A dual-band high gain complementary split-ring resonator (CSRR) loaded hexagonal bowtie antenna with enhanced bandwidth for Vehicle-to-Vehicle (V2V) communication applications

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Abstract *– A highly reliable and efficient communication system is needed for a vehicle to navigate and drive to the destination without human control (known as an autonomous or self-driving vehicle). In this work, we consider various parameters for the antenna design, ensuring reliable communication amongst vehicles and infrastructure. Specifically, we consider the type of antenna, the method used, operating frequency, substrate type (with thickness and permittivity), size and shape, gain, and bandwidth. An optimal threshold value or range of these parameters is identified. Moreover, a complementary split-ring resonator (CSRR) metamaterial (MTM) based hexagonal bowtie antenna for a high gain V2V communication environment is presented. This antenna covers sub-6 GHz fifth generation (5G) bands (3.15-3.95 GHz) and Wi-Fi band 2.4GHz. Printing was done on a low-cost FR4 substrate for the radiating patch. Antenna Bandwidth is enhanced using a partial ground plane. The radiating layer is based on hexagonal patches printed on the double side of the substrate, and the CSSR structure is etched from patches to enrich antenna gain and bandwidth. More importantly, the proposed CSRR employed antenna provides gain and bandwidth of 1.6dBi / 6 dBi and 100MHz/ 8000MHz at 2.4GHz /3.5GHz, respectively. A highly known software, CST microwave studio, simulates the proposed antenna. Simulated and measured results make this arrangement a potential candidate for 5G high gain V2V communication.*

Keywords: *Autonomous vehicle, Optimal antenna parameters, Reliable and efficient communication systems, Metamaterial*

1. INTRODUCTION

Recent research findings conclude that: ***"nearly 1.25 million people die in road crashes each year, on average 3,287 deaths a day, and an additional 20-50 million are injured or disabled around the world"*** [1]. Though demand for automobile use in high numbers is unavoidable, the above numbers are not acceptable, especially if we know that most of these accidents happen due to human error. This poses a significant challenge for the whole world to redesign the existing transportation system irrespective of its serious problem.

The availability of fully Autonomous Vehicles (AVs) is one of the solutions not recently proposed instead in experimentation and evolutionary stages for a long time. The concept of AVs is becoming possible because of the advancements in multiple fields such as sensing, availability of state-of-the-art materials, ultra-fast computing facility, and Artificial Intelligence (AI). However, the underlying problem is not straightforward as it requires an upgraded intelligent transportation system where AVs are the main components [2,3]. Tons of efforts have been devoted in the past [4,5,6,7], which are remarkably commendable to enjoy the latest version of AVs. However, it is surprising that no "fully autonomous vehicles" still exist [8]. Instead, the proposed contemporary solutions still reflect limitations and require improvement to enjoy an optimal version of AVs, specifically fast communication, to make reliable decisions fulfilling safety requirements [9,10].

In [11], a predictive active front steering control system for AVs is introduced where a trajectory is known for finite distance at each time step. Moreover, the front steering angle is determined for trajectory, especially for slippery roads at maximum entry speed. Furthermore, a map-free lane method was presented in [12], utilizing a 2D low-cost laser scanner for near future AVs to bridge the gap between forthcoming AVs and lane-keeping assistants. Moreover, integrated positioning for connected vehicles enhances positioning accuracy and availability, specifically for urban canyons studied in [13]. Furthermore, in [14], an advanced lane-keeping assistance system *(known as LKAS)* was proposed. In [15], a photovoltaic LIFI communication system offering both reliability and efficiency amongst AVs and between vehicles and road infrastructure (V2RI) was developed and termed as an intelligent transportation system keeping its significance compared with a traditional communication system using radio frequency (RF). Finally, it is worth mentioning [16] that an RF-based communication system covering a range of 20 kHz to 300 GHz was presented mainly based on the oscillation rate of an alternating electric current or voltage.

We now consider efforts devoted to wireless-based communication systems [17,18] specifically related to emerging intelligent transport systems (known as ITS). In this regard, a detailed survey is conducted in [17], highlighting what has already been contributed to wireless communication systems. Moreover, readers can enlighten further about methods a) used so far and b) currently under the research and validation phase.

It is further emphasized in [18] that ITS will fulfill the future needs of smart or intelligent communication systems. Consequently, humanity will witness safer highways or, in general, road travel. Here we name a few of the existing widely used and tested technologies such as Wi-Fi (IEEE 802.11xx), WiMAX (IEEE 802.16), 4G-LTE, wireless sensor, and ad hoc networks, and above all 5G. Concluding, the prime functionality of any communication system related to a transportation system is twofold. One is the critical communications between vehicles and infrastructure, addressing increased efficiency and reliable connectivity. Second is the passenger's experience ensuring utmost safety. In this regard, using antennas to communicate among vehicles and infrastructure has gained the attention of arrays and compact antennas [19-22]. a broadband high-gain [23-32], high gain and bandwidth [33], substrate material [34-40], high bandwidth [41-42].

This paper aims first to identify the optimal either threshold value or range for key performing parameters while designing an antenna and then design an antenna based on this for testing and validation. Achieving this, we ensure features such as efficiency, safety, and smooth navigation of AV. The structure of the paper is organized as follows. Section 2 is devoted to contributions made by many recently to identify optimal range or threshold values related to key performing parameters in antenna designing. Section 3 is devoted to designing and fabricating a novel complementary split-ring resonator (CSRR) metamaterial (MTM) based hexagonal bowtie antenna, followed by the conclusion in Section 4.

2. THRESHOLD/RANGE OF KEY PERFORMING PARAMETERS IN ANTENNA DESIGNING

In this section, we have primarily considered the following vital areas related to antenna design for V2V communication: array and compact antenna, broadband high-gain using high-end substrate material, high bandwidth, and high gain and bandwidth [19-22,33-42]. Commendably a lot is technically contributed, which is highlighted in the coming subsection for designing and implementing a novel antenna with the significance of optimal performance. Microstrip patch antennas (also known as planar antennas) are highly attractive as they are used in various applications and offer a range of features such as profile configuration, easy fabrication and manufacturing, cost-effectiveness, and lightweight.

2.1. HIGH GAIN ANTENNA USING WIDEBAND REFLECT ARRAY

In this section, we consider that another important class of antennas (*highly robust, reliable, and cost-effective with easy fabrication)* is the single layer fully planar reflect array antennas [19, 23-26]. Interestingly, these offer a much wider operating frequency range of [10-30 GHz] with 100% fractional bandwidth [19]. Moreover, the following salient features of the proposed single-layer array are highlighted below, which were thoroughly compared with related efforts made by many in [23-26]:

- *Wider operating frequency range of 10GHz to 45 GHz;*
- *Peak gain between range 24.2 to 32.83 dBi for the above-mentioned frequency range;*
- *bandwidth gain from 1 to 3 dB.*

2.2. HIGH GAIN ANTENNA USING HIGHER ORDER MODES

In [20], Govindarajulu et al., with the help of higher order modes, improved gain for an operating frequency of 28 GHz and an array operating at 5.9 GHz. The fabrication of the proposed aperture array for 5.9 GHz and 28 GHz operating frequencies ensured gains of 9.97 dBi and 12.3 dBi, respectively. Moreover, for

DSRC, band isolation of more than 55 dB amongst ports was seen, whereas, for 5G mm-wave, band isolation of 33 dB amongst ports was obtained. Following salient features of the single proposed layer array are highlighted below, which were thoroughly compared with related efforts made by many in [27-32]:

- Using higher order modes ensure high gain.
- Improvement in port-to-port isolation (*an inter-element spacing of 0.5λ*) for lower and upper band frequencies.
- Cost-effective and straightforward PCB-based fabrication because of its simple structure.

2.3. HIGH GAIN ANTENNA BY MODIFYING THE RADIATING PATCH

This section considers efforts devoted to high gain in connection with substrate material and modifying the radiating patch, which is of utmost importance while designing the antenna. We consider efforts invested in [34-39] based on different substrate materials with desired operating frequency band range of (5.88-5.92 GHz). Most of these articles use hexagonal antenna geometry with elliptical slots on the radiating patch, while V shape slots are used in [35]. In [39], gains of 4.37 dBi and 5.6 dBi were obtained without and with defective ground structure (DGS). However, amongst all efforts [34-39] highest gain of 6.02 dBi is ensured in [39]. Therefore, we mention below the salient features of this work:

- Offers the highest gain of 6.02 dBi;
- Antennas operate in the IEEE 802.11p defined vehicular communication band with 5.9 GHz resonant frequency and 200 MHz bandwidth;
- Geometry is less complex, enabling easy fabrication and cost-effectiveness.

2.4. HIGH GAIN AND HIGH BANDWIDTH ANTENNA

High gain and bandwidth antennas offer various attractive features, specifically in AVs applications. It is evident from [40-42] that higher order modes highlight enormous advantages, particularly when the antenna is designed using a single-layer simple patch. These antennas are found in diversified fields covering concealed weapons detection and enhanced vision for biomedical and avionics industries. In [42], optimal peak gain of 11.84 dBi with 17.6% bandwidth and gain of 8.5 dBi with 15.14% bandwidth for Ku and Ka bands is achieved so far, respectively.

2.5. COMPLEMENTARY METAMATERIAL RING RESONATOR (CSRR) ANTENNA

In this era, flat patch antennas with a suitable metal combination are highly desirable by the automotive industry covering high-frequency applications for V2V communication operating at a band of 5-6 GHz. We refer few of the efforts [43-45], where the reader can explore more from these texts. In [43] two complementary metamaterial resonators square patches were added to a rectangular patch antenna to optimize performance with a gain of 18.53 dB.

2.6. SUMMARY OF KEY FINDINGS

This section presents the summary of key findings from sections 2.1-2.5. it is evident from considered research works that efforts are devoted to improving gain using a high-end substrate, or by using an array antenna, and modifying the radiating patch. However, few of these research works focused only on improving bandwidth without enhancing considerable antenna gain. The major requirement for V2V communication antenna must provide both high gain and bandwidth by using low-cost substrate material for large-scale deployment related to vehicular applications [33]. Therefore, the following sections are devoted to incorporating above mentioned key requirements. Moreover, an optimal antenna design fulfilling characteristics such as better gain and bandwidth with a low-cost substrate has been simulated, fabricated, and validated at 3.5GHz.

3. DESIGN GUIDELINES AND STRUCTURE OF PROPOSED ANTENNA

The geometry of the proposed double-sided printed bowtie antenna is given in Fig.1 with the thickness and relative permittivity of the FR4 substrate as 0.8 and 4.3 mm respectively. Bowtie microstrip patch antennas became enticing candidates in modern communication systems due to their small size, which is smaller than that of a traditional rectangular radiating patch antenna at the same operating frequency. Moreover, the double-sided bowtie structures such as hexagonal and circular bowtie radiators help to improve the bandwidth from 10% to 50% [46,47]. So, this paper presents a modified double-sided bowtie design consisting of two hexagonal patches, one printed on the top layer and the other on the bottom layer (see Fig-1 a & b respectively). The double-sided patches have been etched with CSRR-MTM structure as shown in Fig. 1. The dimension and structure of CSRR are shown in Fig.2. Antenna is excited by a 50-Ω microstrip feed line. The step-by-step design of the proposed structure is explained below.

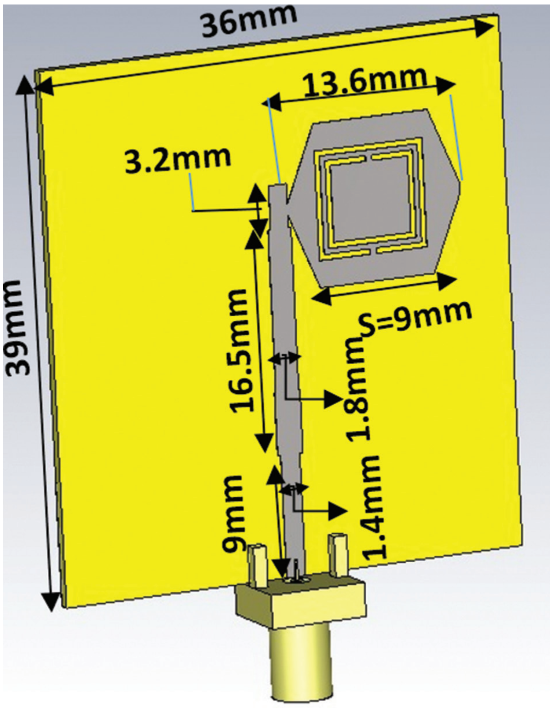
In Fig-3, we present a step-by-step design of the antenna. Initially, the design of the antenna starts with a hexagonal patch bowtie structure printed on the top layer and the bottom layer is the complete ground plane. The sides dimension of the hexagonal radiating patch has been developed from a circular patch because the shape of both patches is close relative to each other. The circular radiating patch antenna resonance frequency is determined by Equation (1) [48]. For TM11 mode, X_{mn} = 1.8411, a_e = effective radius of the circular patch, and *c* is the free space velocity of light. In Step 1, the initial resonant frequency should be 5.8GHz. By substituting the value of f_r in Equation (1), the value of a_e =7.4mm. In Equation (2), *a* represents the circular patch's actual radius, whereas *h* indicates the thickness of the FR4 substrate. Equation (3) shows relations between circular and hexagonal radiating patch areas, whereas '*s*' represents hexagonal radiating patch side length. Equation (1)-(3) has been used to calculate the '*s*'.

$$f_r = \frac{X_{mn}}{2\pi a_e \sqrt{\varepsilon_r}} c \tag{1}$$

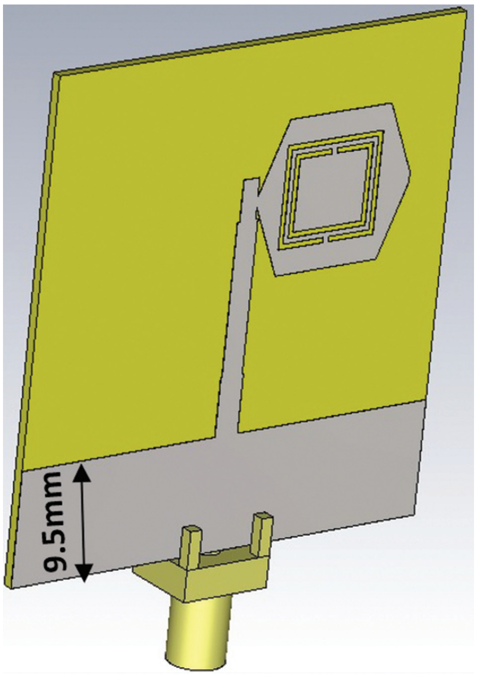
$$a_e = a\left\{1 - \frac{2h}{\pi a \varepsilon_r}\left(ln\frac{\pi a}{2h} + 1.7726\right)\right\}^{0.5} \tag{2}$$

$$\pi a_e^2 = \frac{3\sqrt{3}}{2} s^2 \tag{3}$$

Likewise, it has been shown in Fig.4 that the antenna resonates 5.8 GHz in step 1 with a bandwidth of 350 MHz by simulating the design using CST Microwave Studio. In Step 2, a CSRR structure was etched from the hexagonal patches. This helps to shift the resonating frequency from 5.5 GHz to 4.3 GHz and generated a new resonant frequency at 2GHz. So, the antenna shows a dual-band behaviour. In Step 3, a bandwidth improvement was achieved by moving one of the hexagonal patches to the bottom layer with a partial ground plane and the other one to the top layer. An improved bandwidth of 100MHz / 850 MHz has been achieved at 2.4GHz /3.5GHz, respectively. The final design of the proposed antenna covers a dual-band frequency range between 2.35 GHz- 2.45 GHz and 3.2 GHz- 4.05GHz. The first resonant frequency of the proposed antenna covers the Wi-Fi band, and the second frequency covers the sub-6GHz 5G frequency.



(a)



(b)

Fig. 1. Layout of Proposed Antenna Design (a) Top Layer (b) Bottom Layer

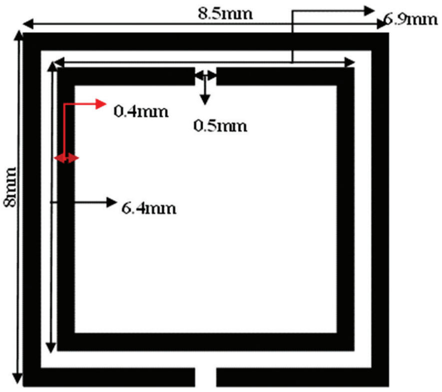


Fig. 2. Layout of Complimentary Split Ring Resonator 11

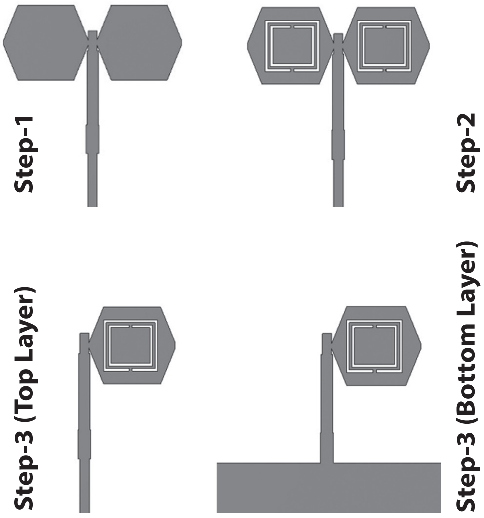


Fig. 3. Step-by-Step Design of Proposed antenna

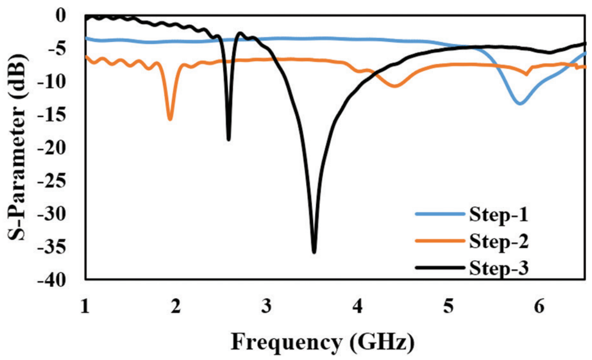
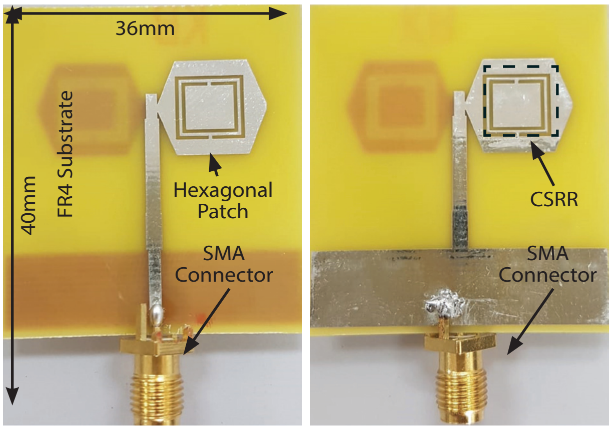


Fig.4: S- Parameter response of step-by-step antenna design

4. RESULT AND DISCUSSION

The fabricated prototype of the proposed CSRR MTM-based double-sided hexagonal bowtie antenna is shown in Fig.5 (a-b). The simulated and measured results of the return loss (S_{11}) for the proposed bowtie antenna are shown in Fig. 6.



(a) (b)

Fig.5. Fabricated prototype of Proposed Antenna Design (a) Top Layer (b) Bottom Layer

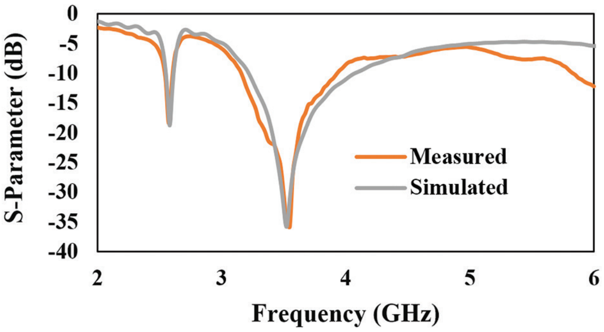
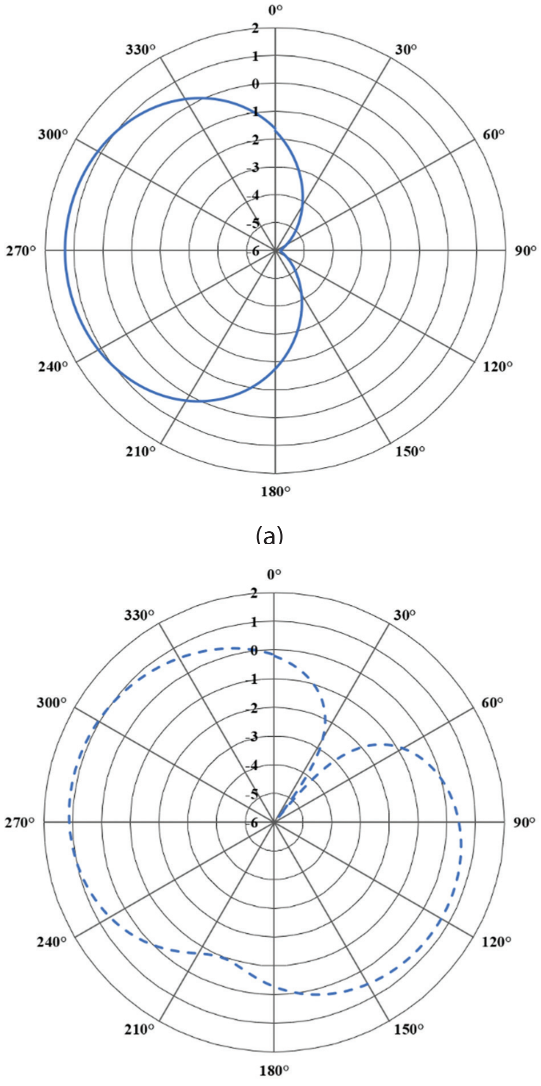


Fig.6. S-Parameter Response of Proposed Antenna

All simulated results were computed using the CST Microwave Studio which works on the FDTD technique. It could be observed from Fig. 6 that the proposed antenna resonates at 2.4GHz and 3.5GHz with a return loss of -20dB and -40dB, respectively.

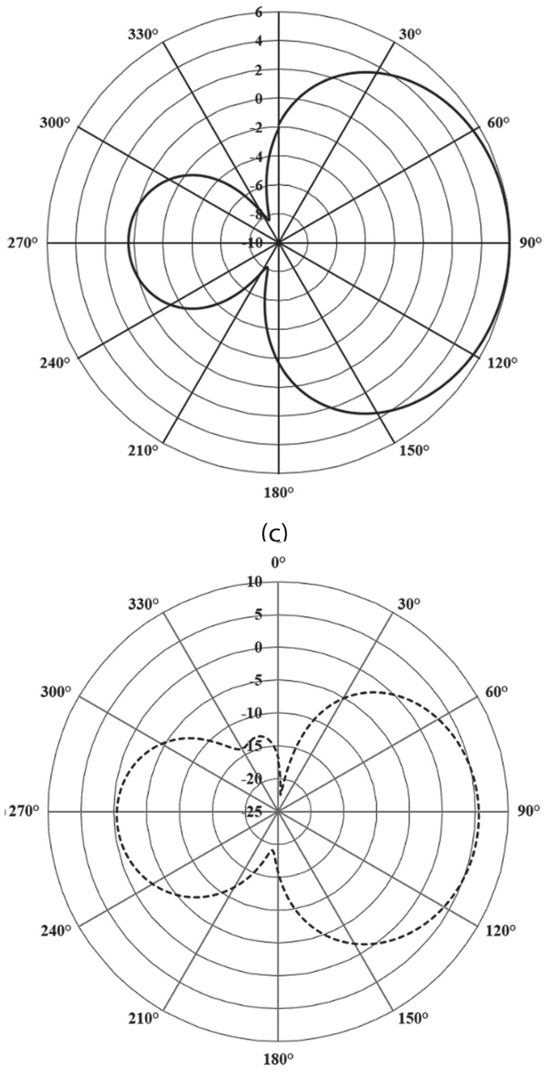
Furthermore, it is observed that the measured results of the proposed antenna cover the dual-band frequency range of 2.38GHz- 2.48GHz and 3.15GHz -3.95GHz. The S_{11} values suggest good impedance matching at 50 Ω and reasonable bandwidth. The S-parameter response shows an excellent agreement between simulated and measured results.

Fig.7 (a-d) shows the proposed antenna's simulated and measured radiation patterns at both the E-plane and H-plane, respectively. It can be observed from **Fig.7 (a-b)** that the proposed bowties antenna is radiating in the direction of -90° having a gain of 1.6dBi at 2.4GHz. Similarly, it has been illustrated in the **Fig.7 (c-d)** that the antenna is radiating in the direction of 90° with a gain of 6dBi at 3.5GHz. At higher frequency, the antenna gain is more as compared to lower frequency and the direction is opposite to each other. This shows that the proposed antenna is an excellent candidate for V2V communication due to its high gain at 3.5GHz and covering two different directions at the same time in two different frequencies. The high gain at 3.5GHz makes the proposed antenna design more suitable to work in the 5G wireless communication systems.



(a)

(b)

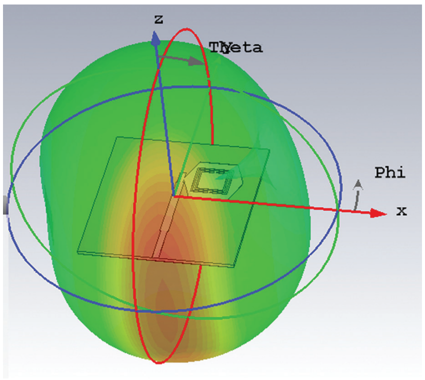


(c)

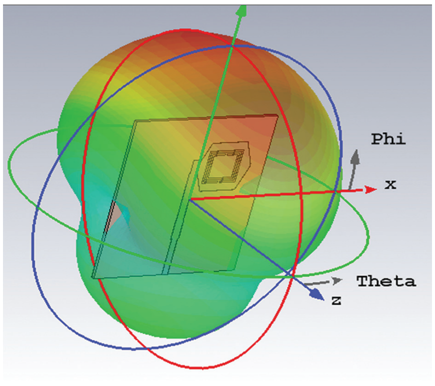
(d)

Fig.7. Two-Dimensional Radiation Pattern of Proposed Antenna (a) E-Plane (b) H-Plane at 2.4GHz (c) E-Plane (d) H-Plane at 3.5GHz

The 3D radiation pattern of the proposed antenna at 2.4GHz and 3.5GHz is shown in **Fig.8 (a-b)**. It can be seen from Fig.8 that the proposed antenna shows that maximum radiation at 2.4GHz and 3.5GHz are opposite to each other. This shows that the proposed antenna was a promising candidate for V2V communication.



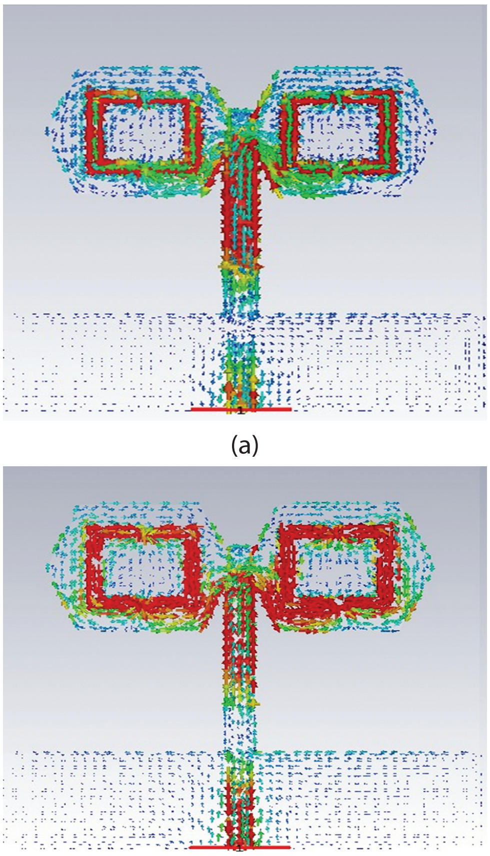
(a)



(b)

Fig.8. 3D Radiation Pattern of Proposed Antenna (a) 2.4GHz (b) 3.5GHz

After measuring the 3D radiation patterns, the surface current distribution of the designed and proposed antenna is simulated to understand the antenna behavior. **Fig.9 (a-b)** shows the antenna surface current response at 2.4GHz and 3.5GHz, respectively. It can be observed from the results in **Fig.9 (a-b)** that the surface current distribution is high around the CSRR structure and low at the corners. **Fig.10** shows the simulated radiating efficiency of the proposed antenna. It can be realized from Fig.10 that the proposed antenna shows a radiating efficiency of 90% at 3.5GHz.



(a)

(b)

Fig.9. Proposed antenna surface current distribution at (a) 2.4GHz and (b) 3.5GHz, respectively

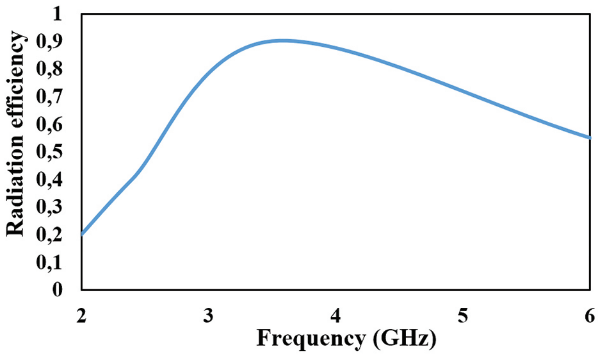


Fig.10. Radiating Efficiency of Proposed Antenna

Table 1. Comparison of Proposed antenna design with the existing designs [34,44, 49-51]

Ref	Centre Frequency (GHz)	Single / Dual-band	10dB -Bandwidth (%)	Gain (dBi)	Size (mm × mm)
[34]	5.9	Single	3	5.6	20.2 × 24.1
[44]	2.45, 3.6	Dual	10, 8	3	35 × 10
[49]	3.5	Single	12.57	7	37.4 × 37.4
[50]	3.5, 5	Dual	14, 28	2.5, 4.1	32 × 20
[51]	5.8	Single	8.27	6.15	200 × 200
This Work	2.4, 3.5	Dual	4, 23	1.6, 6	36 × 39

A comparison of the proposed antenna with the previously published work on antennas for vehicular application is summarized in Table 1. The researchers are attempting to either enhance the bandwidth or improve the gain at 3.5 GHz/ 5.9GHz in most of the designs described in Table 1. The proposed work shows the bandwidth and gain improvement of the antenna together at 3.5GHz, which is considered the main requirement for the antenna design of V2V Communication.

5. CONCLUSION

Smart cities are becoming a necessity for the whole world due to their benefits, for which one of the main components is intelligent transportation systems and AVs. Keeping this in mind, famous car makers, Google, Apple, and Uber, are investing huge amounts of money. As a result, the autonomous and semi-autonomous vehicle market is expected to reach $500 billion by 2035 [15]. Furthermore, AVs are considered the best solution for the increased number of accidents happening due to human errors. Therefore, a noticeable improvement to autonomous vehicles and transportation systems is developed by designing a smart communication process between the vehicles and the surroundings to guarantee safety. One of the key components in this regard is the antenna which plays a vital role in reliable communication. Considering this, a CSRR MTM-based hexagonal bowtie antenna is presented to enjoy better gain and bandwidth, specifically for V2V applications. The proposed antenna covers sub-6 GHz fifth generation (5G) bands (3.15-3.95 GHz) and Wi-Fi band 2.4GHz with radiating patch printed on a low-cost FR4 substrate. Furthermore, the proposed antenna achieved a gain and bandwidth of 1.6dBi / 6 dBi and 100MHz/ 800MHz at 2.4GHz /3.5GHz. Finally, simulated and measured results make this arrangement a potential candidate for 5G high gain Vehicle-to-Vehicle (V2V) communication.

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