A Novel and High Gain Antenna Design for Autonomous Vehicles of 6G Wireless Systems

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2021 International Conference on Green Energy, Computing and Sustainable Technology (GECOST) | 978-1-6654-3865-0/21/$31.00 ©2021 IEEE | DOI: 10.1109/GECOST52368.2021.9538702

Abstract—**Future 6G communication systems will include full autonomous system to some applications, such as Autonomous Vehicle. Autonomous vehicle with integrated RADAR technologies will require antennas with different gains, half-power beamwidths (HPBW), and different radiation zones for different purposes such as parking assistance, lane change, emergency braking, and traffic jam assist. Millimeter-wave (mmW) frequency bands are being recommended by the Federal Communication Commission (FCC) for the vehicular RADAR system. This paper describes a novel tooth-shaped patch antenna development with better performance for autonomous vehicles. The antenna is designed at 77 GHz. The designed patch antenna exhibits lower mutual coupling effect with higher gain. Gain and current distribution of the novel tooth-shaped patch antenna was found as 9.4 dB and 1.36 $*10^{03}$ A/m. On the other hand the corresponding values in case of conventional patch were 7.2 dB and 4.99 $*10^{02}$ A/m. The return loss of the tooth-shaped antenna is -37.9441 dB. The designed antenna can be used in future 6G autonomous vehicles.**

Keywords—Antenna gain, radiation patterns, microstrip patch, impedance matching, mutual coupling effect, vehicular RADAR

I. Introduction

Future 6G wireless communication systems will support full autonomous systems to different technologies, one of them is autonomous vehicles. Researches on autonomous vehicular RADAR technologies, as a part of next generation autonomous vehicle, have increased over the past years. According to a report on road traffic injury from the World Health Organization (WHO) the number of yearly fatalities in South Asia was 212 thousand in the year 2010 and the projected number of yearly fatalities would be 330 thousands in 2020 [1]. The projected data shows about 55.66% increase in fatalities. A large number of road accidents occur due to human errors. Fuel consumption increases about 50% due to traffic jam and inefficient driving which causes huge economic damage [2]. Ddevelopment of autonomous vehicular networking infrastructure is needed for the safety and dynamic road traffic system. Millimeter wave RADAR systems have been chosen for different sensors of autonomous vehicles. They can provide stable target detection even under inclement weather conditions such as rain weather or snow [3]. Vehicular RADAR technology has been identified by the EU policy for the improvement of road safety through detecting the location and movement of objects near a vehicle [4]. Some of the features of autonomous vehicles (Fig.1) are:

a. *Automatic Cruise Control (ACC) with stop and go* features,
b. *Blind Spot Detection (BSD),*
c. *Car to GPS communication features,*
d. *Lane change assistance (LCA),*
e. *Parking aids,*
f. *Pedestrian protection systems,*
g. *Rear and Side Crash Warning (RSCW),*
h. *Remote speed sensing,and*
i. *Vehicular networking.*

Due to an increase in demand for high-speed, larger channel capacity, higher digital data rates, the utilization of millimeter-wave frequency bands has received more attention. 60 GHz system can be used for short range communication systems [5-6]. The 76~81 GHz frequency band is made mandatory for automotive applications in EU from 2018 [7]. RADAR systems at 76~81 GHz frequency band require high gain antenna with broad field of view in the azimuth direction, and narrow beam in elevation [7]. Autonomous vehicles require RADAR technologies with higher performing antennas to understand the surrounding environment. One of the reasons behind using the 76~81 GHz frequency range for autonomous vehicles is the reduction of interferences from other devices. RADARs of autonomous vehicles can be classified as major three types- (a) Short Range RADAR (SRR), (b) Medium Range RADAR (MRR), and (c) Long Range RADAR (LRR).

Some of the characteristics parameters of microstrip patches are radiation pattern, gain, return loss (RL) bandwidth, efficiency, and polarization diversities. Design complexities of a patch antenna increases with the miniaturization of the patch. Patch antennas suffer from different limitations such as impedance mismatch, low gain, and poor return loss performance. An effort to improve one parameter, such as return loss, results in other issues. Detailed methods of antenna design and optimization are described in [8]-[13]. Generally a microstrip patch consists of a metallic plate, which may take different shapes, on a grounded metallic plate [8]. Dielectric medium between the patch and ground plane, called the substrate, plays a very important role in determining antenna performance

This paper describes a novel and better methods of patch antenna development for SRR and LRR those can be utilized in autonomous vehicles of 6G wireless systems. The paper is organized as follows. Section II describes the development process of inset fed patch antenna at 77 GHz through insertion of tooth-shaped slots and optimization of different parameters in order to improve the mutual coupling effect. Section III describes the method of improving the mutual coupling effect

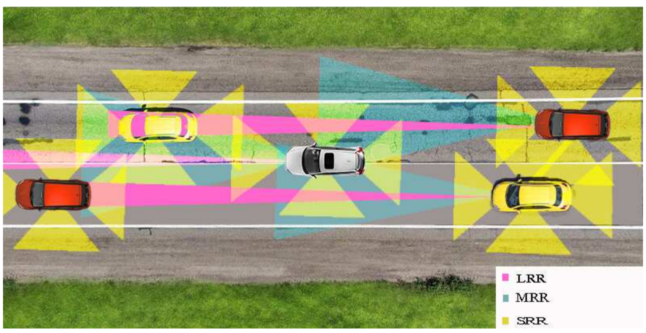
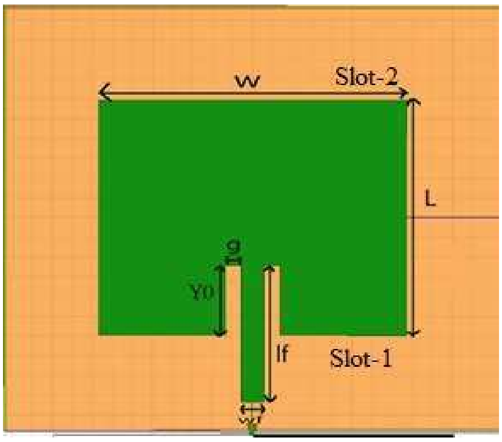


Fig. 1 *Autonomous vehicles with different RADAR technologies.*

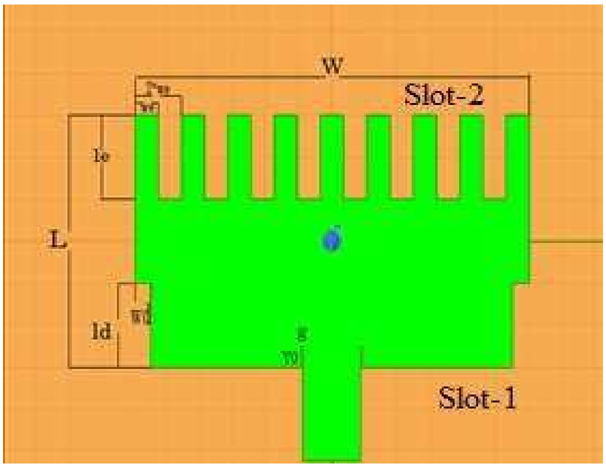
through tooth-shaped patch. Finally section IV concludes the paper.

II. Development of Tooth-Shaped Patch Antenna

Different published papers claim that a good matching condition can be obtained with inset feed of patch [8], [10]. Good matching is achieved by properly controlling the inset position and width [13]. An antenna occupying more space in a spherical volume will have a wider bandwidth [8]. One way to increase the bandwidth is to increase the height (h) of the substrate. However higher value of h may result in surface waves that travel within the substrate which results in



(*b) Conventional inset fed patch antenna.*



(a) Novel tooth-shaped patch antenna

Fig. 2 *Novel and conventional patch antenna*

undesired radiations and issues. In this paper we have described a novel and better patch antenna design method considered Rogers RO/Duroid 5880 as substrate which has a relative permittivity of 2.2. The advantage of Rogers RO/Duroid 5880 is that it has a high melting point of 260^0 C. It absorbs very low moisture and has very low loss tangent (0.0009). Besides that, Duroid 5880 is cheap and easily available. We have chosen micro strip feed mechanism for better RL performance. During the HFSS simulations, initially we considered the substrate height as 0.190 mm at 77 GHz, since the substrate height at this frequency should be less than 0.05λ [9], which is equivalent to 0.194 mm. Though higher thickness of substrate provides more bandwidth [8] but at the same time it causes the shifting of resonant frequency to lower values. We have considered a moderate value of 0.190 mm. At the second stage we have tried to improve the performance of the patch antenna through insertion of cuts along Slot-1 and Slot-2 and optimizing some parameters of the patch which are summarized in Table I. The designed novel patch antenna along with conventional inset fed patch is shown in Fig.2.

Table I *Design Parameters of proposed patch antenna at 77 GHz*

Antenna Parameters	Values
Center frequency	77 GHz
Patch Length =L	1.2 mm
Patch Width =W	2.43 mm
Substrate dimension	Length = 2.905 mm Width= 4 mm Height= 0.19 mm
Ground dimension	Length= 2.905 mm Width= 4 mm
Lf	0.555 mm
Wf	0.3 mm
Y0	0.25 mm
g	0.01 mm
le	0.4 mm
ld	0.3 mm
W_e	0.142 mm
W_d	0.1 mm

III. Improvement of Mututal Coupling Effect Through Tooth-Shaped Patch Antenna

Patch antenna can be analyzed assuming transmission line model [9]. Input admittance of a patch antenna at slot-1 (Figs. 2-3) can be obtained by transferring the admittance of slot-2 using the admittance transformation equation of transmission lines [9]. Actual separation of the two slots is slightly less than λ/2 since the length of the patch is electrically longer than the actual length. The total resonant input impedance can be expressed as follows by taking into account mutual coupling effects between the slots:

$$Z_{in} = \frac{1}{2(G_1 \pm G_{12})} \quad (1)$$

Where G_{12} is the mutual conductance and can be expressed as:

$$G_{12} = \frac{1}{|V_0|^2} Re \iint_S \mathbf{E_1} \times \mathbf{H_2^*} . ds \quad (2)$$

Where $\mathbf{E_1}$ the electric field is radiated by slot-1 and $\mathbf{H_2}$ is the magnetic field radiated by slot-2. It can be observed from (2) that the effect of mutual coupling can be reduced if the magnetic field $\mathbf{H_2}$ at slot-2 is reduced. Reduction of $\mathbf{H_2}$ can reduce the mutual conductance which in turns can improve the return loss performance. In the later part of the section we will explain that $\mathbf{H_2}$ can be reduced by changing the shape of the patch at slot-2.

Through proper adjustment of the reduction of the patch length the transformed admittance of slot-2 can be expressed as [9]:

$$\tilde{Y}_2 = \tilde{G}_2 + j\tilde{B}_2 = \tilde{G}_1 - j\tilde{B}_1 \quad (3)$$

And total resonant input admittance becomes real which can be expressed as:

$$Y_{in} = Y_1 + \tilde{Y}_2 = 2G_1 \quad (4)$$

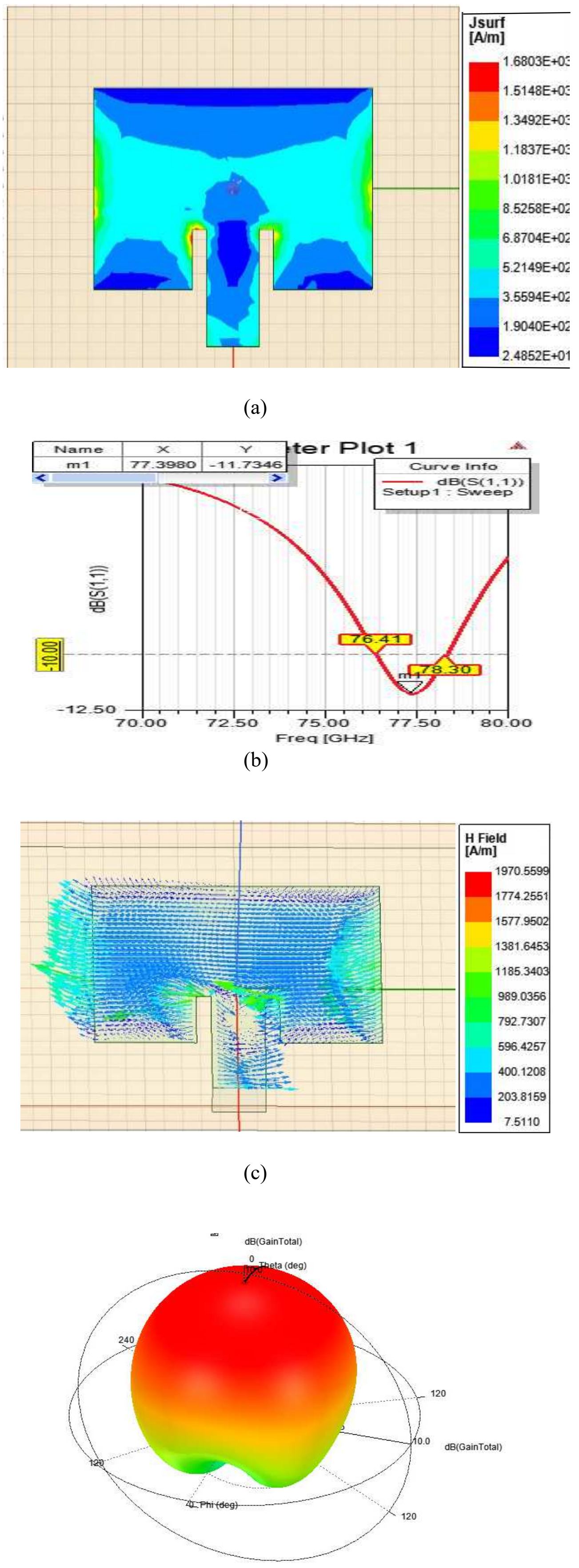


Fig. 3 (a) Surface Current Distribution, (b)Return Loss (dB), (c) Top view of H-field distribution, (d) 3D-Radiation Pattern of inset fed patch antenna at 77.39 GHz.

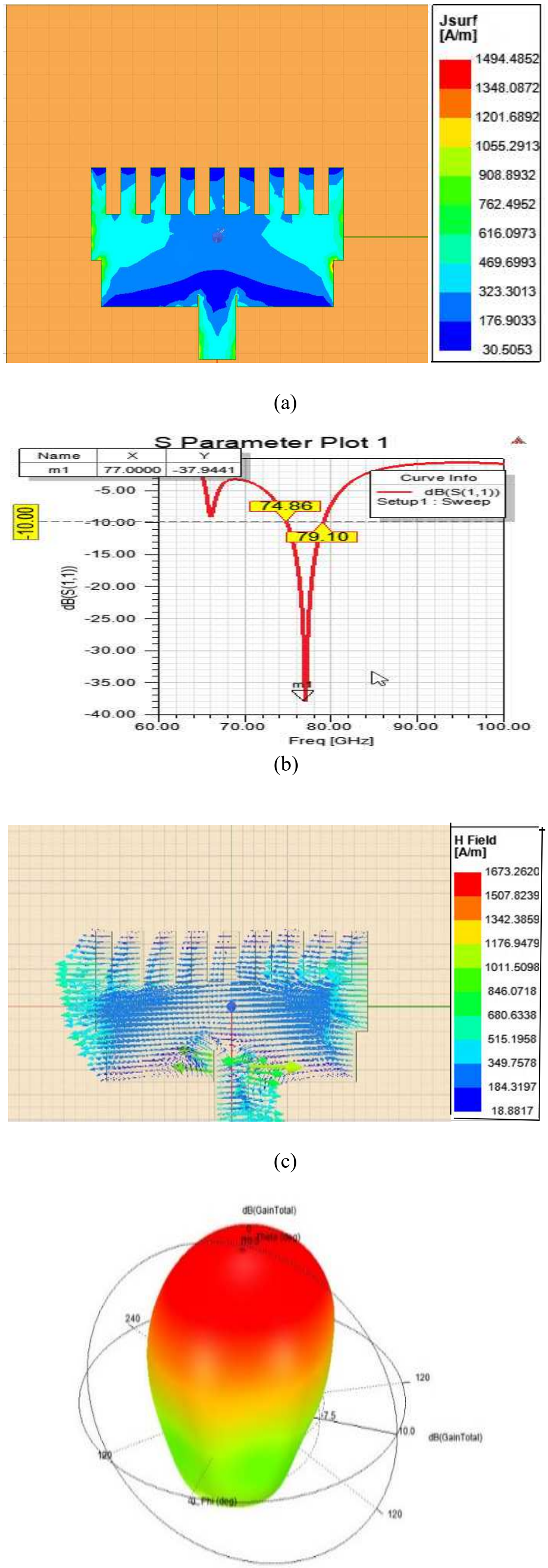
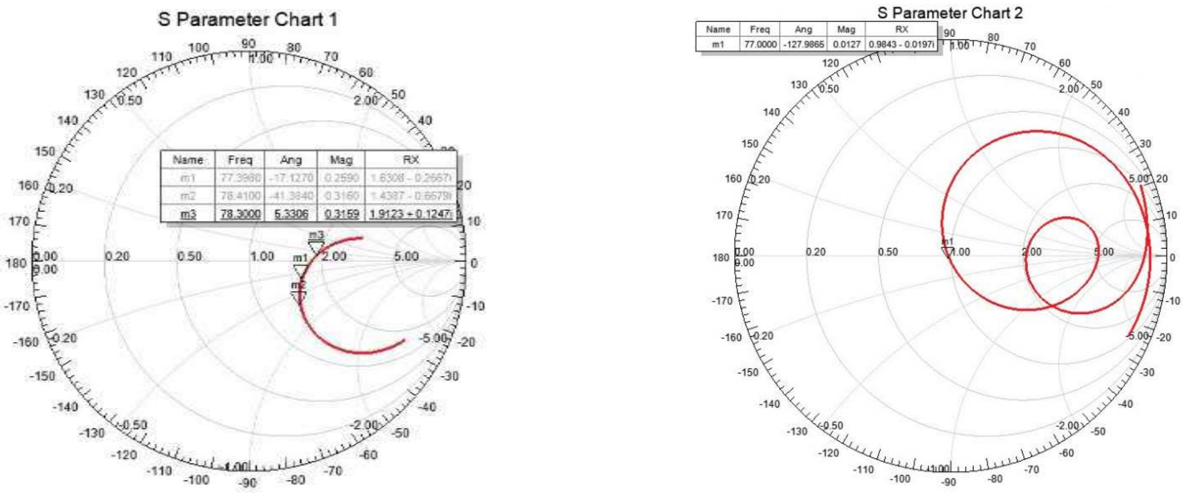


Fig. 4 a) Surface Current Distribution, (b) Return Loss (dB), (c) Top view of H-field distribution, (d) 3D-Radiation Pattern of inset fed patch antenna at 77 GHz.



(a) (b)

Fig. 5 *Smith chart plots of S-parameters for (a) Inset fed Patch (at 77.39 GHz) and (b) Novel Tooth-shaped Patch (at 77 GHz).*

The total resonant input impedance also becomes real:

$$\boldsymbol{Z_{in}} = \boldsymbol{R_{in}} = \frac{\mathbf{1}}{\mathbf{2}\boldsymbol{G_1}} \qquad (5)$$

In order to make the total resonant input admittance real we have changed the patch shape at Slot-2 (as shown in Fig. 2.a). We have created 8 equally spaced cuts in the patch with total area of $l_e \times w_e$ and 2 cuts at lower edge of the antenna with dimensions$l_d \times w_d$. Parameters of the cuts are summarized in Table I.

It was found through HFSS simulation that the impedance matching, gain, return loss performance, and current distribution of novel tooth-shaped patch antenna was better than the corresponding parameters of conventional patch antenna. From the admittance charts comparison (Fig.5) of two patches it was observed that the input admittance of novel patch is more realistic than that of conventional patch. Magnetic field patterns H_2 of the proposed antenna is reduced (Fig. 4.c) by changing the shape at Slot-2 which supports the more realistic input impedance of (5) and can be verified from the admittance-charts plot of Fig. 5(b). Gain and current distribution of novel patch antenna was found as 9.4 dB and 1.36 $*10^{03}$ A/m. On the other hand the corresponding values in case of conventional patch were 7.2 dB and 4.99 $*10^{02}$ A/m.

Considering the cavity model of rectangular patch, when the feed point is far away from one of the edges the magnetic field associated will be less. However, when the feed point is at one of the edges, the magnetic energy density quadruples or increases. This eventually leads to the increase of mutual coupling effect.

The approach of making cuts along the Slot-2 made significant effect on improving the impedance matching which can be observed from the current distribution shown in Fig. 4 (a). The gain has increased 2.35dB more than that of conventional patch. The two cuts along Slot-1 helps redirecting the magnetic fields in desired direction that reduces the mutual coupling effect further and can be observed comparing the H-field distributions in Fig-3(c) and Fig. 4(c).

The width of the conventional patch was designed using the following equations:

$$w = \frac{c}{2f}\sqrt{(\in r + 1)} \qquad [9]$$

Simulating with the calculated parameters through HFSS simulation did not give us good results. The gain has to be higher to facilitate the autonomous vehicles. For this we started the change the width and length of the patch antenna until the desired output is received. The variation of the length and width of the patch was done respecting the general characteristics of the patch antenna. The length should be $\lambda_0 /3 < L < \lambda_0 /2$ and the height should be $0.003\ \lambda_0 < h < 0.05\ \lambda_0$. The value of λ_0 for our case was 0.389 cm.

From the smith chart-plots of Fig-5 it can be easily understood that the impedance matching has greatly improved in case of tooth-shaped patch. Generally, the input impedance is complex and it consists of a resonant and non-resonant part. The non-resonant part is usually reactive. The variation of the real and imaginary part of the impedance occurs as a variation of frequency. At 77 GHz the matching is closest to the value 1 indicating that the matching is perfect. The value of the admittance 0.9843-0.00197i denotes that the novel tooth-shaped patch has achieved perfect matching with a negligible reactive value. The return loss of the tooth-shaped antenna is -37.9441 dB.

IV. Conclusion

In this paper a novel tooth-shaped patch antenna at 77 GHz is designed and proposed for the autonomous vehicular RADAR of future 6G systems. Impedance matching of inset fed patch antenna was achieved by reducing the overall mutual coupling effect. Reduction of magnetic field at Slot-2 causes the improvement of return loss as well as antenna gain. It was found that the return loss of the proposed patch antenna is improved by 6.16 dB and gain is improved by 2.2 dB. This single patch can be used for SRR system in 77 GHz automotive vehicular radar technology. Fabrication and testing of the designed tooth-shaped patch antenna is a future research work.

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