper band of IEEE 802.11ax, and a four ring circular Complementary Split Ring Resonator (CSRR) is etched on the cross shaped radiating element to cover the lower band of IEEE802.11ax. Thus the dual bands of 802.11ax are achieved. In order to enhance the gain, 2×2 array hexagonal metamaterial unit cell is positioned behind the substrate. To extract the constitutive parameters of the circular CSRR, NRW (Nicolson-Ross-Wier) retrieval method is used. The measured maximum gain is approximately 6 dBi, 10 dBi for 2.4 GHz, 5 GHz, respectively. Parametric study on the geometrical dimensions is investigated using HFSS 15.0.

1. INTRODUCTION

The challenges coming up with the Wi-Fi system is to design a compact, low cost and high gain antenna for recently introduced and upcoming IEEE standards. The IEEE 802.11 working group is going to release a new standard 802.11ax in December 2018 for Wi-Fi applications to improve the spectral efficiency and area throughput in the real world [1]. There is a necessity to design an antenna for the same. If any artificial electromagnetic structure satisfies the homogeneous limit $p < \lambda g/4$, then that structure is called metamaterial [2]. Metamaterials can be used to improve patch antenna parameters such as gain, bandwidth, directivity, and efficiency. Reduction of size, side lobe and a back lobe of the patch antenna is also achieved by using metamaterials.

The gain is improved by using complicated artificial metamaterial superstrate [3]. Omega like CSRR array using a thick dielectric substrate antenna is developed for surface wave suppression characteristics [4]. A 2×2 square CSRR array loaded with the ground plane is designed for gain enhancements for single band operation with too large substrate size [5]. By employing an OCSRR (Open Complementary Split Ring Resonator), a triband monopole antenna is designed for PAN's and WLAN applications with low gain [6]. A 2.4/5.2 GHz dual band dipole antenna is proposed by implementing a stacking technique on a dog-bone shaped patch with large size 38 mm $\times$ 40 mm [7]. Meandered CPW feed line and hexagonal split ring resonator achieve size reduction of the single band [8]. By the loading of a square split ring resonator, an electrically small patch antenna is obtained [9]. Metamaterial inspired antennas have been reported for antenna improvements such as impedance matching [10], multiband antenna design [11, 15], bandwidth enhancement [12], and directivity [13]. A metamaterial inspired dual band antenna for mobile applications is presented with low gain [14]. A μ-negative (MNG) metamaterial MSRR (Multiple Split Ring Resonator) loaded with an inset-rectangular

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microstrip patch is obtained for dual bands of 2.78 GHz WLAN and 5.8 GHz RF-ID applications with $25 \times 31 \times 1.6\,\text{mm}^3$ [16].

In the existing work, antennas have either large size or low gain, and also they are not designed for specific application. In order to overcome this, a cross shaped patch antenna with CSRR is proposed in this paper. A cross shaped radiating patch is used for miniaturization. A four ring circular CSRR and 2×2 hexagonal CSRR array loaded patch antenna is used to obtain dual bands and enhance the antenna gain, respectively.

2. GEOMETRY AND DESIGN OF PROPOSED ANTENNA

2.1. Antenna Geometry

The conventional microstrip antenna geometry is shown in Figure 1(a). The length and width of the radiating element are designed for 5 GHz. The physical width (W_p) and electrical length (L_p) of the patch are calculated by using the formulas below [17].

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

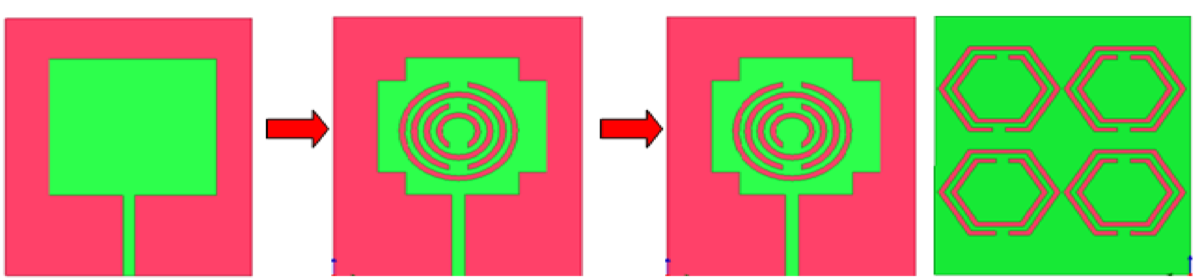
$$L = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} - 2\Delta L \tag{2}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12h}{W}\right]^{\frac{-1}{2}} \tag{3}$$

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

where c is the velocity of light; f_r is the resonance frequency of the patch; h and ε_{eff} are the height and effective dielectric constant of the substrate, respectively. Increase in patch length due to fringing fields is $2\Delta L$.

The antenna is excited by 50 ohm microstrip feed. The antenna with a rectangular patch offers a resonance frequency around 5 GHz. The rectangular patch has been modified into a cross shape to increase the electrical length of the antenna. The four ring circular CSRR is loaded in the center of the radiating element to obtain another resonant frequency of 2.4 GHz as shown in Figure 1(b). Finally, the 2×2 hexagonal CSRR array is loaded on the base of the substrate to enhance the antenna gain at 2.4 GHz and 5 GHz frequency bands as shown in Figure 1(c).



(a) Conventional antenna (b) CSRR loaded patch antenna (c) CSRR loaded patch antenna with 2 x 2 hexagonal CSRR array

Figure 1. Evolution stages of the antenna.

The proposed antenna geometrical views are shown in Figure 2. The geometrical parameters of the antenna are tabulated in Table 1.

Table 1. Dimension of the proposed antenna for IEEE802.11 ax applications.

Parameter	L_g	W_g	L_p	W_p	W_e	L_f	W_f	w & w_1	s & s_1	R	g	g_1
Value in mm	25	20	13.2	13.5	2.2	7.86	2	0.5	0.5	4.8	1.5	1

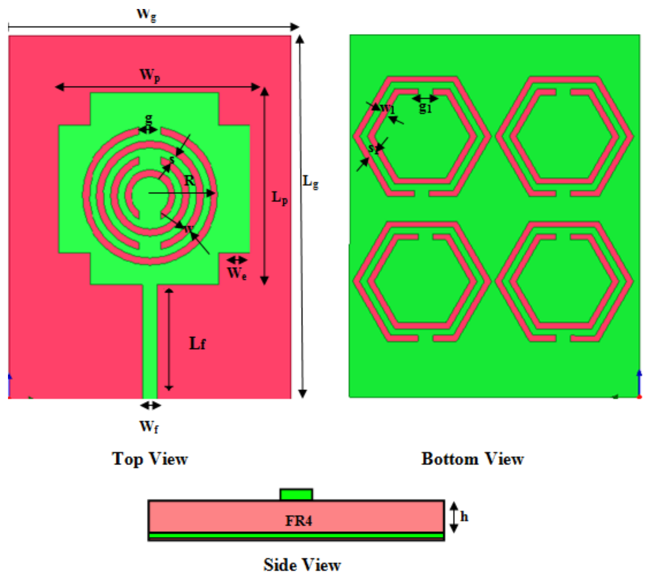


Figure 2. Geometry of the proposed cross shaped patch antenna.

2.2. Analytical Formulas of Four Ring Circular CSRR Metamaterial

The four ring circular CSRR is designed for 2.4 GHz. It has been used for miniaturization. The etched CSRR structure alters the dispersion characteristics of the substrate. The equivalent circuit of the four ring circular CSRR is shown in Figure 3.

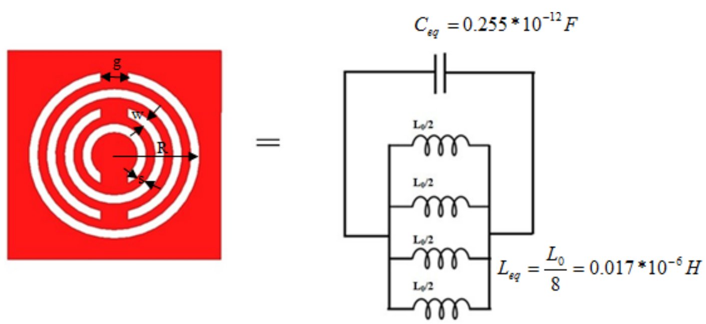


Figure 3. Equivalent circuit of four ring circular CSRR structure.

The CSRR is the dual complement of the SRR. SRR has negative permeability characteristics, whereas CSRR has negative permittivity characteristics. Based on the duality theorem, SRR and CSRR have an approximately same resonant frequency. The following equations determine the resonance frequency of CSRR [18], and geometrical values of the four ring circular CSRR are given in Table 1.

$$f = \frac{1}{2\Pi\sqrt{L_{eq}C_{eq}}} \tag{5}$$

$$Leq = 0.00508\left(2.303\log\left(\frac{4l}{w}\right) - \theta\right) \tag{6}$$

$$Ceq = \left(\frac{(\Pi r_{avg} - g)C_{pul}}{g}\right) + \frac{\varepsilon_0 wt}{2g} \tag{7}$$

$$Cpul = \frac{\sqrt{\varepsilon_e}}{cZ_0} \tag{8}$$

$$r_{avg} = R - w - \frac{s}{2} \tag{9}$$

Leq and Ceq are the total inductance and capacitance of the CSRR, respectively. R is the radius of the outer ring of the SRR from the center. C_{pul} and Z_0 are the per unit length capacitance between the rings and the impedance of the medium, respectively. t and w are the thickness and width of the ring. c is the velocity of light in vacuum. ε_e is the effective permittivity of the medium. l and d are the length and width of the wire, respectively. θ is a constant and varied with wire geometry. θ values for circular SRR and hexagonal SRR are 2.451 and 2.636 [19].

2.3. Parameter Extraction of Four Ring Circular CSRR

Based on the work of Smith et al., the negative permittivity is retrieved from the S-parameters [20]. In this paper, the NRW method is implemented for obtaining the negative permittivity of the four ring circular CSRR structure. The NRW approach is introduced by introducing the composite terms.

$$V_1 = S_{21} + S_{11} \tag{10}$$

$$V_2 = S_{21} - S_{11} \tag{11}$$

$$S_{11} = re(S_{11}) + j(im(S_{11})) \tag{12}$$

$$S_{21} = re(S_{21}) + j(im(S_{21})) \tag{13}$$

$$\mu = \frac{2}{jk_0 d} * \frac{1-V_2}{1+V_2} \text{ and } \varepsilon = \frac{2}{jk_0 d} * \frac{1-V_1}{1+V_1} \tag{14}$$

where K_0 is a wave number, and d is a thickness of the substrate. Using HFSS, the retrieving S-parameters of the four ring circular CSRR waveguide setup are shown in Figure 4. The transmission and reflection coefficients are computed using HFSS [21].

The negative permittivity (ε) characteristics are retrieved from S_{11} and S_{21} of the four ring circular CSRR structure using MATLAB code. The negative permittivity of the four ring circular CSRR at

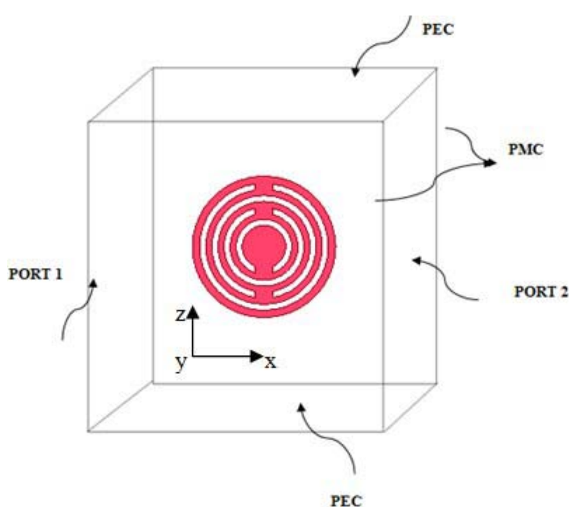


Figure 4. Waveguide setup for retrieving the S-parameters.

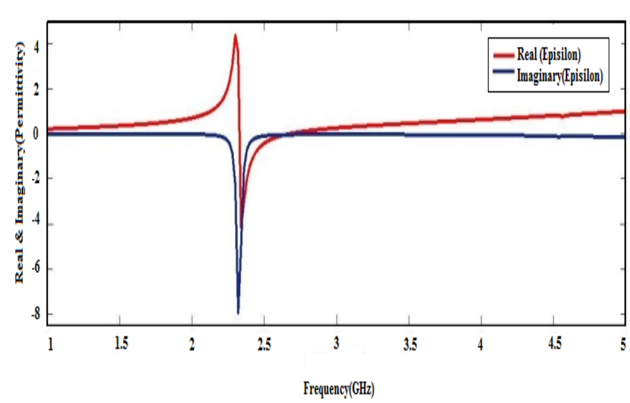


Figure 5. Negative permittivity of the four ring circular CSRR structure.

2.4 GHz is shown in Figure 5. Due to the strong electric coupling of the four ring circular CSRR, electric resonance phenomenon is generated which introduces negative permittivity at 2.4 GHz only.

3. PARAMETRIC ANALYSIS FOR PROPOSED ANTENNA USING HFSS FOR OPTIMIZATION

The parametric study of the proposed antenna was done by using HFSS. The proposed four ring circular CSRR consists of four rings and four slits. A parametric study is done for the effect of width (w), space of rings (s), gap distance (g) and other parameters (L_p, W_p, W_f and W_e). Simulated return loss characteristics of the proposed antenna for most influencing parameters such as varying width, space and gap distances are shown in Figures 6–8. As shown in Figures 6–8, the CSRR with $w = 0.5$ mm, $s = 0.5$ mm & $g = 1.5$ mm produces two resonant frequencies of 2.4 GHz and 5 GHz with return losses of -15 dB and -18 dB, and good impedance matching, respectively.

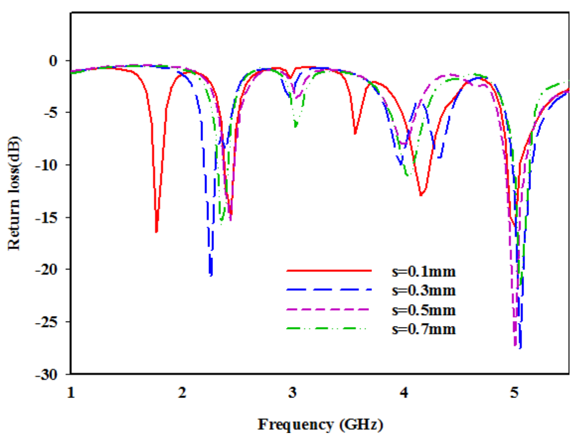


Figure 6. Simulated return loss for various space dimensions of the proposed antenna.

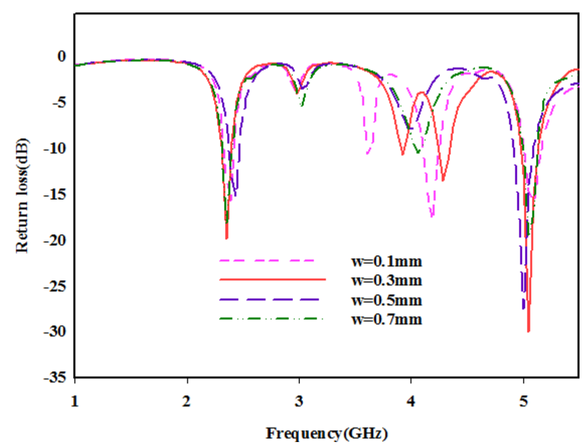


Figure 7. Simulated return loss for various width dimensions of the proposed antenna.

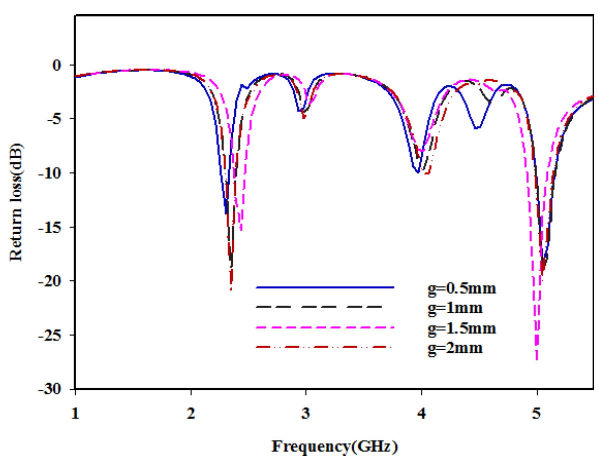
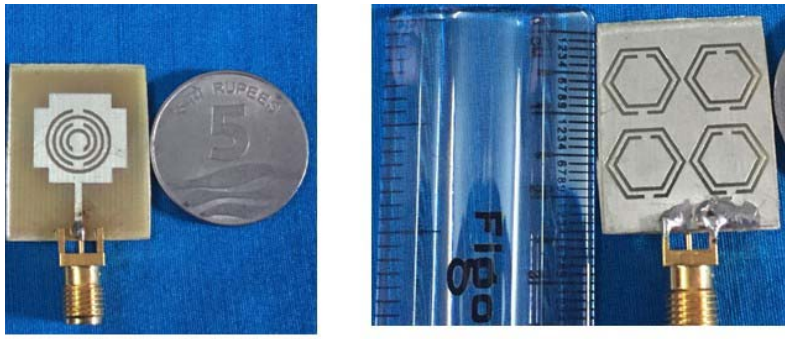


Figure 8. Simulated return loss for various gap dimensions of the proposed antenna.

4. RESULTS AND DISCUSSION

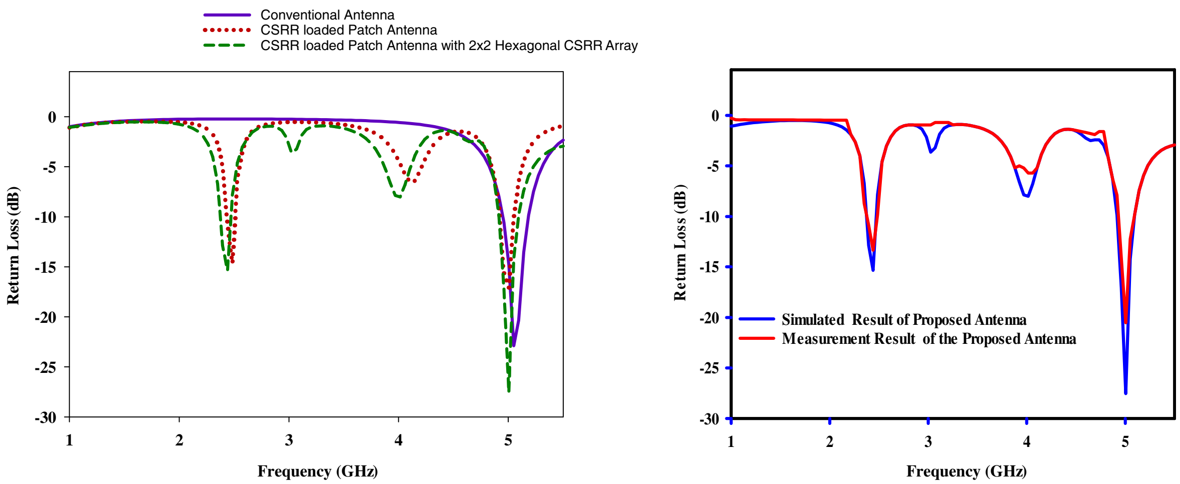
The antenna is fabricated and tested using the Agilent Vector Network Analyzer. The top and rear views of the fabricated antenna are shown in Figure 9. Figure 10(a) shows the simulated return loss



Top View

Rear view

Figure 9. Photograph of the proposed cross shaped patch antenna.



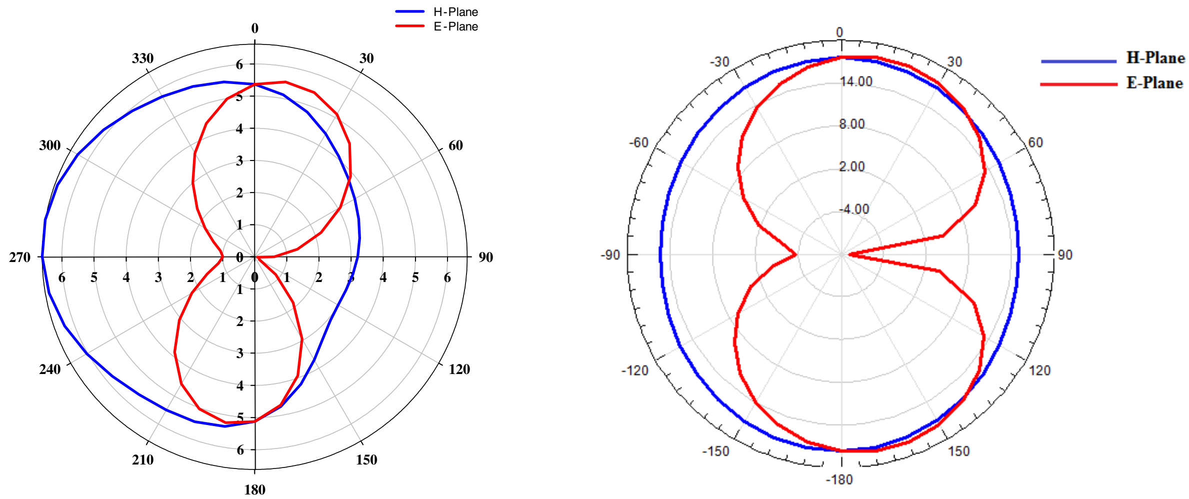
(a) (b)

Figure 10. (a) Simulated return loss characteristics of various evolution stages of antennas. (b) Simulated & measured return loss Characteristics of the proposed antenna.

characteristics of the proposed antenna at various evolution stages. Figure 10(b) compares the measured and simulated return loss characteristics of the proposed antenna. The proposed antenna exhibits a measured -10 dB bandwidth of 90 MHz for lower Wi-Fi band from 2.395 to 2.485 GHz and a bandwidth of 135 MHz from 4.96 to 5.095 GHz for the upper Wi-Fi band.

Table 2. Comparison of various evolution stages of proposed antenna for IEEE802.11 ax applications.

S. No	Evolution stages	Resonant Frequency (GHz)	Simulated Gain (dBi)
1	Conventional antenna	5	3.4
2	CSRR loaded patch antenna	2.485 & 5	1.9 & 1.7
3	CSRR loaded patch antenna with 2×2 hexagonal CSRR array	2.4 & 5	6.64 & 10.1



(a) (b)

Figure 11. (a) Simulated E and H Plane radiation pattern at 2.4 GHz. Simulated E and H Plane radiation pattern at 5 GHz.

The simulated results of radiation pattern at 2.4 GHz and 5 GHz are shown in Figures 11(a)–(b). The results show that same dipole radiation pattern exhibits within the E-plane, and omnidirectional radiation pattern exhibits within the H-plane for all operating bands.

The simulated gain of proposed antenna is compared with the 2nd evolution stage of antenna and is tabulated in Table 2. It can be seen that the measured gains from 2.4 GHz and 5 GHz are respectively 6 dBi and 10 dBi. The contrast between the proposed antenna and existing antennas based on dimension, covered band, gain is shown in Table 3.

Table 3. Comparison between the proposed antenna with existing antennas based on dimension, covered band, gain.

	Patch Dimensions ($L \times W \times h$) mm^3)	**Frequency (GHz)**	**Measured Gain**
[5]	$40 \times 46 \times 1.6$	2.4–2.5	5 dBi
[10]	$31 \times 24.57 \times 1.6$	5 & 5.8	2.51 dBi
Proposed	$20 \times 25 \times 1.6$	2.4/5	6 dBi/10 dBi

5. CONCLUSION

In this paper, a compact gain enhanced cross shaped patch antenna has been proposed for IEEE 802.11ax applications. The designed an optimized cross shaped radiating element and four ring circular CSRR resonates at 5 GHz and 2.4 GHz respectively. Both of them have been properly combined to fulfill the dual band requirement of upcoming 2.4 GHz and 5 GHz Wi-Fi applications by the proposed antenna with compact dimensions of $20 \times 25 \times 1.6\,\text{mm}^3$. The four ring circular CSRR pass band characteristics is investigated by a waveguide theory method to get its negative permittivity at 2.4 GHz. Metamaterial loading is an advantageous approach to miniaturize as well as to enhance the gain of the antenna without altering the dimensions and size. From the measurement results, the introduction of the array of the 2×2 array hexagonal CSRR provides a gain enhancement in proposed antenna compared to conventional patch antenna.

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