Design and Experimental Investigation of a High-Performance X-Band Patch Array Antenna for Automotive Radar Applications

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Abstract

Radar technology has become increasingly important in automotive applications, particularly for car-speed detection and monitoring systems. The antenna plays a crucial role in determining the performance of these systems. This paper presents the design, simulation, and experimental investigation of a high-performance X-band patch array antenna for automotive radar applications. The antenna was fabricated and tested, and the experimental results validate the simulation results. The prototype antenna operates at a center frequency of 10 GHz and achieves a gain of 15.48 dB, directivity of 17.96 dBi, and $|S_{11}|$of -18.85 dB. Its impedance bandwidth extends from 9.69 to 10.20 GHz, with a beam width of 10 degree and corresponding radiation efficiency is 86.17% at 10 GHz. The simulation and experimental results demonstrate excellent agreement, validating the antenna's performance for car-speed detection and monitoring radar systems. The results show that the designed patch array antenna is suitable for automotive radar applications, offering impressive accuracy and reliability.

Keywords: *Patch array antenna; Automotive Radar; Radiation efficiency; center frequency; beam width, bandwidth.*

I. INTRODUCTION

The rapid advancement of advanced driver-assistance systems (ADAS) and autonomous vehicles has sparked a growing interest in radar technology for automotive applications, particularly for car-speed detection and monitoring systems [1]. Patch antennas have emerged as a popular choice for radar applications due to their compact size, light weight, and ease of fabrication [2]. However, designing a high-performance patch antenna that meets the stringent requirements of car-speed detection and monitoring radar systems remains a challenging task [3]. Recent studies have explored various aspects of patch antenna design and radar systems for automotive applications. Li et al. (2022) proposed a novel patch antenna design with a gain of 15 dB and directivity of 16 dBi for X-band radar applications [4]. Similarly, Patel et al. (2023) developed a patch antenna array for automotive radar applications, achieving a ($|S_{11}|$) of -25 dB and impedance bandwidth of 10% [5]. Zhang et al. (2023) designed a radar system using a patch antenna array for car-speed detection and monitoring, achieving an accuracy of 96.5% [6]. Other notable contributions include the work by Wang et al. (2022) on a compact patch antenna design for automotive radar applications [7], and the study by Kumar et al. (2023) on a novel patch antenna array design for X-band radar applications [8].

Further advancements in patch antenna design and radar systems have been reported in recent studies. Chen et al. (2024) proposed a meta-surface-based patch antenna design for automotive radar applications, achieving a gain enhancement of 3 dB [9]. Lee et al. (2024) developed a machine learning-based approach for optimizing patch antenna design for radar applications, resulting in improved performance and reduced design time [10]. Singh et al. (2023) investigated the use of patch antenna arrays for multi-target detection in automotive radar systems, demonstrating improved detection accuracy and robustness [11]. Despite the growing demand for automotive radar technology, there is a limited amount of research on X-band patch array antennas specifically designed for car-speed detection and monitoring radar applications. Existing patch antenna designs for automotive radar applications often suffer from limitations such as low gain, poor directivity, and inadequate $|S_{11}|$. Many existing studies on patch antenna design and radar systems rely heavily on simulations, with limited experimental validation. The work addresses this gap by providing experimental results that validate the performance of the proposed antenna design and radar system. The authors use a combination of theoretical design and simulation-based optimization to develop a high-performance patch array antenna that meets the requirements of car-speed detection and monitoring radar applications. The authors integrate the proposed antenna design into a radar system and demonstrate its performance in a real-world setting.

This paper presents the design, simulation, and experimental investigation of a high-performance X-band patch array antenna for car-speed detection and monitoring radar applications. The proposed antenna operates at a center frequency of 10 GHz and is designed to achieve high gain, directivity, and efficiency. The influence of patch elements spacing distance on the antenna performance is analyzed, and both simulated and experimental results are presented. The simulation and experimental results demonstrate good agreement, validating the antenna's performance for car-speed detection and monitoring radar systems. This paper is made up of four Sections. Section One presents introduction to the study; Section Two reports on the adopted methodology; the results obtained from the research methodology and the corresponding analyses and discussions are presented in Section Three; finally, Section Four concludes the study.

II. MATERIALS AND METHODS

A. Substrate Material

The radiation characteristics of the patch antenna depend on the substrate material used for the antenna design. Rogers RT/Duroid 5880 substrate material with a dielectric constant ε_r of 2.2, and a loss tangent δ of 0.0009 is selected for the antenna design. RT/Duroid has a relatively low dielectric constant to minimise the size of the antenna patch. Rogers RT/Duroid 5880 substrate is found to be most suitable due of its qualities, such as high gain, minimal return loss, uniform electrical characteristics over frequency of operation and cheaper cost of the substrate material [12] among others. RT/Duroid 5880 is designed for applications such as airline broadband antennae, patch antennas, and missile guidance systems.

B. Antenna Design

The design requirements are prepared as shown in Table 1. The acceptable gain and directivity of a good performing antenna should be ≥ 6 dBi and ≥ 5 dBi respectively [12]. The X-band (8 - 12 GHz) is the radar frequency band assigned for short-range mapping, tracking, traffic speed monitoring, ground surveillance, marine and weather radar, and missile guidance [14]. The 3 dB illumination beam-width of 10^o requirement emerged based on the relevant recommendations for radar systems operation [15, 16].

Table 1: Antenna Design Requirements

Operational Parameter	Values
Operational Frequency Band	(8 – 12) GHz
Center Frequency (f)	10 GHz
$\|S_{11}\|$	≤ -10 dB
HBPW θ_{-3dB} Azimuth	10°

The size of the 4 × 4 patch radiators can be determined based on the single element patch antenna dimensions. The patch width (W) was obtained using Eq. (1), according to the transmission line model given by [17], as:

$$W = \frac{c}{2f\sqrt{\frac{(\varepsilon_r+1)}{2}}} \tag{1}$$

Effective dielectric constant (ε_{reff}) was estimated by Eq. (2) [18]:

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

The design of effective patch length (L_{eff}) was done by using Eq. (3) given by [19], as:

$$L_{\text{eff}} = \frac{c}{2f\sqrt{\varepsilon_{reff}}} \tag{3}$$

The design of the patch length extension (ΔL) was executed by using Eq. (4) given by [18], as: $\Delta L = 0.412h\left(\frac{\left(\frac{W}{h}+0.264\right)(\varepsilon_{eff}+0.3)}{\left(\frac{W}{h}+0.8\right)(\varepsilon_{eff}-0.258)}\right)$ (4)

The actual patch length (L) was estimated by using Eq. (5) given by [19], as:

$$L = L_{eff} - 2\Delta L \tag{5}$$

The dimensions of the ground plane for single radiating patch were obtained as by Eqs. (6-7) [19]:

$$L_g = 6h + L \quad (6)$$

$$W_g = 6h + W \quad (7)$$

where c is the velocity of light in free space, ε_r is the relative dielectric constant of the substrate, *f* is the center frequency of the antenna, L_g and W_g are the length and width of the ground plane.

The patch antenna structural parameters are presented in Table 2.

Table 2: Designed Parameters of Single Patch Antenna

Parameters	Values and Units
Dielectric substrate	Rogers RT/Duroid 5880
Patch material	Copper
Operating frequency, *f*	10 GHz
Patch length, *L*	9.05 mm
Patch Width, *W*	11.85 mm
Height of the substrate, *h*	1.6 mm
Dielectric constant, ε_r	2.2
Effective dielectric constant	1.98
Dielectric loss tangent, $\boldsymbol{\delta}$	0.009
Size of the ground plane, $L_g \times W_g$	18.65 mm (*L*) × 21.45 mm (*W*)

The 3 dB illumination beamwidth of a uniform amplitude broadside array is given by [21], as:

$$\theta_{n\times m} = \left[\pi - 2cos^{-1}\left(\frac{1.391\lambda}{\pi N d}\right)\right] \quad (8)$$

where:

N = total Number of patch elements

d = the patch elements spacing distance

λ = signal wavelength (λ = 30 mm)

$\theta_{n\times m}$ = illumination beamwidth of the antenna array

n = the horizontal-axis patch elements

m = the vertical-axis patch elements

Table 3 is the result of the mathematical computation of illumination beam-width using Eq. (8) by varying the distance between patch elements of a 4×4 planar array in both *x*-axis and *y*-axis while keeping the number of elements constant throughout the variation. The Table shows a decrease in the illumination beamwidth as the inter-element spacing was increased, when the element spacing of 0.32λ was mathematically evaluated; while the corresponding value of illumination beamwidth was 9.92°. The illumination beamwidth of 32.13° was obtained at 0.1λ patch elements spacing. The illumination beamwidth requirement of 10° is provided with 16 elements of the 4×4 patch array according to the computation results in Table 5. It could be observed from the Table 5 that the illumination beamwidth of 10° occurs at an inter-element spacing distance of 0.32λ (9.525 mm) with sixteen radiating element of 4×4 patch array antenna. Sixteen elements of 4×4 patch array antenna with inter-element spacing of 9.525 mm produces an estimated illumination beamwidth of 10°. The simulation and analysis of a 4×4 patch array antenna was then carried out to check if the estimated value of the illumination beamwidth and other antenna radiation performance parameters met the antenna design specifications for radar applications.

Table 3: 4×4 Antenna Array Illumination Beamwidth at Different Spacing

Inter-element spacing (d)	Antenna array illumination beamwidth ($\theta_{4\times4}$)
0.1λ = 3 mm	32.13°
0.2λ = 6 mm	15.91°
0.3λ = 9 mm	10.58°
0.31λ = 9.3 mm	10.24°
0.32λ = 9.6 mm	9.92°

The feeding method for the arrays was single port probe feed. The feed port source impedance Z_1 value of 50 Ω was used for the design being the most available standard. To achieve a good impedance matching of the feeding network, the microstrip line parameters were selected by inputting 50 Ω input impedance, Z_1 to 50 Ω, it splits into 100 Ω, that is Z_2 = 100 Ω as depicted in Fig. 1. Width, W_2 of the feed line at Z_1 = 50 Ω is found to be = 2.4412 mm and width, W_1 of inter-element feed line at Z_2 = 1.4089 mm, respectively.

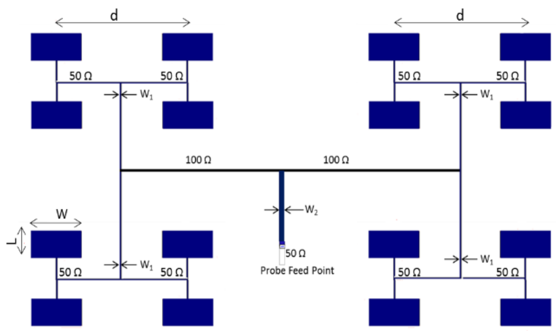


Fig. 1: The Designed 4×4 Patch Array Antenna Configuration with Feed Lines

Table 4 depicts the summary of the final design configuration parameters of the 4×4 patch array antenna. With these preliminary geometric values listed in table 6, sixteen elements 4×4 patch array antenna was simulated in CST microwave studio.

Table 4: Final Designed Patch Array Structural Parameters

Parameter	Value
Array pattern	4×4
Patch element width (W)	11.85 mm
Patch element length (L)	9.05 mm
Antenna separation distance (d)	9.6 mm
Wavelength (λ)	30 mm
Operating center frequency (f)	10 GHz

C. Analysis and Simulation

Computer Simulation Technology (CST) microwave studio simulation software [41] was used to simulate and study the performance of the designed patch array antenna prior to fabrication. The radiation pattern plot of the 4×4 patch array is shown in Fig. 2. It produced an illumination beamwidth of 10.37° with minimum side lobe. The computer simulations of radiation pattern, gain and directivity were analysed to determine how efficiently the antenna will radiate at 10 GHz. The directivity and antenna gain obtained from the simulation are 19.35 dBi and 17.23 dBi respectively.

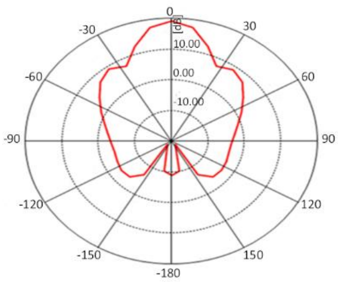


Fig. 2: Simulated Radiation Pattern of the 4×4 Patch Array Antenna

A careful location of the single probe feed point was needed to mitigate the effect of the feed lines from affecting the radiation performance of the array. This was achieved by carrying out a complete parametric S_{11} analysis of various feed points using CST MWS software to determine the feed point that produces the best S_{11} for X-band patch array antenna. The selected feed point location excites a stronger current which produce better directional radiation pattern and good impedance matching, resulting in a wider bandwidth. The lengths of the transmission feed line (x in the plot of Fig. 3) is the distance between the feed point and centre of the substrate. To evaluate the robustness of the design, the influence of the spacing of radiating layers affecting the stability of antenna performance was investigated. The variation plots of $|S_{11}|$against the operational frequency range was carried out (see *Figure 3*). With decreasing spacing distance, the center frequency increases, accompanied by a sharp decline in impedance bandwidth. The final simulation output of $|S_{11}|$plots for the patch array is as shown in Fig 4. The S_{11} simulation at best feeding point (x = 8 mm) which presents a wider bandwidth, with a S_{11} value of -21.23 dB. From the graph, the designed patch array antenna resonates at the operating frequency of 10 GHz, with a S_{11} of -21.23 dB, which is a good value for radar system applications.

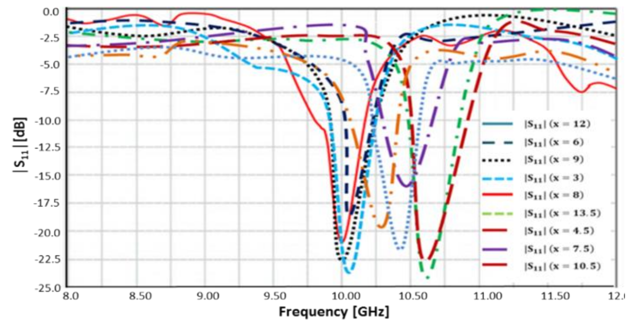


Fig. 3: Parametric Analysis for Feed Point Determination of The 4x4 Patch Array Antenna

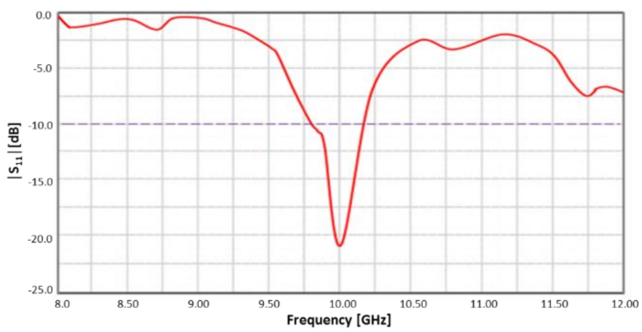


Fig. 4. Simulated $|S_{11}|$ of 4×4 Array at Best Feed Point

Fig. 5 is the simulated radiation efficiency curve from 8 GHz to 12 GHz. The radiation efficiency is 89.01% at the center frequency of operation of 10 GHz. Table 6 depicts the summary of the simulation results at 10 GHz.

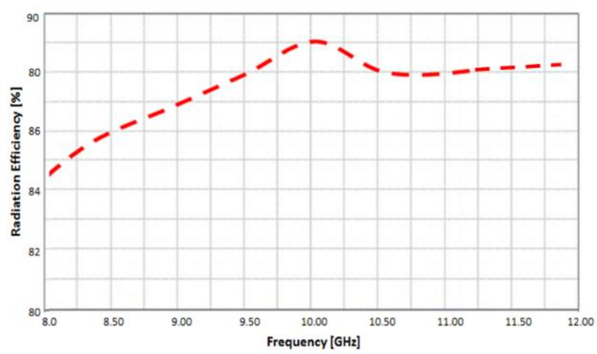


Fig. 5: Patch Array Antenna Radiation Efficiency Plot

Computer simulations results of reflection coefficient ($|S_{11}|$), directivity, beam-width, and the radiation efficiency are shown in *Table 5*. At 10 GHz, the gain is 17.23 dBi, directivity is 19.35 dBi and the radiation efficiency is

89.02%. The impedance bandwidth is 530 MHz, ($|S_{11}|$< -10 dB) from 9.67 to 10.20 GHz.

Table 5: Simulation Results of Patch Array Antenna

Parameter	4×4 Array	Min. Standard
Center Frequency	10 GHz	As per need
Bandwidth	530 MHz	As per need
$\|S_{11}\|$	-21.23 dB	< -10 dB
Gain	17.23 dBi	> 6 dBi
Directivity	19.35 dBi	> 5 dBi
3 dB Beamwidth	10.37^0	As per need
Radiation Efficiency	89.02 %	≥ 70%

The final drawings of the 4×4 antenna array on one side of the Rogers RT/Duroid dielectric substrate of thickness 1.6 mm, with dielectric constant of 2.2 and the ground plane on the other side of the substrate is presented in Figs. 6 and 7 prior to prototyping. It consist of the 4x4 radiating patches, cross sectional view, and ground plane with total size of 88 mm × 74 mm ×1.6 mm.

D. Experimental Measurement

The developed antenna prototype has been subjected to relevant measurements. The capability of the fabricated antenna for applications in radar system is also demonstrated. The prototype antenna is shown in ***Fig. 8***. Its reflection coefficient $|S_{11}|$ was measured with a vector network analyzer, VNA (see ***Fig. 9***), and a comparison of the measured and simulated plots is shown in ***Fig. 10***.

(a) **(b)** **(c)**

Fig. 8: Prototype Antenna: a) Front Layer; b) Back Layer; c) Cross Sectional Layer.

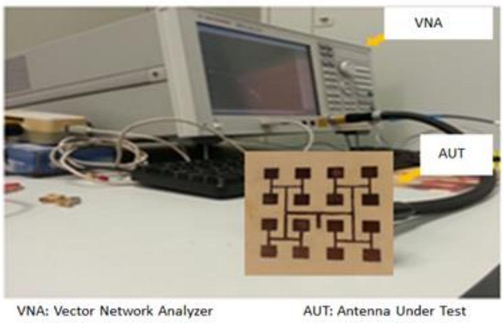


Fig. 9: Photograph of $|S_{11}|$Measurements

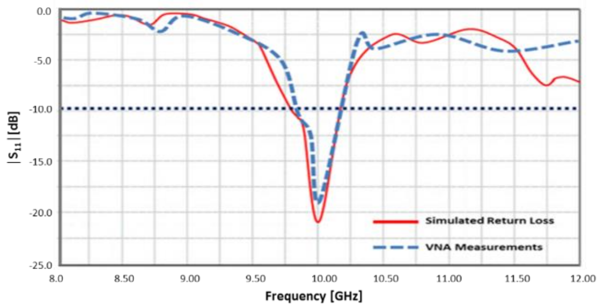


Fig. 10: Simulated and Measured |S11|.

The patch array operates with $|S_{11}|$value below -10 dB. The antenna radiation measurements were carried out at 10 GHz as shown in ***Fig. 11***. The radiation characteristics of the X–band 4×4 array are presented in ***Fig. 12***.

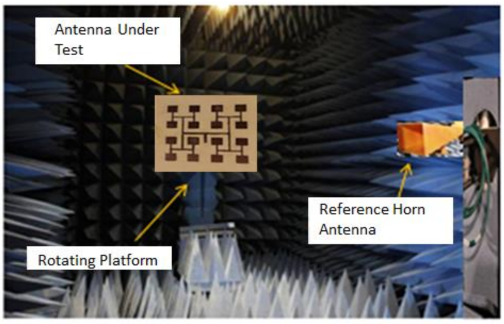
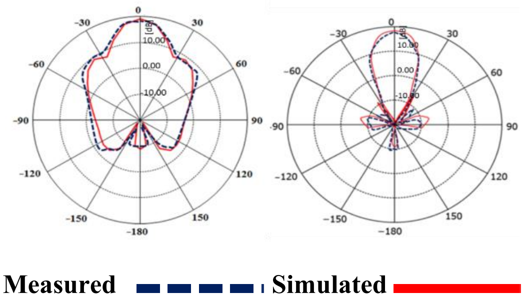


Fig. 11: Photograph of Radiation Pattern Measurements



(a) **(b)**

Fig. 12: Simulated and Measured Radiation Pattern

E. Field Test

The fabricated antenna was finally incorporated into the computer-controlled linear continuous-wave frequency modulated radar system. This section presents the testing of the fabricated patch array antenna for radar system applications. To test the accuracy of the antenna for applications in radar, measurements were taken for ground distance (range), car (target) speed monitoring, and radar antenna resolution, were carried out.

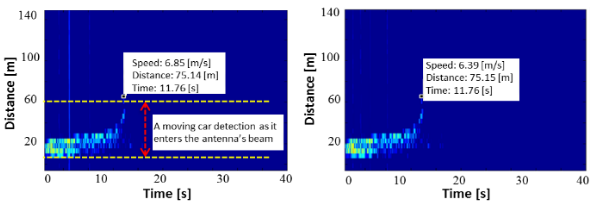
The fabricated radar antenna was experimentally tested for radar applications by monitoring a moving car speeds in outdoor experiments carried out in Ilorin, Nigeria, located at 8.5°N latitude and 4.55°E longitude, under the environmental condition with temperature of 19° C, humidity of 43%, pressure of 1013.9 mb, and under clear sky. The experiment was conducted with the assembling of the radar sensor device [21], antenna stand, saloon car which has a size of 2.0 m ×1.5 m × 1.0 m, laptop computer, and the fabricated patch array antenna. The RF radar was powered by eight 1.5 V battery packs, which produced a total voltage of 12V. For each experiment, a laptop computer was connected to the RF radar system and used to record the output of the experimental scene profiles.

The radar antenna was placed 1.3 m above the ground to have better coverage of the car during the experiment. The experiment started with the car positioned at 100 m away from the test setup area and moving toward the antenna. From the initial location, the car moved past the antenna at an initial speed of 25 km/h. The car's actual speed was controlled and monitored by using an on–board diagnostics (OBD2) scanner/device in the car. The car maintained a controlled speed of 25 km/h when approaching the radar antenna. The car speed was set at 75 km/h, 50 km/h, and 25 km/h. ***Fig. 13*** shows photographs of the test site and the experimental setup. The speeds of the saloon car were obtained and compared with the actual set speeds of the car.

(a) **(b)**

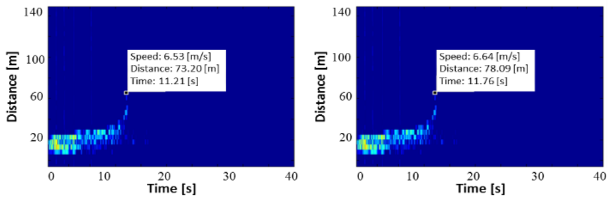
Fig. 13: Photograph of the Car Speed Monitoring Test: (a) Test Site, (b) Measurement Setup

The radar pulse transmitted strikes the speeding car and reflected back to the measuring device through the antenna. Figs 14 to18 show the measured speed plot in the experiment.



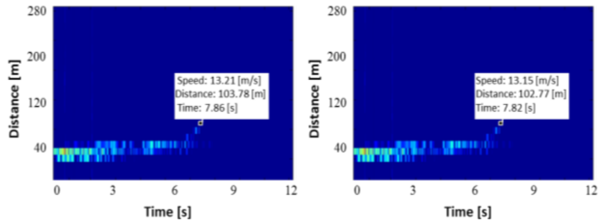
(a) **(b)**

Fig. 14: Measured Speed Plot of the: a) Car Detection in the Antenna's Beam; b) 25 km/h for 1st Attempt.



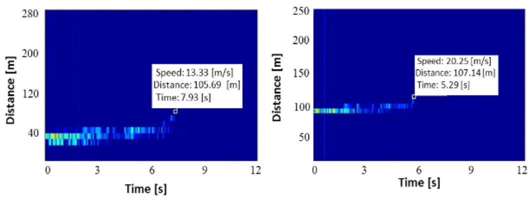
(a) **(b)**

Fig. 15: Measured Speed Plot of the: a) 25 km/h for the 2nd Attempt; b) 25 km/h for the 3rd Attempt.



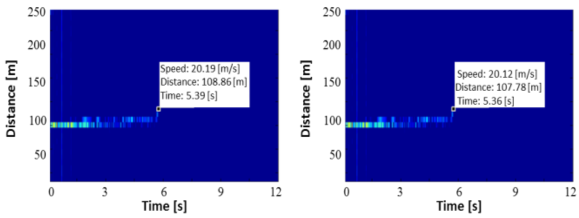
(a) **(b)**

Fig. 16: Measured Speed Plot of the: a) 50 km/h for the 1st Attempt; b) 50 km/h for the 2nd Attempt.



(a) **(b)**

Fig. 17: Measured Speed Plot of the: a) 50 km/h for the 3rd Attempt; b) 75 km/h for the 1st Attempt.



(a) **(b)**

Fig. 18: Measured Speed Plot of the: a) 75 km/h for the 2nd Attempt; b) 75 km/h for the 3rd Attempt.

III. RESULTS AND DISCUSSIONS

The developed patch array antenna's radiation pattern and reflection coefficient $|S_{11}|$ were measured, and a comparison of the measured and simulated results is presented in Table 6. The simulated patch array antenna resonates at 10 GHz, with S_{11} value of -21.23 dB. A measured reflection coefficient, $|S_{11}|$ of -18.85 dB has been achieved, demonstrating an impedance bandwidth of 510 MHz ($|S_{11}| < -10$ dB) from 9.69 GHz to 10.20 GHz. The measured S_{11} is -18.85 dB, which is better than the minimum requirement of -10 dB for most wireless applications. The measured gain and directivity were 15.48

dBi and 17.96 dBi respectively. The 3dB beam-width was 11.02° (Horizontal-plane). The developed antenna model achieves a radiation efficiency of 86.17%. The differences observed from the measurement and simulation results could be as a result of either the fabrication tolerance and alignment required at X-band or simulation settings.

The field test results presented in Tables 7 to 9 demonstrate the antenna's capability in radar applications, including range measurement and target detection.

Table 6: The Patch Array Antenna Performance Parameters

Parameter	Simulated Value	Measured Value	Minimum Standard
Frequency Range	8 GHz – 12 GHz	8 GHz – 12 GHz	As per need
Resonant Frequency	10 GHz	10 GHz	As per need
Directivity	19.35 dBi	17.96 dBi	≥ 5 dBi
Beamwidth (HPBW)	10.37°	11.02°	As per need
Gain	17.23 dBi	15.48 dBi	≥ 6 dBi
-10 dB bandwidth	530 MHz	510MHz	As per need
S_{11}	-21.23 dB	-18.85 dB	≤ -10 dB
Radiation Efficiency	89.02%	86.17%	≥ 70%

Table 7: Car Speed Monitoring Results at 25 km/h.

Measurement Attempt	Set Speed (km/h)	Measured Speed (km/h)	Measurement Error (%)
1st	25	23.00	8.00
2nd	25	23.51	5.96
3rd	25	23.89	4.44

Table 8: Car Speed Monitoring Measurement Results at 50 km/h

Measurement Attempt	Set Speed (km/h)	Measured Speed (km/h)	Measurement Error (%)
1st	50	47.55	4.90
2nd	50	47.33	5.34
3rd	50	47.98	4.04

Table 9: Car Speed Monitoring Measurement Results at 75 km/h

Measurement Attempt	Set Speed (km/h)	Measured Speed (km/h)	Measurement Error (%)
1st	75	72.89	2.81
2nd	75	72.70	3.07
3rd	75	72.42	3.44

Field tests conducted validate the antenna's capability in radar applications with results showing a percentage measurement error of 4.21% in range measurement. The percentage measurement error was computed by comparing the actual speed of the car with the measured speed as shown in Eq. (9)

$$\text{Measurement Error (\%)} = \frac{\text{Set Speed} - \text{Measured Speed}}{\text{Actual Speed}} \times 100 \tag{9}$$

These results indicate that the proposed antenna design is suitable for ground-based lightweight surveillance radar systems. The tests show a close correlation between measured and actual distances. The proposed antenna design offers a compact, high-gain, and wideband solution for ground-based surveillance radar systems. The differences observed between the set speed and measured speed results (Tables 7 to 9) could be attributed to several factors such as Doppler shift, radar system thermal noise and interference, speed measurement processing rounding errors, non-ideal radar system characteristics, and other environmental factors.

IV. CONCLUSIONS

This paper presents a report of design, implementation, and testing of X-band 4×4 patch array antenna for car speed detection and monitoring radar system.. The purpose was to develop a low volume, lightweight, low S_{11} antenna with high directivity and excellent gain. The analysis of radiation pattern of the developed patch array antenna has also been presented. The measured radiation pattern was found to compare favorably well with simulated values.

The radar antenna was designed to operate in X-band at center operating frequency of 10 GHz. The work used a 4×4 rectangular patch planar array antenna configuration to achieve high gain and radiation efficiency antenna requirements. The antenna array has been simulated and fine-tuned for car speed detection radar application by using Computer Simulation Technology Microwave Studio Software. The simulation results were compared with minimum standard for antenna radiation characteristics required for radar so as to determine the suitability of the developed radar antenna to achieve the main goal of this study. The results obtained meet the requirements of radar system for intended purpose. A prototype antenna array has been constructed by employing precision photo-engraving and chemical etching on copper board. The antenna array was fed by a 50 Ω coaxial probe with SMA RF connector. Computer simulation results of S_{11} ($|S_{11}| > -10$ dB), radiation efficiency, directivity, gain and the radiation patterns were obtained and presented.

The performance of the radar antenna was tested through field experiments. The capability of the fabricated antenna for applications in radar system has also been demonstrated. The X-band radar antenna was capable of measuring a car's speed for application in traffic speed monitoring and target detection. The antenna measures a car speed at 75 km/h, 50 km/h, and 25 km/h with an average percentage measurement error of 4.67%. The differences observed between the actual measurement and experimental measurement results during field test could be as a result of the low sensitivity of the trainer radar sensor, alignment required at X-band, measurement settings, SMA soldering effect, cable loss in the measuring process, or the fact that the road might not be perfectly straight. The radar antenna would offer opportunities for applications in car speed measurement, traffic monitoring, surveillance, and target detection.

As recommendations for future research on this subject, the antenna testing output can perform better on a high standard radar device with high resolution analog-to-digital converter processor or high-level integrated circuit to increase the rate of data processing and measurement accuracy. A synthetic aperture radar measurement procedure can also be implemented to improve antenna performance by setting up the antenna on a moving platform to allow better system stability and reliability. This work could be extended to a multiband antenna that could operate at multiple frequencies for multiple applications.

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