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Research Article

Development of Rogers RT/Duroid 5880 Substrate-Based MIMO Antenna Array for Automotive Radar Applications

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In this paper, a novel 2 × 2 multiple-input multiple-output (MIMO) antenna array with four patch elements is designed. The proposed antenna is the first dual band, operating at two prominent working frequencies: 24 (24.286-25.111) GHz and 77 GHz (75.348–79.688), of automotive radars. This structure is composed of two antenna modules colocated on a single substrate, whereas each module is made up of a corporate fed planar array of two elements. This attractive feature enables us to utilize the antenna in two different ways; either both modules serve as the transmitting/receiving antenna of a monostatic radar or one module serves as a transmitter and the other one as the receiver of a bistatic radar. Most of the existing autonomous radar applications operating at 24 GHz are going to become obsolete, and all countries have plans of shifting towards the 77 GHz band. Hence, our design is very attractive as it operates with the required performance in both the bands with another added feature of the MIMO structure. The placement of antenna elements is also optimized in terms of inter- and intraelement separation of greater than $\lambda/2$ so as to ensure high diversity gain of 9.6 dBi. Moreover, the proposed antenna structure with only two antenna elements is able to achieve a high gain of around 11.8 dBi and 11.3 dBi at the dual operating modes of 24 GHz and 77 GHz, respectively. In addition to the above-mentioned benefits, this design also addresses mutual coupling reduction that is a common problem in MIMO structures by using complementary split ring resonator (CSRR) structures. State-of-the-art comparison with the recent literature shows that the proposed antenna has less number of antenna elements, an adequate gain, an excellent VSWR value, and high isolation.

1. Introduction

The revolution in the automobile industry is supported on a large scale by the developments in electronics, artificial intelligence, communication, and radar technology. All these technologies are highly in the mandate for the upgrade of automotive cars/vehicles into a higher level. Thus, the highly automated vehicles (HAV) that incorporate various customer needs such as safety, flexibility to handle, money-saving, and luxury are in huge demand in the market. The above services can easily be provided by the innovation and implementation of suitable technologies in autonomous systems. Recently, there is an enormous growth in the automation industry using advanced driver assistance systems (ADAS). ADAS includes the most important automatic emergency braking system (AEBS) and adaptive cruise control (ACC) that falls in the coverage range of up to 150 m. On the other hand, long-range radar (LRR) used in these systems is operated at the low-frequency range of 24 GHz (24–24.25 GHz). These automotive cars are additionally supported by techniques such as blind spot detection (BSD) and cross-traffic alert (CTA) whose maximum range is 30 m and hence are being supported by short-range radars (SRR). For short-range radar applications, the 24 GHz NB of bandwidth 250 MHz is suitable for simple cases such as BSD, and ultrawide band (UWB) of bandwidth up to 5 GHz is needed for high-range resolutions. Due to spectrum regulations developed by the European Telecommunications Standards Institute (ETSI) and the Federal Communications Commission (FCC), the 24 GHz band will be phased out soon [1, 2]. Hence, shifting towards the 77 GHz band is highly needed. This band is enabled in applications such as traffic jam regulation, accident detection, vehicle counting, and so on and is already implemented in countries such as Japan and in Europe. The higher 77–81 GHz band is suitable for SRR applications and is a new entrant; this band has recently gained significant traction both from a worldwide regulation perspective as well as industry adoption. The availability of wide bandwidth up to 4 GHz in this band makes it attractive for applications requiring high-range resolution. Moving forward, most of the 24 GHz automotive radar sensors will likely shift towards the 77 GHz band. For the above-mentioned reasons, the 77 GHz is also better than the existing 24 GHz band in the aspects of wide bandwidth, reduction of antenna size (–3x smaller), minimized interference (high atmospheric absorption) with existing cosystems, and improved target resolution. Now, this is the turn of 77 GHz radar sensors to become the mainstream leveraging the benefits discussed above, with few drawbacks such as the requirement of series-fed linear array structure and complex multiple antenna arrays.

Extensive research has been carried out on antenna design at the 24 GHz band for radar and sensor applications [3–6]. In [4], MIMO antenna, a 25.1–37.5 GHz band is proposed with a maximum gain of 5dBi and high isolation. The antenna for Doppler radars was designed in [5] with a 2×2 MIMO structure reported a bandwidth of 510 MHz and isolation of 36.7 dB. In [6], an antenna at millimeter-wave band from 23.2 to 24.6 GHz was developed using Teflon as a dielectric substrate with a bandwidth of 1.4 GHz and mutual coupling of 23 dB.

But the design at 77 GHz witnessed only very few developments. In [7], the antenna for radar application at 77 GHz by means of an array of series-fed rectangular patches in the order of 10×4 and 12×4 was proposed with an overall array size of $20.43 \times 7.8\,mm^2$ and $16.72 \times 10.75\,mm^2$, respectively. Ushemadzoro Chipeng et al. [8] have simulated the radar system design using a single column of five-element series-fed patch antenna as TX antenna and four columns of five-element serial-fed array as RX antenna with the gain of 15 dB and 20 dB, respectively. The recent radar structure proposed in [9] used multiple transceiver bistatic radar around the autonomous vehicle so as to provide coverage for the entire 360°. All those bistatic modules were mostly rows of the serial-fed array of patch elements, which occupy more space. Thus, the recent state-of-art researches on the radar are using mostly series-fed patch antennas in multiple columns that form the MIMO structure so as to simultaneously receive EM waves from multiple directions to/from the target.

Research on MIMO radar is very drastic due to its advantages over its phased array counterpart. The maximum number of targets that can be uniquely identified by a MIMO radar can be up to Mt (number of transmit antennas) times higher than its phased-array counterpart [10]. Different planar antenna designs suitable for a multitude of applications in the mm-wave range were studied in [11], and the beam forming using power dividers or Rotman lenses was discussed in detail. But one of the serious limitations of MIMO is the mutual coupling between the colocated elements. Many works have suggested various techniques to reduce the coupling effect. Metamaterial (MTM) has attracted much interest over the last few years to improve antenna performance such as isolation, gain, and bandwidth [12] using MTM-inspired split-ring resonators (SRRs) [13] and complementary SRR (CSRR) [14, 15]. In [14], the negative permittivity of CSRR is used to obtain the dual-band characteristics at 2.4 GHz and 3.4 GHz because of its special property of zero-mode resonance. Prem P. Singh et al. have proposed a triple antenna using the same CSRR structure in [15] for WLAN, Satellite TV, and Radar Applications. Most of the recent works on dual or triple band MIMO antenna design using CSRR have focused on the sub 6 GHz millimeter range. The most recent work in [16] has designed a 2×2 MIMO structure at 24 GHz radar application using a slotted structure on the patch and defected ground structure (DGS). The gain reported was around 9.8 dBi with high isolation of 45 dBi.

But our proposed work focuses on dual-band antenna design above the 6 GHz range, thus covering one at Ka-band (24 GHz) and the other at W-band (77 GHz) for autonomous radar application. The objective of this paper is to design a transceiver antenna with two ports on the same substrate for simultaneous transmission and reception. The substrate consists of a 2×2 MIMO structure with each module having two patch elements fed by the input/output port in the corporate feed structure in contrast with the conventional series feed. This helps in gain enhancement. Each patch antenna unit present in the array is also optimized by incorporating a novel CSRR structure on the patch for dual-band operation and mutual coupling reduction. Thus, the design provides optimal performance in terms of gain, directivity, reflection coefficient, and isolation that will be discussed in the forthcoming sections. Moreover, the proposed design provides better inter- and intraelement isolation by the optimization of patch locations just by avoiding the complicated DGS structures used in the previous literature for isolation improvement. The organization of the paper is as follows: Section 2 details the design procedure of the proposed antenna; Section 3 presents simulation results of the designed antenna; and Section 4 covers the performance comparison of the proposed antenna with other reported antennas.

2. Antenna Design

2.1. MIMO Radar Design Challenges and Requirements. The frequency-modulated continuous-wave (FMCW) radar sends the frequency modulated reference RF signal at the frequency of f_c Hz (24/77 GHz) and gets reflected by the targets with the shifted frequency of $f_c + \Delta f$. The reflected echo with a frequency shift of $f_c + \Delta f$ is mixed with the reference carrier signal producing the intermediate signal (IF) of frequency equal to Δf. This is further processed by the signal processing unit for target identification, speed, range, and so on.

There are so many challenges involved in this process of target identification with parametric resolutions in speed and range in spite of environments with complex targets with diverse radar cross-section (RCS), high diversity backscattering, closed spaced objects, and moving objects. Multiple input and multiple output (MIMO) radar serves as the key component in solving all the above challenges by incorporating multiple antenna elements at both transmitter and receiver sides [8]. MIMO is capable of providing both diversity gain and spatial multiplexing gain by exploiting the channel's rich scattering phenomenon and by sending multiple signals through multiple antennas, respectively.

In the former case, the diversity gain achieved by the MIMO radar is effectively useful in situations, where complex targets with diverse RCS characteristics are spread around the vehicle. The complex target is approximated by the collection of a large number of scatterers, where each scatterer constitutes separate multipath behavior in the wireless channel. The transmitted RF signals originating from "M" transmitting antennas impinges on the multiple, closely spaced scatterers and getting reflected. The reflected signal is received by "N" multiple receiver elements and combined. Thus, the $(M \times xN)$ MIMO radar constitutes "MN" paths between the source and destination antenna. The "MN" waveforms are received simultaneously to be completely independent of each other; the "M" transmitted antennas must be well separated from each other. Thus, spatial separation of more than half wavelength is required, or else, transmitted signals must be orthogonal to each other.

In the latter case, the array gain of the MIMO antenna supports the number of parallel targets handled simultaneously by the MIMO radar array. This is much useful in identifying multiple targets such as pedestrians, bicycles, adjacent cars, and other objects besides the road surrounding the autonomous vehicle. This illustrates the need for multiple-beam formation by the MIMO radar. Covering the surrounding multiple simultaneous beams can easily be produced by the MIMO radar with "M" transmitting antennas supplied with "M" distinct RF waves serving "N" sensors. According to [6], the larger the distance between the transmitting and receiving antennas, the higher the number of point target identification.

The conventional antenna used for radar application is the commercial horn antenna of gains around 24 dBi. The horn antennas are later replaced by planar patch antennas for their compact size and easy fabrication. But all the current radar used in automotive applications is using more number of patch antennas in serial array structure so as to increase the gain value of around 20 dBi. This again increases the size and manufacturing difficulties irrespective of the high gain achieved. Recent literature [3, 4, 9] used multiple such serial-fed array structures that occupy more space. Hence, the antenna designed in this paper is a MIMO antenna that is suitable for two scenarios: multitarget detection and complex target identification. This can be achieved by our colocated antenna structure with two modules A1 and A 2 supporting two different modes: (i) both the modules A_1 and A_2 are used as transmitter and receiver units, respectively (bistatic) and (ii) both A_1 and A_2 are used as transmitter units, while another similar structure must be used as a receiver unit (monostatic) depending upon the way how the input RF signals are applied. The proposed antenna has another unique feature of working at the dual resonant modes prominent frequency bands 24 GHz and 77 GHz.

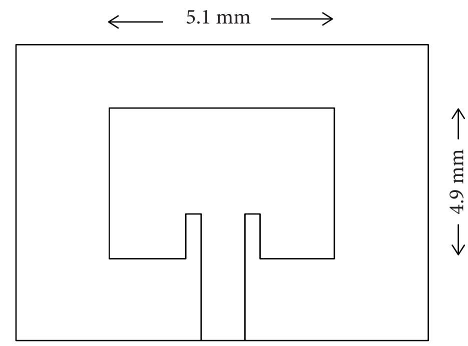

Figure 1: Rectangular patch antenna with the dimension.

2.2. Antenna Design Analysis. The first step involves the design of a rectangular patch antenna with the dimension of 4.9 mm × 5.1 mm (Wp1 × Lp1) as shown in Figure 1 whose resonant frequency was calculated theoretically as 18.8 GHz using the standard design formula [17]. The substrate used in our design is Rogers RT/duroid 5880 with thickness of $h = 0.5$ mm, relative permittivity of $\varepsilon_r = 2.2$, and loss tangent of $\tan\delta = 0.0009$. This material is selected since it has a low dielectric constant and low dielectric loss, making them well suited for high frequency/broadband applications. The change in material changes its dielectric constant that in turn changes the radiation efficiency.

The objective of the design is to resonate the antenna in dual mode at prominent radar frequencies of 24 GHz and 77 GHz. In [18], it was suggested that the anisotropic properties of the CSRR allow designing dual-band miniaturized antennas in opposition to dual-band antennas designed by the radiation of slots, in which the resonant frequencies are dependent on the physical dimensions of the slot. Hence, to obtain dual-band behavior in our design, a novel CSRR structure is proposed.

In the second step, two concentric rings were inducted as shown in Figure 2 that resonate with the antenna under dual

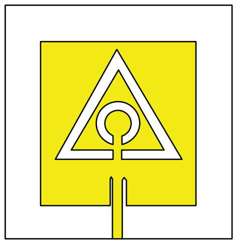

Figure 2: The proposed CSRR structure.

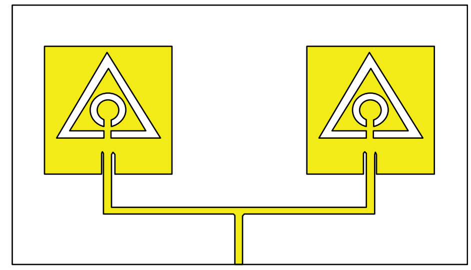

Figure 3: Two patch element antenna module.

modes: one at 24 GHz and the other at 77 GHz. The two rings form the CSRR structure with the split openings facing the same direction rather than facing the opposite as in conventional CSRR. Moreover, the design proposes two dissimilar-shaped (outer-triangle and inner-circular) concentric rings in the CSRR structure in opposition to standard CSRR structures that are made of using two concentric circular (or square) rings. The parametric analysis of the proposed CSRR structure yields the design shown in Figure 2 with the measurements as illustrated in the design. The dimensions of the outer triangular ring and inner circular ring and the distance between the two rings are optimized for resonating the antenna at dual modes.

The third step in the design is the gain enhancement since the antenna is designed in millimeter-wave frequency that has a very high attenuation due to high atmospheric losses in millimeter-wave propagation. This is achieved by using two patch elements in each antenna module as illustrated in Figure 3.

In the fourth step, a 2×2 MIMO antenna is designed, and the placement of each antenna element is optimized in terms of inter- and intraelement spacing between the MIMO antenna elements so as to reduce the mutual coupling between the elements. The proposed antenna structures possess a MIMO antenna of size $[2 \times 2]$ that is composed of four virtual antennas that support four distinct wireless channels. The four antenna elements are labeled into A_{11}, A_{12}, A_{21}, and A_{22}, where A_{ij} refers to j^{th} element of i^{th} array (Figure 4). In the above, the elements A_{11} and A_{12} form the transmit-array module, whereas the other two A_{21} and A_{22} forms receive array module of the colocated antenna structure for a bistatic radar.

The rectangular substrate of dimension (20.6×22.5) mm^2 is embedded with four patch elements of size (5.1×4.9) mm^2. Figure 4 shows the spacing between the interelements A_{11} and A_{21} of the colocated array as 5 mm, which is also equal to the spacing between A_{12} and A_{22}. Similarly, the spacing between the intraelements of transmit- and receive-array structures is equal to 6 mm. As discussed in the previous section, for diversifying the transmitted signals from/towards the MIMO transmit/receive antenna, the separation of 6 mm between the intraelements of the Tx/Rx array is much higher than the required $\lambda/2$ distance ($\lambda/2 = 1.9$ mm at $f = 77$ GHz). Also, in the case of former, the separation of 5 mm ensures better isolation between transmit and receive modules. This satisfies the condition of multiple target detection that requires a minimum of $\lambda/2$ spacing between them. Another advantage of our optimized MIMO design is that it does not require additional

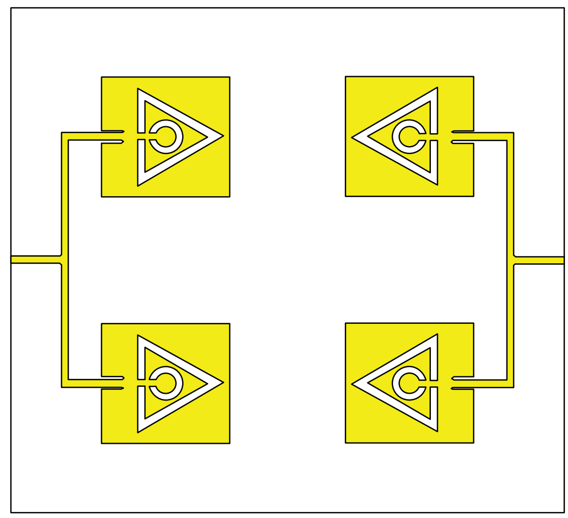

Figure 4: Proposed MIMO antenna array.

Table 1: Antenna design parameters.

Parameters	Dimensions (mm)
Ground width (Wg)	22.5
Ground length (Lg)	20.6
Substrate width (W)	22.5
Substrate length (L)	20.6
Substrate height (h)	0.5
Patch width (W_p)	4.9
Patch length (L_p)	5.1
Length of feed line (L_f)	2
Width of inset feed (W_{inf})	0.1
Length of inset feed (L_{inf})	0.78

mechanisms such as defected ground structures (DGS) or electromagnetic bandgap structures to improve isolation. Hence, a finite ground plane of the same length L and width W lies on the other side of the substrate and thus simplifies the design further. The type of feeding is the inset feeding, and the feeding length and width are optimized for perfect impedance matching [17]. The optimized design parameters are given in Table 1.

Thus, the proposed design offers the following advantages:

(i) Diversity gain for complex target detection using two antenna elements in both Tx and Rx elements

(ii) Design criteria $\longrightarrow$ intraelement spacing $> \lambda/2$

(iii) Multiple beams forming using the MIMO structure
(iv) Design criteria ⟶ interelement spacing > $\lambda/2$
(v) Compactness by means of colocated antenna structure
(vi) Dual operating frequency of 24 GHz and 77 GHz by means of CSRR
(vii) High gain by means antenna array of two elements

3. Results and Discussion

3.1. Antenna Surface Current Density. One of the major design challenges of all MIMO antennas is the mutual coupling reduction (isolation improvement) between the antenna elements. This can easily be achieved by the reduction in the flow of surface current between the patch radiators that in turn decides the amount of mutual coupling between them. Since the antenna module proposed here holds four patch radiators on the same substrate, the surface current measurement by exciting either of the two ports at a given time illustrates the amount of coupling between them. Figures 5 and 6 show the distribution of the surface current at ports 1 and 2, respectively, at the first resonant mode of 24 GHz, while Figures 7 and 8 illustrate the same at 77 GHz frequency. The metamaterial dual CSRR structure of the patch and the separation between the elements completely eradicate the reactive power coupling between the ports. Reduction in the reactive coupling from ports 1 to 2 reduces the induced current across the ports. The simulation results ensure reduced mutual coupling effects between ports under both resonant modes. It is clear that the current density at port 2/port 1 is almost zero at 77 GHz, while port 1/port 2 is excited, whereas at 24 GHz the induced current density is slightly higher at around 8 a.m. Thus, the 77 GHz operating mode is highly optimized for the application of autonomous vehicles in which both the antenna modules A_1 and A_2 can be simultaneously used with zero coupling effect.

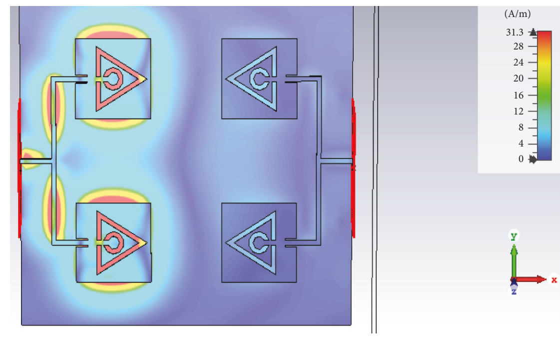

Figure 5: Surface current distribution at 24 GHz excited at port 1.

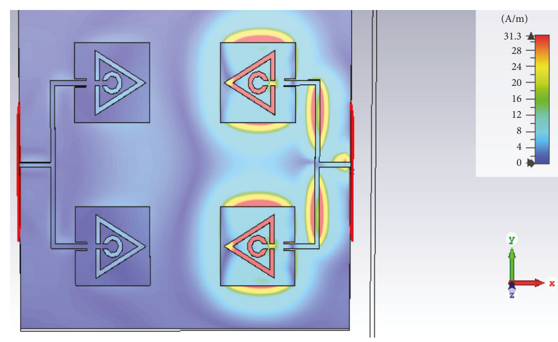

Figure 6: Surface current distribution at 24 GHz excited at port 2.

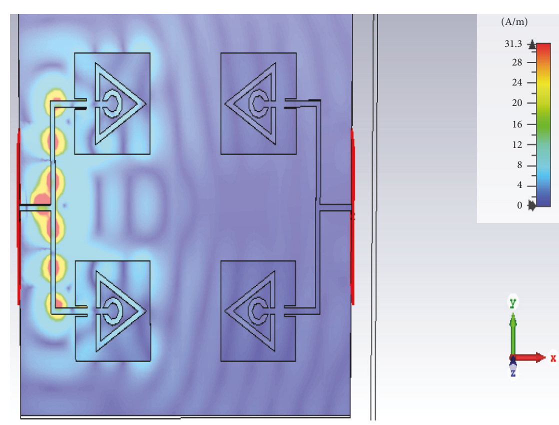

Figure 7: Surface current distribution at 77 GHz excited at port 1.

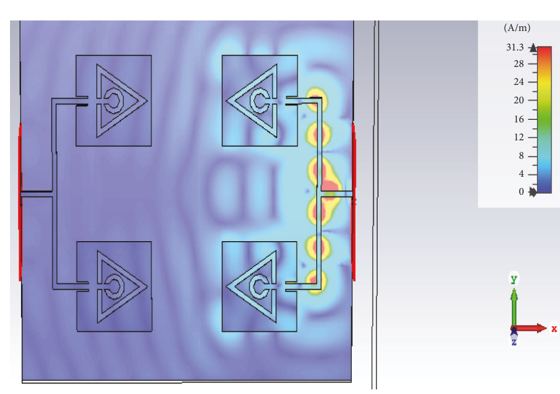

Figure 8: Surface current distribution at 77 GHz excited at port 2.

3.2. Antenna S-Parameters and VSWR. Figure 9 shows the simulation results of the S_{11} parameter of the proposed antenna module. For an antenna optimized with the values shown in Table 1, dual resonant modes are obtained as follows: the first mode exhibits impedance bandwidth of 825 MHz from 24.286 to 25.111 GHz having a center frequency of 24.6985 GHz, while the second mode is operating from 75.348 to 79.688 GHz with 4.3 GHz impedance bandwidth at the center frequency of 77.329 GHz.

As shown in Figure 10, the designed four-element array with the optimized intra- and interelement separation of 6 mm and 5 mm, respectively, yields a minimum coupling of $|S_{12}|$ as −25 dB over the entire antenna bandwidth, which is extremely higher than the existing array antenna structures. Much interestingly, $|S_{12}|$ attains a higher −44.26 dB value at the 77 GHz band that makes this colocated array design a perfect candidate in the automotive MIMO radar. Another important parameter of observation is VSWR characteristics with values of 1.02 and 1.1 at the dual modes of 24 and 77 GHz, respectively, as shown in Figure 11 that is in good

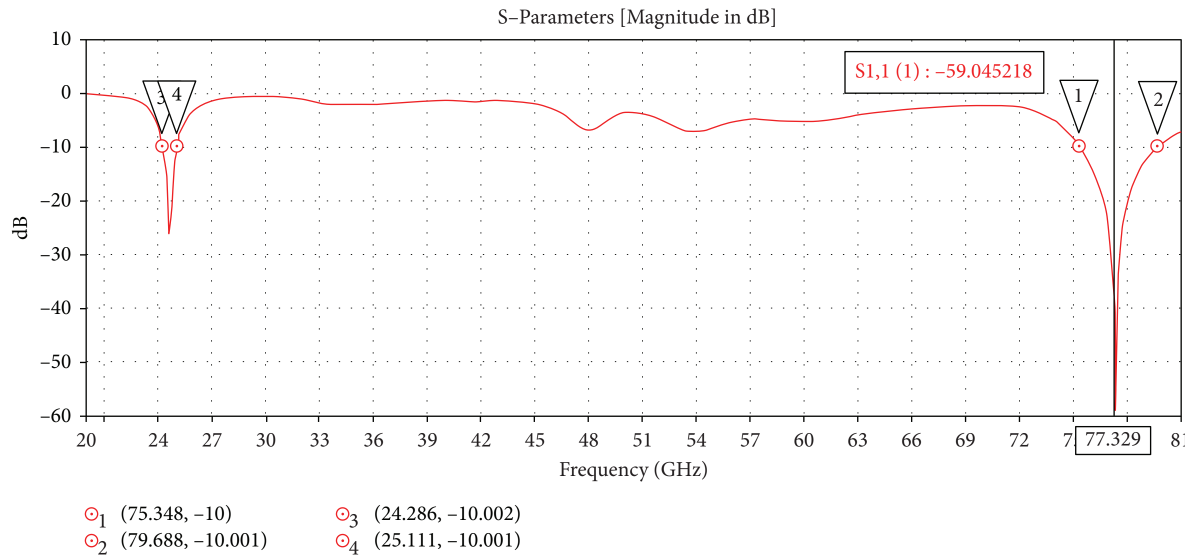

Figure 9: Simulated reflection coefficient (S_{11}) of the proposed antenna.

Figure 10: Simulated S-parameter (S_{12}) of the proposed antenna.

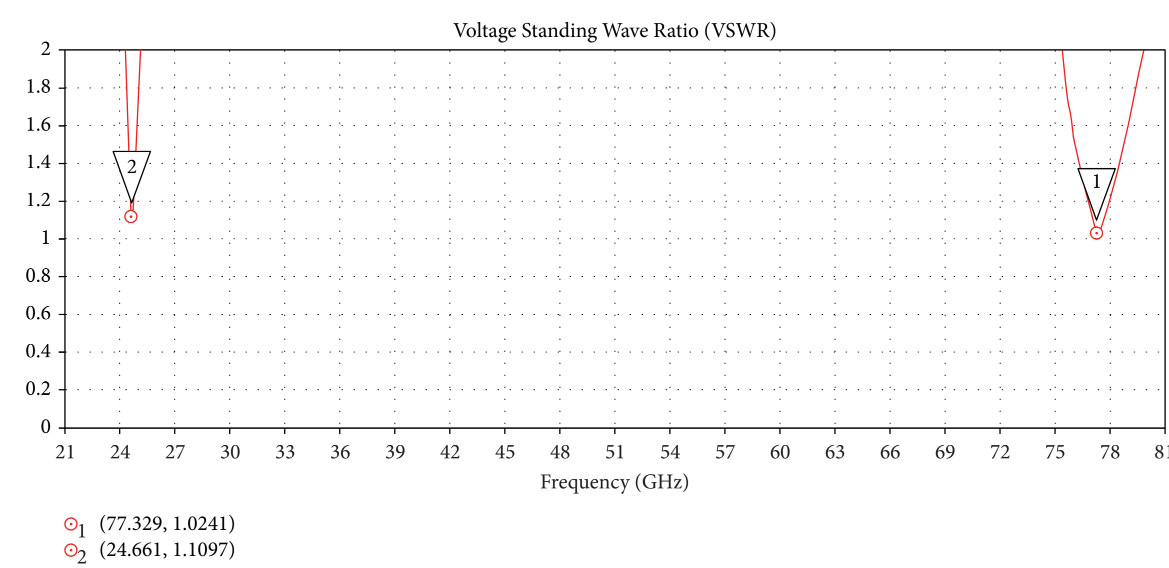

Figure 11: VSWR characteristics of the proposed antenna.

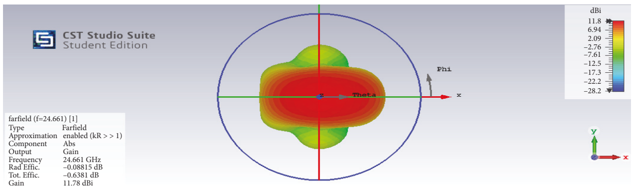

Figure 12: Gain of the antenna: 24 GHz – port 1.

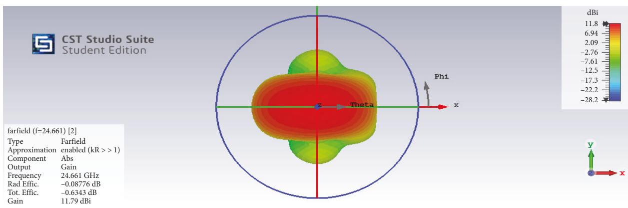

Figure 13: Gain of the antenna: 24 GHz – port 2.

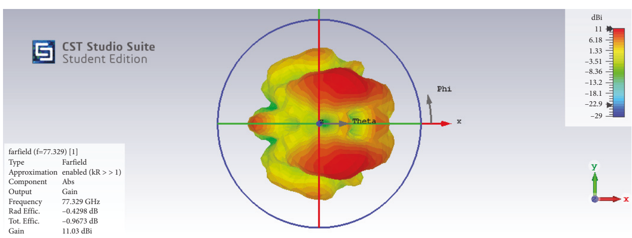

Figure 14: Gain of the antenna: 77 GHz – port 1.

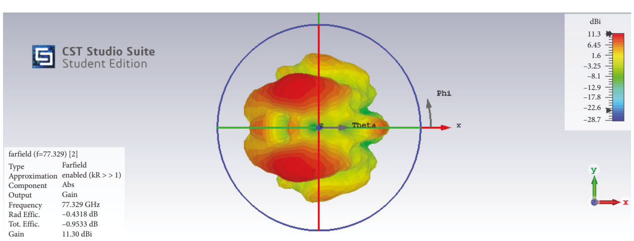

Figure 15: Gain of the antenna: 77 GHz – port 2.

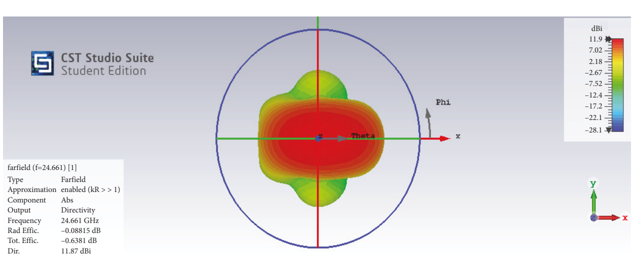

Figure 16: Directivity of antenna: 24 GHz – port 1.

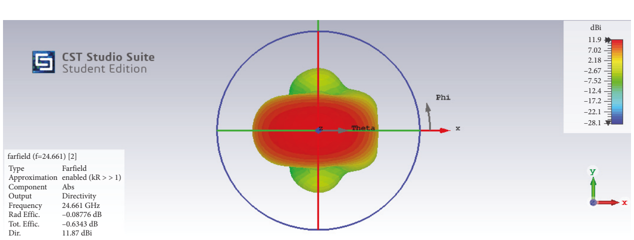

Figure 17: Directivity of antenna: 24 GHz – port 2.

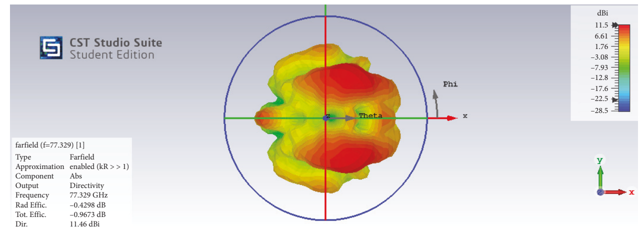

Figure 18: Directivity of antenna: 77 GHz – port 1.

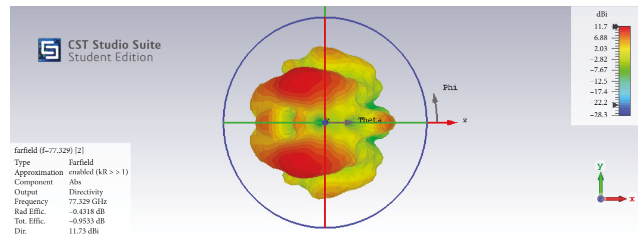

Figure 19: Directivity of antenna: 77 GHz – port 2.

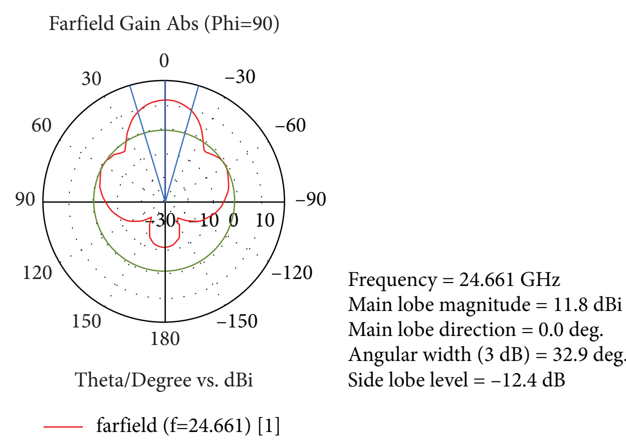

Figure 20: 2D radiation pattern: 24 GHz – port 1.

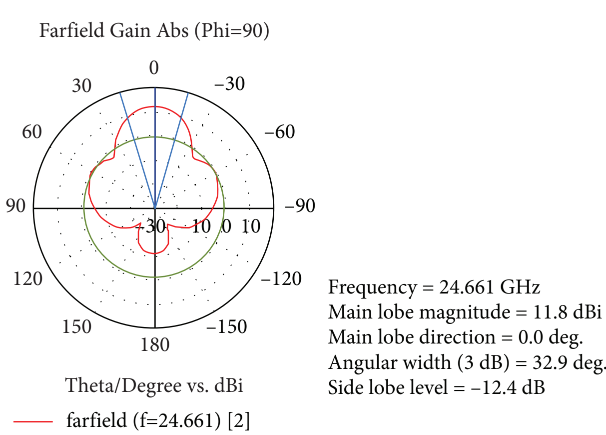

Figure 21: 2D radiation pattern: 24 GHz – port 2.

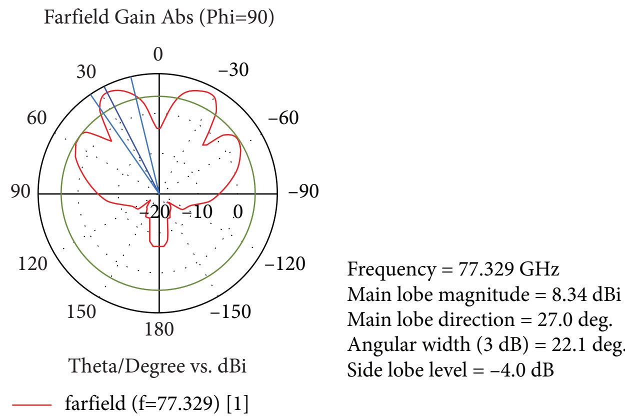

Figure 22: 2D radiation pattern: 77 GHz – port 1.

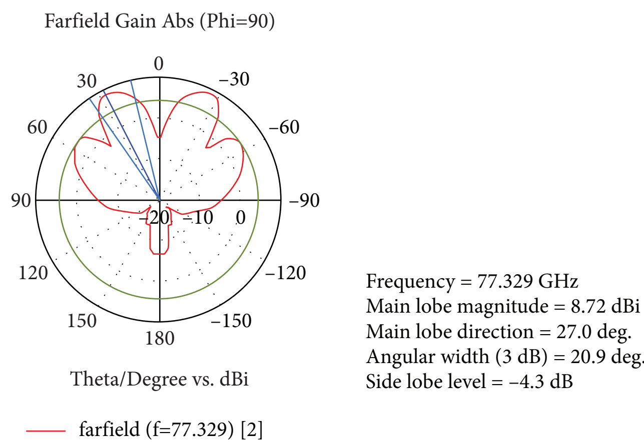

Figure 23: 2D radiation pattern: 77 GHz – port 2.

agreement with the optimal values. The proposed dual-mode design shows a broad impedance bandwidth, which is significantly wider than those obtained by conventional microstrip array antennas operating in single mode [10].

3.3. Antenna Gain and Directivity. The 3D far-field pattern of gain and directivity at 24 GHz and 77 GHz is plotted in Figures 12–19. It is evident that the gain of the antenna array is dominantly higher in 90% of the area with ~11 dBi. Almost the same or slightly higher than this is achieved in conventional arrays used in autonomous radars with more number of series patch antennas. Similar performance is also evident from the simulation results shown in Figure 14 in terms of directivity. In the end, our proposed work produces a much higher gain of 11.8 dBi operating at two prominent modes of radar 24 GHz and 77 GHz in contrast to the most recent work proposed in [16] in which the MIMO design reported a maximum gain of 9.8 dBi at the single resonant mode of 24 GHz.

However, the main feature of the proposed array antenna is to keep high gain and maximum radiation efficiency. The maximum radiation efficiency η of 0.99 and 0.96 is observed using the gain and directivity values ($\eta = G/D$ and D) at the dual-frequency bands 24 GHz and 77 GHz, respectively. Figure 20–25 show the radiation pattern of antenna with 3 dB angular width and side lobe level. The side lobe level between −4 and −12.4 dB is obtained at the dual bands of 24 GHz and 77 GHz. But the same parameter was achieved between −9 and −11 dB using 10–20 elements in [7]. Henceforth, our proposed model that is able to provide much better performance with just two elements can be chosen as the best alternative to the conventional series-fed patch antennas.

3.4. MIMO Antenna Parameters. The envelope correlation coefficient (ECC) is the parameter that gives the measure of the impact of one antenna element over the other in a MIMO system. ECC is calculated from the return loss (S_{11}) and isolation factor (S_{12}) using the following equation:

$$\mathrm{ECC} = \frac{\left|s_{11}^{*}s_{12}+s_{21}^{*}s_{22}\right|^{2}}{\left(1-\left|s_{11}\right|^{2}-\left|s_{21}\right|^{2}\right)\left(1-\left|s_{22}\right|^{2}-\left|s_{12}\right|^{2}\right)}. \quad (1)$$

The ECC values simulated for the frequency range covering the two resonant bands are much less than 0.1 in the frequency range of interest that is nearer to the ideal value of zero. Also, in the frequency range from 77 GHz to 81 GHz, the ECC value nears the optimum value of zero that is much better than the existing MIMO designs [10].

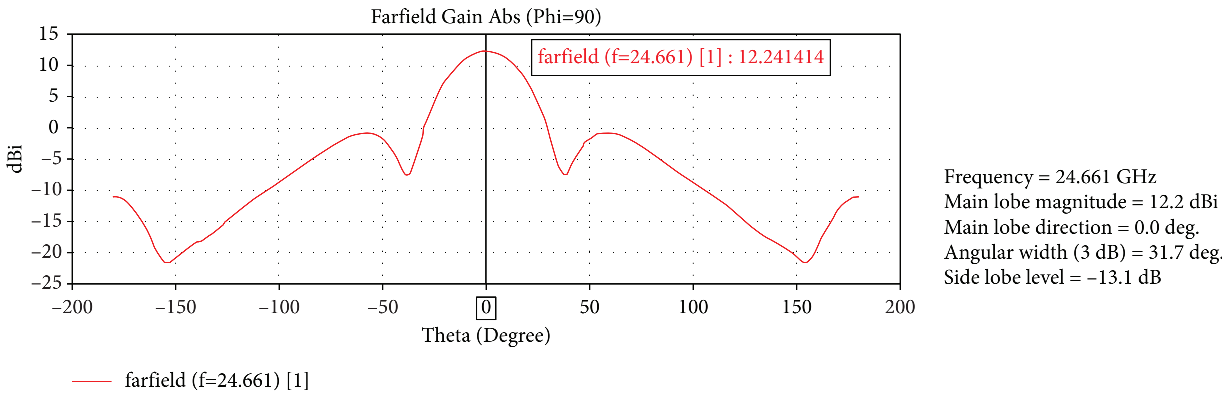

Figure 24: Far-field radiation pattern: 24 GHz – port 1.

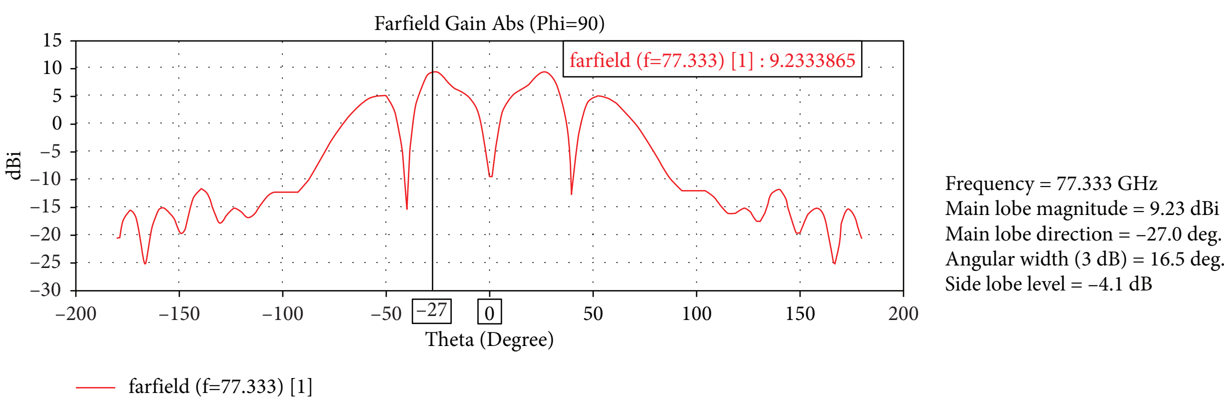

Figure 25: Far-field radiation pattern: 77 GHz – port 1.

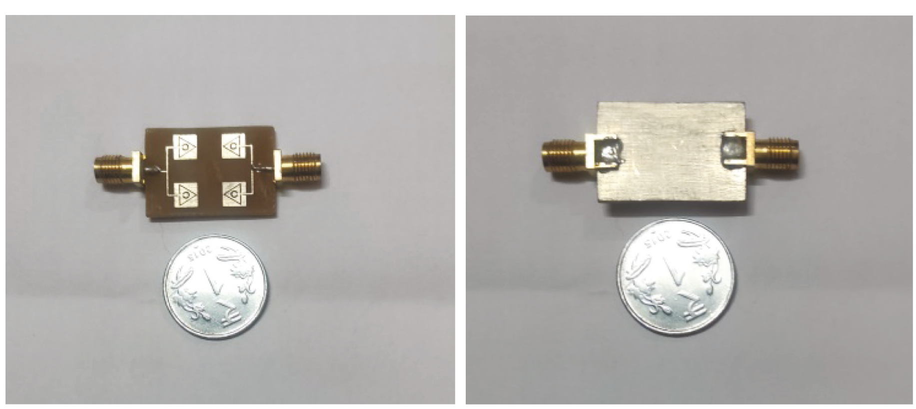

Figure 26: Fabricated antenna prototype.

$$\text{Diversity gain} = 10\sqrt{1 - \text{ECC}^2}, \quad (2)$$

$$\text{TARC} = \sqrt{\frac{(S_{11} + S_{12})^2 + (S_{22} + S_{21})^2}{2}}. \quad (3)$$

The next parameter of observation is the diversity gain (DG) that quantifies the improvement in SNR at the receiver side by means of diversifying the transmitted signals in space. Hence, as the diversity gain is more, the improvement in SNR will also be high. Diversity gain and total active reflection coefficient (TARC) are all calculated from the S-parameters using the equations given in (2) and (3), respectively. The simulated DG in the range specified earlier was calculated, and it is evident that the value is more than 9.6 dBi in the band of interest. This achieves the ideal value of DG of 10 dB. The TARC value is also more than −10 dB in the desired band of interest. Thus, the proposed array antenna has a low profile, simple feed, fairly steady gain, and high efficiency over a broad frequency range, which makes

Table 2: Comparison of the existing works with the proposed work.

Reference paper	Antenna array	Total size (mm^2)	Frequency (GHz)	Gain (dBi)	Reflection coefficient (dB)	No. of bands
Aulia et al. [4]	(1) 10 × 4 patch antenna array (2) 12 × 4 leafy patch antenna array (with a proposed waveguide to microstrip feeding technique)	20.43 × 7.83 16.72 × 10.75	77	19.8 19.6	−21.98 −11.17	Single
F D L Peters et al.	10-element patch antenna array with Wilkinson power divider	<0.9 cm^2	77	22	−18	Single
Oh-Yun Kwon et al.	4 × 4 patch array (with single input)	16.3 × 24 (one transmitter or receive array)	77	11.8	(1) −18 (2) <−25	Single
Ushemadzoro Chipengo et al. [5]	5-element serial-fed array as TX antenna 4-column/5-element serial-fed array as RX antenna	—	77	−15 dB −20 dB	−30	Single
Joerg Scho et al. [7]	8-column/12-row array	—	—	Approx. 15 dBi	—	Single
Wang Wei and Xuetian Wang	8-row/6-unit series-fed weighted antenna array with Wilkinson 1:8 unequal divider	50 × 30	77	—	−15	Single
Manoj Sharma et al.	2 × 2 MIMO with slotted patches and DGS	40 × 6	24	9.8	−18	Single
Proposed	2 × 2 MIMO with CSRR	22.5 × 20.6	24 & 77	11.8 at 24 GHz 11.3 at 77 GHz		Dual

the antenna a good candidate for MIMO radar applications. The proposed MIMO antenna is fabricated on Rogers RT/duroid substrate with dimensions (20.6 × 22.5 × 0.5) mm^3 as shown in Figure 26.

3.5. Performance Comparison. Table 2 summarizes the performance of the proposed work in comparison with the existing works operating under the same band for a similar application.

4. Conclusion

The proposed 2 × 2 MIMO antenna consists of four identical patch elements that are loaded with a novel CSRR structure. The CSRR structure helps in resonating the antenna under two prominent frequencies of autonomous radar 24 GHz and 77 GHz with a wide operating bandwidth of 700 MHz and 4 GHz, respectively. The two-element corporate feed patch array in each transmit/receive unit of the MIMO structure resulted in high gains of 11.3 dBi and 11.8 dBi at the above two operating frequencies, respectively. The optimized inter- and intra-element spacing of patch elements on the colocated substrate resulted in very high isolation of more than −44.26 dB makes this colocated array design a perfect candidate for automotive MIMO radar. Another important parameter, VSWR also achieved optimum values of 1.02 and 1.1 at the dual modes of 24 GHz and 77 GHz, respectively. The antenna was fabricated using Rogers RT/duroid substrate with dimensions (20.6 × 22.5 × 0.5) mm^3. This proposed design is the first dual-band antenna operating in both the present and future operating modes of autonomous radar with high gain in comparison with the recent literature on 2 × 2 MIMO that achieved the maximum gain of 9 dBi. The MIMO performance of the proposed antenna is also validated by means of MIMO diversity parameters such as ECC, DG, and TARC. For improved target detection higher directivity is needed that can be achieved by increasing antenna elements. In the future development of this work, the design of 6 and 8 elements will be done.

Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, they are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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