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Design, Simulation, and Performance Analysis of X-Band Patch Array Antenna for Car-Speed Detection Radar

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Abstract

The antenna is an essential component that plays important role in radar target detection and parameter estimation. This paper presents the design and simulation analysis of X-band patch array antenna for car-speed detection and monitoring radar system. A patch array antenna was designed at a center operating frequency of 10 GHz. The designed patch array antenna was simulated with a Computer Simulation Technology (CST) Microwave-Studio to analyze the antenna radiation pattern and other broadband properties. A compact and light-weight X-band 4×4 patch array antenna was realized on RT/Duroid 5880 copper board with 1.6 mm thickness and dielectric constant of 2.2. The patch array antenna shows high gain and good radiation characteristics with a simulated gain of 19.35 dBi, and corresponding radiation efficiency of 89.02%. The fabricated antenna was experimentally characterized and tested for real-world car-speed detection radar system. The studied patch array antenna demonstrates impressive performance suitable for radar applications.

1. Introduction

In parallel with improving technology and developments in automotive engineering, the maximum speeds that can be reached by cars increase day by day. Reckless driving at high speed puts human lives in danger. The speeds of cars need to be monitored by both drivers and traffic law enforcement officers to prevent this danger. The speed of approaching cars can be measured by antenna-based radar system for speed limit violations to alert the drivers or traffic police. Radar antennas perform an important role in target speed tracking and various surveillance purposes to maintain a secure society.

The word RADAR is an acronym for Radio Detection and Ranging, officially invented in the United States of America [1]. It refers to electronic equipment that detects the presence of objects by using reflected electromagnetic energy to detect an object and identify its direction, distance, and altitude [2, 3]. The radar system is often mounted on a spacecraft, an airplane, or a ground-based platform. The atmospheric penetration level at radar microwave frequency domain of the electromagnetic spectrum is very high. Due to this, the radar operation is not seriously dependent on weather conditions and time of the day.

The most common antennas in the microwave region are the horn, slot, and patch antennas. Bob Munson invented the Patch antenna in 1972 but earlier worked on by Dechamps, dating back to 1953 [4]. The radiating patch and the feed lines of patch antennas are usually photo-etched on the dielectric substrate. Patch antennas have received wide interest and extensive applications in radar and wireless communication applications [5,6] due to their properties of small volume, lightweight, lower cost of production, and ease of integration with feed network [7, 8]. Nonetheless, its properties need improvement by using patch element array configurations. Its arrays structure is used, to synthesize a desired pattern that may be difficult to achieve with a single patch element. It is possible to construct an array of some sort using a single element to form an array of choice. A patch array antenna consists of two or more patch antennas structure driven by a single source. This structure consists of orderly arranged patches in columns and rows to achieve high gain, high directivity, good radiation efficiency, and improved power handling capacity [9, 10]. Through in-depth review, several related articles have been found in the investigation, design, and development of patch antenna for wireless system and radar applications.

Various related works were reviewed in the course of this research. It was observed that many techniques have been proposed to the use of patch antenna for different radar applications. The study [11] designed and simulated an inset fed rectangular patch antenna and studied the effect of antenna dimensions length (L) and width (W). The antenna was realized on a substrate material (RT/duroid 5880) with a height of 1.57 mm, dielectric constant of 2.2 at 2.4 GHz operating center frequency. The study in [12] designed an X-band patch antenna for radar system applications. The antenna was implemented on a substrate with thickness of 1.58 mm, dielectric constant of 4.4, and loss tangent of 0.02. The patch dimension of the antenna was estimated as 9.13 mm × 6.27 mm based on transmission line model. A rectangular patch antenna at 1.3 GHz for radar surveillance application was investigated in [13] using a minimal loss FR-4 substrate with dielectric constant of 4.3. The dimensions of the patch were determined by transmission line model. In their study, [14] simulated, designed, constructed and evaluated a patch antenna with a partial ground configuration for various wireless communication and radar applications. A circular patch antenna with operating frequency of 0.5 GHz was designed and simulated for ground-penetrating radar [15]. The antenna was backed by a reflector, this has influenced the radiation characteristics of the patch antenna, and the antenna gain value has improved from 4.3 to 7.43 dBi, an operational bandwidth was within the range of 0.4 to 1.25 GHz. The work [16] designed and analysed a patch antenna for radar applications. The design in this study consist of copper radiator with a coupled copper extension to the extreme end of the patch element through three frequency bands of operation at 6.19 GHz, 7.63 GHz, and 10 GHz to address the narrow bandwidth problem of single element patch antenna.

A study in [17] worked on a high-stability patch antenna with a coplanar waveguide (CPW) feeding technique that straightly linked the top antenna and the transmitting receiver modules. To improve the durability of the antenna, both the sub-miniature push-on (SMP) connector and the feed-pin are separated through coplanar waveguide. The study in [18] also designed a compact patch antenna at three frequency bands for military radar applications. The size of the designed antenna was 7 mm × 7 mm × 1 mm. The design was implemented on a substrate material (FR4) with dielectric constant of 4.4 and loss tangent of 0.02. A patch antenna with a meta-material configuration that achieved high antenna bandwidth and high directivity for objects detection using radar was studied in [19]. Three split ring resonators were incorporated into the radiating patch. The authors designed a circular patch antenna with width of 10 mm and length of 15 mm.

In many of these researches, single patch antenna was adopted for various wireless applications. Researchers, like [20-23], considered the use of patch array antenna but used arbitrary large inter-element spacing distance which affected the over-all performance of the antenna unit. Hence, there was wide beamwidth which led to poor illumination and noticeable scan losses. In addition, the radiation patterns of these patch antennas had grating lobes that negatively affected the antenna performance, thus reducing the suitability of the antenna model for radar applications. Quite a number of researchers concentrated on alterations to the geometry of the patch [24]; however, such modifications in geometry could potentially affect the radiation properties and overall performance of the patch antenna for intended purpose. Some other researchers that experimented with patch array antenna for radar applications based their designs on maximum patch array antenna gain and low reflection coefficient (S11). In these researches, although a number of antennas have high gain, the sizes of the antennas were huge considering the frequency of operation [25, 26]. Meanwhile, some antennas had small sizes with top-level antenna gain. All the same, in these antennas, recurrent external stress at the linked point along the antenna and transmit-receive module accumulate mechanical fatigue during testing, that caused physical damage to the antenna and resulted in strong defects in transmission of electrical energy from the transmit-receive module to the antenna as observed in [27].

Amongst all recently reviewed works on patch antennas for radar applications, only very few applied the developed patch antenna for practical radar applications. Majority of these research works only analysed the antenna performance parameters to see if the antenna characteristics met the radar application criteria for various wireless applications. They didn't go further to test the capabilities of the developed antenna for various possible radar system applications. In particular, [28] in their research project implemented the developed antenna for practical application in radar to measure azimuthal resolution of a target. Their work did not consider using the developed patch antenna for other everyday life applications such as aerial surveillance, moving targets monitoring, ground distance measurement (ranging), and ground mapping, e.t.c.

The present work focused on investigating the patch elements spacing distance and feed point parametric analysis so as to develop a patch antenna array with small size, low volume, lower cost with efficient radar target detection and parameters estimation. 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.

2. Methodology

2.1 Design Requirements

The first thing to consider before designing a patch antenna is the design requirements based on its intended application. The design requirements are selected based on the relevant regulating authority's recommendations for radar systems and review of previous researches by different authors. The design requirements are prepared as shown in Table 1. The antenna reflection coefficient (S_{11}) is one of important parameters that determine the antenna's performance in wireless communication [29, 30]. The ratio of antenna transmitted power to reflected power is regarded as the antenna S_{11}. It is important to concentrate the transmitted radio waves or received radio signal in a particular direction, known as the directivity, to know the precise direction of a target. The antenna gain and its directivity are designated according to the requirements of the project. The acceptable gain and directivity of a good performing antenna should be ≥ 6 dBi and ≥ 5 dBi respectively [31].

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 [32]. The 3 dB illumination beamwidth of 10° requirement emerged based on the relevant recommendations for radar systems operation [33, 34]. The design steps are implemented according to the design requirements of this study.

Table 1 *Antenna design requirements*

Operational Parameter	Values
Operational Frequency Band	(8 – 12) GHz
Center Frequency (f)	10 GHz
S_{11}	≤ -10 dB
Gain	12 dBi
Directivity	11 dBi
HPBW (θ_{-3dB}) Azimuth	10°

2.2 Patch Antenna Design

The design of the single patch antenna was done firstly; it will serve as the base antenna used to form the patch array antenna structure. The structure of the selected rectangular patch antenna is shown in Fig. 1.

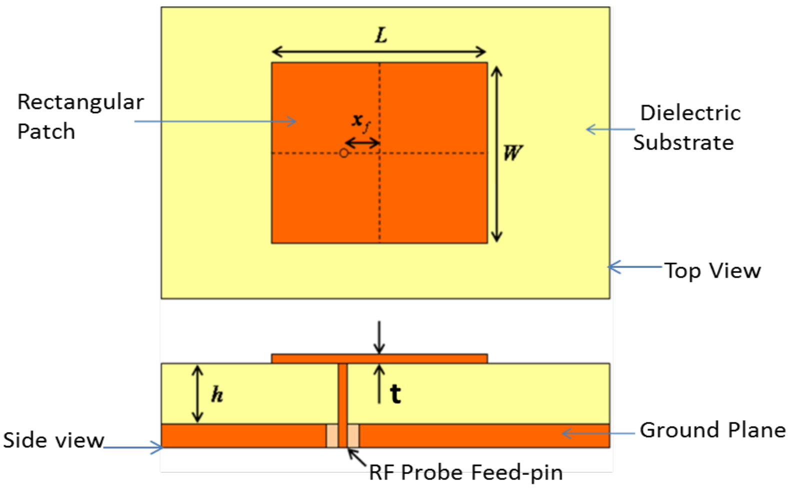

Fig. 1 *The single rectangular patch antenna structure*

The patch antenna was designed using relevant transmission line model equations [35]. The central operating frequency (f) of the antenna was set at 10 GHz, with corresponding wavelength (λ) of 30 mm. The substrate height that would lead to adequate operational bandwidth and efficient radiation pattern was estimated using the graph in Fig. 2.

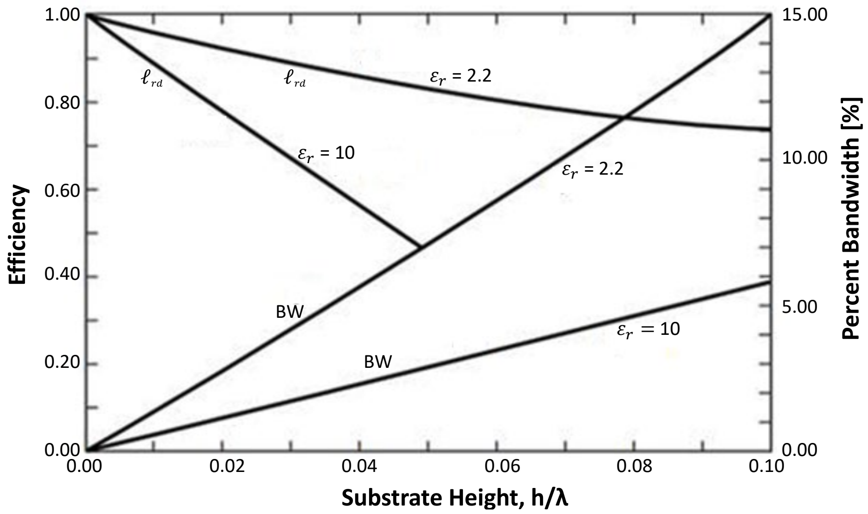

Fig. 2 *Rectangular patch radiation efficiency and bandwidth versus substrate height for various substrates [35]*

From the information contained in Fig. 2, a minimum substrate thickness, *h,* of approximately 1.6 mm and dielectric constant of 2.2 are required to achieve a radar antenna of high efficiency and competitive bandwidth. These substrate parameter values (ε_r = 2.2 and h = 1.6 mm) served as initial guide to search for the substrate material. The Rogers database was consulted and RT/Duroid 5880 dielectric substrate [36] with dielectric constant (ε_r) of 2.2, substrate thickness (h) of 1.6 mm, and dielectric loss tangent (tan δ) of 0.0009 was chosen to fulfill the aim of the study. The detailed procedures for designing the rectangular patch antenna element are discussed hereunder.

2.2.1 Patch Width, W Computation

The estimation of the dimension of the patch width (W) was done using Eq. (1). The patch width was estimated according to the transmission line model equation given by [37], as:

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

Substituting values of parameters for the X-band and Duroid 5880 substrate (c = 3×10^{11} mm/sec, ε_r=2.2 and f=10 GHz) in Eq. (1) gives the effective patch antenna width, W as:

$$W = \frac{3 \times 10^{11}}{2 \times 10 \times 10^9 \times \sqrt{\frac{(2.2+1)}{2}}} = 11.85 \text{ mm}$$

Therefore, the width, W of the patch element is = 11.85 mm.

2.2.2 Effective Dielectric Constant, $\varepsilon_{r_{eff}}$ Estimation

Effective dielectric constant (**ε_{reff}**) was estimated by Eq. (2) [38], as:

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

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Substituting values of ε_r=2.2, W=11.85 mm and h=1.6 mm gives ε_{reff} as

$$\varepsilon_{reff} = \frac{2.2+1}{2} + \frac{2.2-1}{2}\left[1+12\times\frac{1.6}{11.85}\right]^{-\frac{1}{2}} = 1.98$$

where ε_r is the dielectric constant of the dielectric material.

2.2.3 Effective Patch Length, L_{eff} Evaluation

The design of effective patch length (L_{eff}) was done by using Eq. (3) given by [38], as:

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

Substituting c = 3×10^{11} mm/s, f=10 GHz and ε_{reff} = 1.98 gives L_{eff} as:

$$L_{\text{eff}} = \frac{3\times10^{11}}{2\times10\times10^{9}\times\sqrt{1.98}} = 10.685 \text{ mm}$$

2.2.4 Patch Length Extension, ΔL Determination

The design of the patch length extension (ΔL) was executed by using Eq. (4) given by [39], as:

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

Substituting ε_{r} =1.98, W =11.86 mm and h=1.6 mm gives ΔL as:

$$\Delta L = 0.412\times1.6\left[\frac{(1.98+0.3)\left(\frac{11.85}{1.6}+0.264\right)}{(1.98-0.258)\left(\frac{11.85}{1.6}+0.8\right)}\right] = 0.8158 \text{ mm}$$

2.2.5 Actual Patch Length, L Computation

The actual patch length (L) was estimated by using Eq. (5) given by [40], as:

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

Substituting L_{eff} = 10.685 mm, and ΔL= 0.8158 mm gives L as:

$$L = 10.685 - 2(0.8158) = 9.05 \text{ mm}$$

2.2.6 Ground Plane Dimensions, L_g and W_g Estimation

The The dimensions of the ground plane for single radiating patch were obtained as [40]:

$$L_g = 6h + L \tag{6}$$

$$W_g = 6h + W \tag{7}$$

where L_g and W_g are the length and width of the ground plane respectively.
Substituting L= 9.05 mm, W =11.85 mm and h = 1.6 mm gives L_g and W_g

$$L_g = 6(1.6) + 9.05 = 18.65mm$$

$$W_g = 6(1.6) + 11.85 = 21.45mm$$

The computed patch antenna dimensions are presented in Table 2. The cross-sectional view and top view geometry of the X-band patch antenna is as shown in Fig. 3.

Table 2 *Patch antenna dimensions*

Parameters	Values and Units
Patch width (W)	11.85 mm
Patch length (L)	9.05 mm
Effective dielectric constant (ε_{reff})	1.98
Ground plane width (W_g)	21.45 mm
Ground plane length (L_g)	18.65 mm

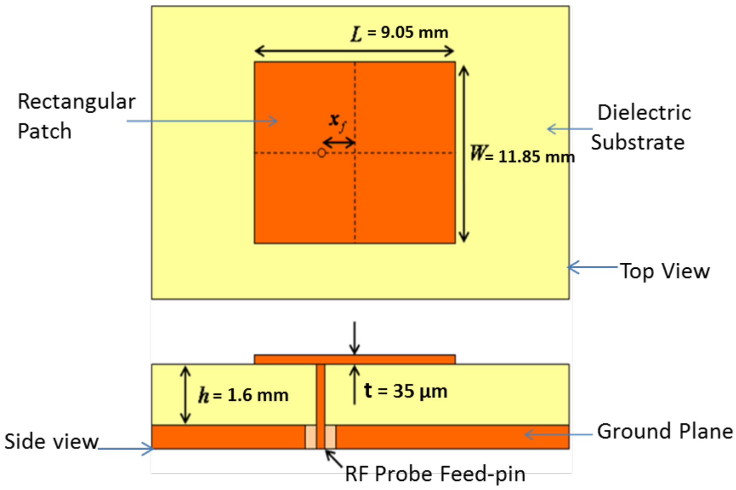

Fig. 3 *Designed patch antenna with dimensions*

The physical size of RT/Duroid 5880 substrate ($Wg \times L_g \times h$) is 21.45 mm × 18.65 mm × 1.6 mm and size of the patch is ($W \times L \times h$) is 11.85 mm × 9.05 mm × 1.6 mm. Fig. 3 shows the schematic diagram of the designed single element antenna.

The physical size of RT/Duroid 5880 substrate ($Wg \times L_g \times h$) is 21.45 mm × 18.65 mm × 1.6 mm and size of the patch is ($W \times L \times h$) is 11.85 mm × 9.05 mm × 1.6 mm. Fig. 3 shows the schematic diagram of the designed single element antenna.

The summary of the various dimensions of the patch antenna is presented in Table 3.

Table 3 *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 × W_g	18.65 mm (L) × 21.45 mm (W)

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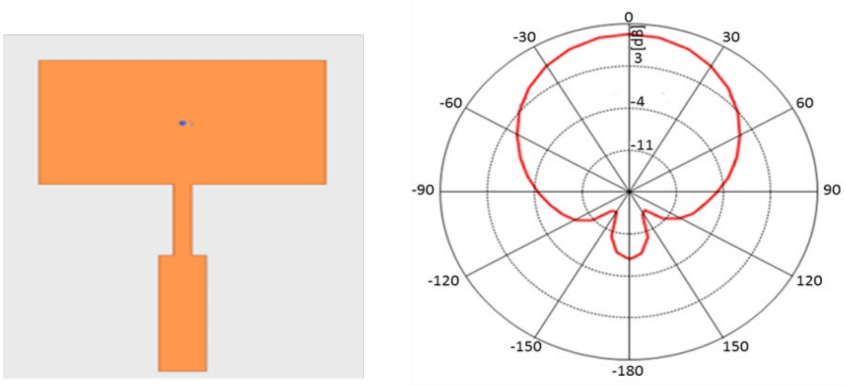
2.3 Simulations of the Single Element Patch Antenna

It is a common practice to evaluate the system performances through computer simulation before the real time implementation of the design. Computer Simulation Technology (CST) microwave studio simulation software [40] was used to simulate and study the performance of the designed patch antenna to help in reducing the fabrication cost by having the knowledge of the antenna configuration that meets the best desired results before the real antenna fabrication. Fig. 4(a) shows the simulated single patch antenna on RT/Duroid substrate with dielectric constant ε_r of 2.2 and thickness of 1.6 mm. The industry standard full-wave electromagnetic field software based on the finite element method (FEM) was used for the simulation. The antenna radiation characteristics parameters which include gain, Half Power Beamwidth (HPBW), reflection coefficient (S_{11}), radiation pattern, and directivity.

The radiation pattern of the single element patch antenna at 10 GHz is shown in Fig. 4(b). The antenna radiation pattern is the shape and direction of the beam of electromagnetic wave that the antenna exhibited. It was observed that the antenna had an azimuth beamwidth of 64° at -3 dB point. Placing the antenna element in an array configuration would improve the antenna radiation patterns and power handling capacity. The gain of an antenna is a measure of how far signals can travel through space, while the ability of the antenna to concentrate energy in a particular direction is called directivity of an antenna. The directivity of 8.83 dBi and gain of 8.30 dBi were obtained from the computer simulation of the designed single element patch antenna using CST, where the gain 6 dBi and directivity 5 dBi are acceptable [41].



(a) **(b)**

Fig. 4 *Simulated single element patch antenna: (a) Geometry; (b) Radiation pattern*

The S_{11} is a fraction of signal reflected to the antenna source. Fig. 5 shows the $|S_{11}|$ of the single patch antenna in dB at operating central frequency of 10 GHz. The reflection value is expressed in decibel (dB); it determines the impedance matching of the antenna. In practice, a S_{11} of -10 dB indicates that one-tenth of energy is reflected. From Fig. 5, the designed patch antenna resonates at 10 GHz, with S_{11} of -13.25 dB; it is less than -10 dB and indicates minimum power was reflected to the source. The range of frequencies within which antennas transmit and receive energy appropriately is referred to as an antenna bandwidth. From Fig. 5, the -10 dB impedance bandwidth of 250 MHz, from 9.80 to 10.05 GHz at resonant frequency of 10 GHz was obtained from the single element patch antenna. The impedance bandwidth of the designed antenna is 2.5%, and could be improved by antenna array configuration.

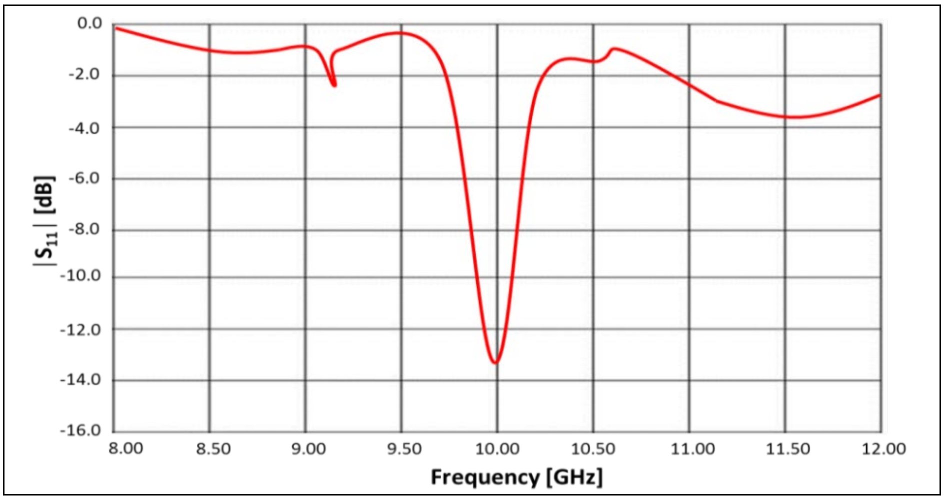


Fig. 5 *Single element patch antenna simulated* $|S_{11}|$

Table 4 depicts simulation results produced by the designed single element patch antenna at 10 GHz.

Table 4 *Simulation results of the single patch antenna*

Parameters	Values and Units	Minimum Standard [42]
No. of Patch Element	Single patch (1)	As per need
Resonant Frequency (*f*)	10 GHz	As per need
Wavelength at 10 GHz	30 mm	As per need
Bandwidth	250 MHz	As per need
HPBW (degree)	64^o	As per need
S_{11}	-13.25 dB	≤-10 dB
Gain	8.30 dBi	>6 dBi
Directivity	8.83 dBi	>5 dBi

2.4 Patch Array Antenna Design

The distance between two or more patch elements is a fundamental parameter for the design of an array patch antenna; it determines the overall gain display by the antenna. The patch elements spacing distance must be decided carefully to avoid spurious radiations that can lead to increase side lobe which, otherwise, causes low antenna gain. An appropriate technique is to first take into consideration the specified performance parameters of the antenna, the number of elements and its separation distance. Initially, the single patch antenna which has a rectangular shape with a patch width (*W)* and patch length (*L)* was designed using numerical calculations and transmission line model [43]. The antenna array design was implemented by using CST (version 16.0) software package and iteration of inter-element distance from 0.1λ up to 0.5λ. The inter-element spacing distance should be less or equal to 0.5λ [44] to avoid or minimize grating lobes.

The main focus of the design was to produce an antenna with radiation pattern that displays an illumination beamwidth that results in antenna resolution efficient for the radar system applications [45]. The antenna was projected to exhibit a HPBW value of 10° which gives a competitive radar resolution.

2.4.1 Patch Array Antenna Design Assumptions

The design of the patch array antenna for X-band radar system applications was based on the following assumptions [46]:

i. The signal excitation amplitude between patch elements is uniform.
ii. The configuration of the array is symmetric about the midpoint.
iii. The elements have uniform phase.
iv. Each element has the same dimensions.
v. Equally spaced patch elements that form the antenna array.

The basic geometry of the uniform planar antenna array is shown in Fig. 6.

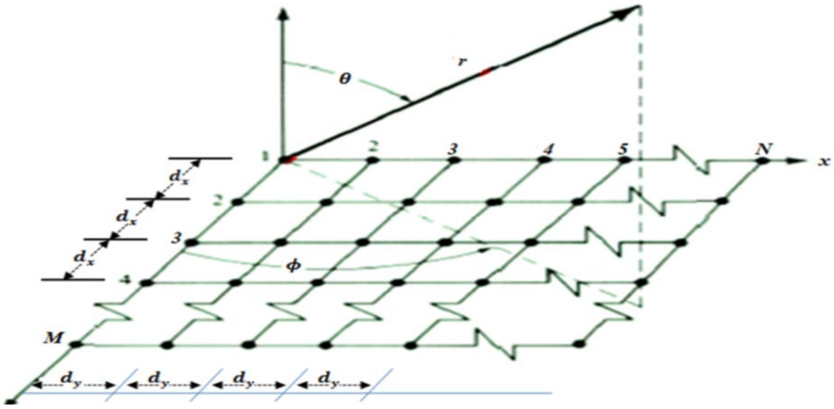


Fig. 6 *The basic planar array patch antenna configuration [46]*

The 3 dB illumination beamwidth of a uniform amplitude broadside array is given by [46], 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

2.4.2 Design and Performance Analysis of 4×4 Patch Array Antenna

Table 5 is the result of the mathematical computation of illumination beamwidth 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 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 5 *4×4 antenna array illumination beamwidth at different inter-element distance*

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°

2.4.3 Feed Network Configuration of the 4×4 Patch Array Antenna

The adopted 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. 7. 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.

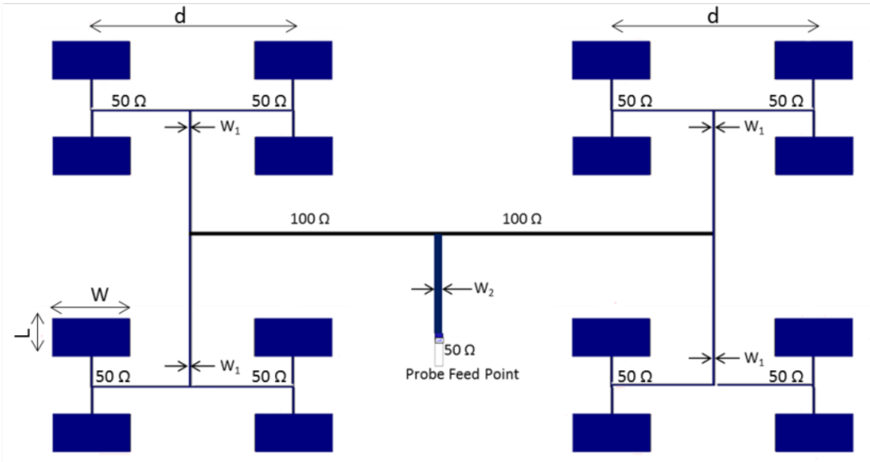


Fig. 7 *The designed 4×4 patch array antenna configuration with feed lines*

2.4.4 Final Design Parameters

The final design configurations and associated parameters selected for performance analysis are as follows:

a) Dielectric Substrate
- i. Substrate Material = RT/Duroid 5880
- ii. The substrate dielectric constant of: ε_r = 2.2
- iii. Dielectric substrate height: h = 1.6 mm
- iv. The loss tangent of dielectric material: tan δ = 0.0009

b) Single Patch Element
- i. Patch element length: L = 9.05mm
- ii. Patch antenna element width: W = 11.85 mm

c) Patch array antenna Feed Dimensions
- i. X-Band 4x4 planar patch array antenna feed inter-element spacing, d = 9.525 mm
- ii. Width of inter-element line = 1.4 mm
- iii. Width of 50 Ω transmission line = 2.4 mm

The schematic diagram of the 4×4 planar patch array antenna is shown in Figs. 8 and 9.

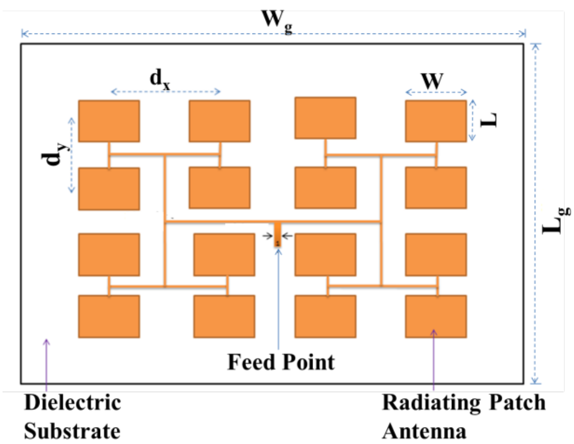


Fig. 8 *Schematic diagram showing the front view of 4×4 patch array antenna*

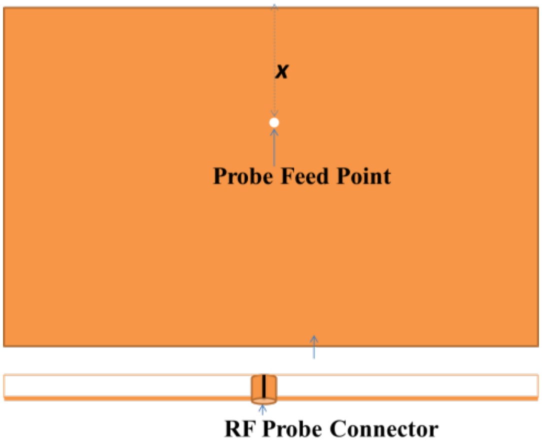


Fig. 9 *Schematic diagram showing the back view and side view of 4×4 patch array antenna*

Table 6 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 6 *Final designed patch array structural parameters*

Parameters	Values and Units
Patches in the array	16
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

2.4.5 Simulation of the 4×4 Patch Array Antenna

The simulation of the 4×4 patch array antenna begins by inputting the value of the selected substrate dielectric constant, ε_r, of 2.2, and substrate thickness, h of 1.6 mm and parameter for the antenna design. The antenna radiation patterns characteristics parameters: S_{11}, antenna gain, directivity, and radiation performance efficiency values were obtained by simulating the designed patch array antenna using electromagnetic simulator, CST microwave studio. The final simulated array structure of the antenna is 88 mm × 74 mm. The planar configuration of 4×4 patch antenna with simulation CST is presented in Fig. 10.

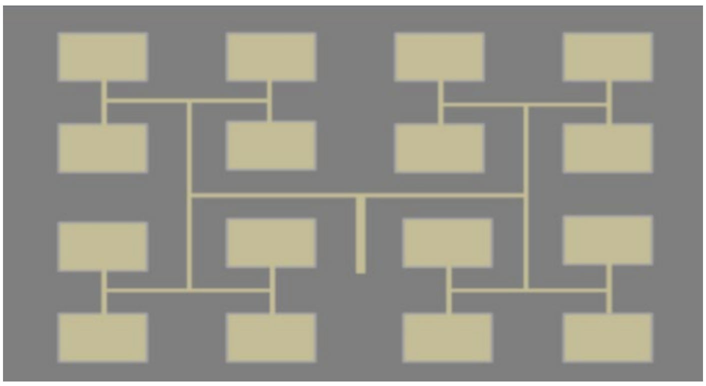


Fig. 10 *Planar arrangement of the 4×4 patch antenna using CST*

2.4.5.1 Patch Array Antenna Design Assumptions

The radiation pattern plot of the 4×4 patch array is shown in Fig. 11. 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.

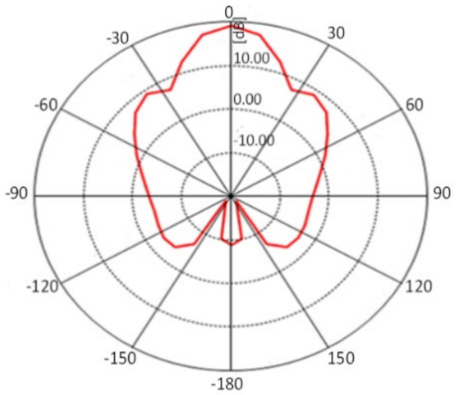


Fig. 11 *Simulated radiation pattern of the 4×4 patch array antenna*

2.4.5.2 Simulations of the Reflection Coefficient of 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. 12) is the distance between the feed point and centre of the substrate. The final simulation output of S_{11} plots for the patch array is as shown in Fig 13. 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.

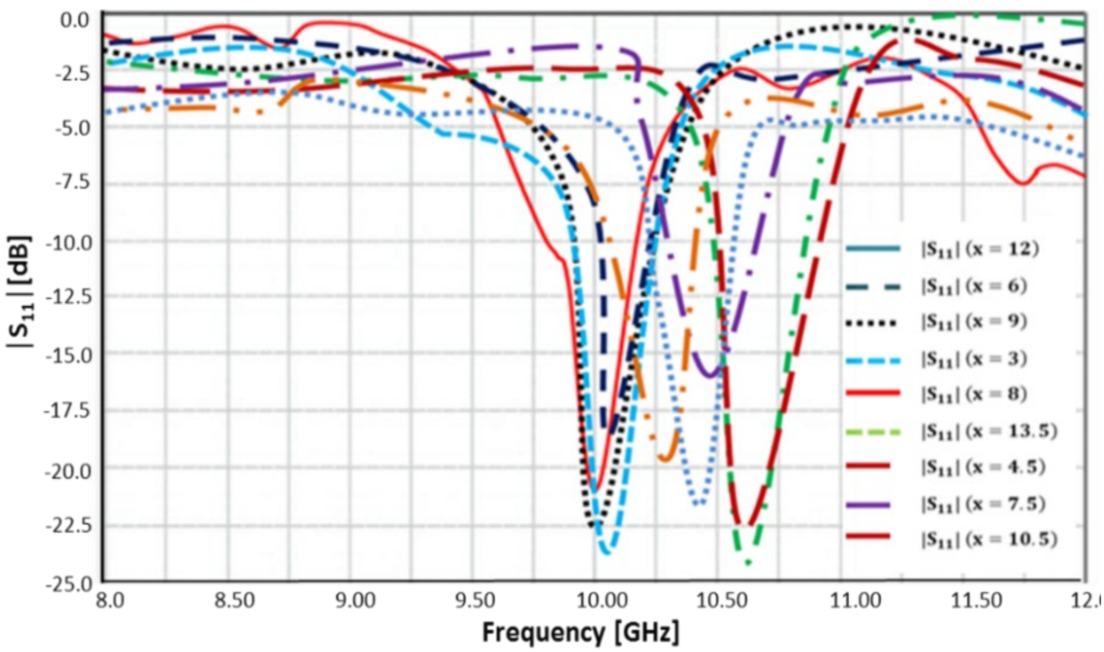


Fig. 12 *Parametric analysis for feed point determination of the 4x4 patch array antenna*

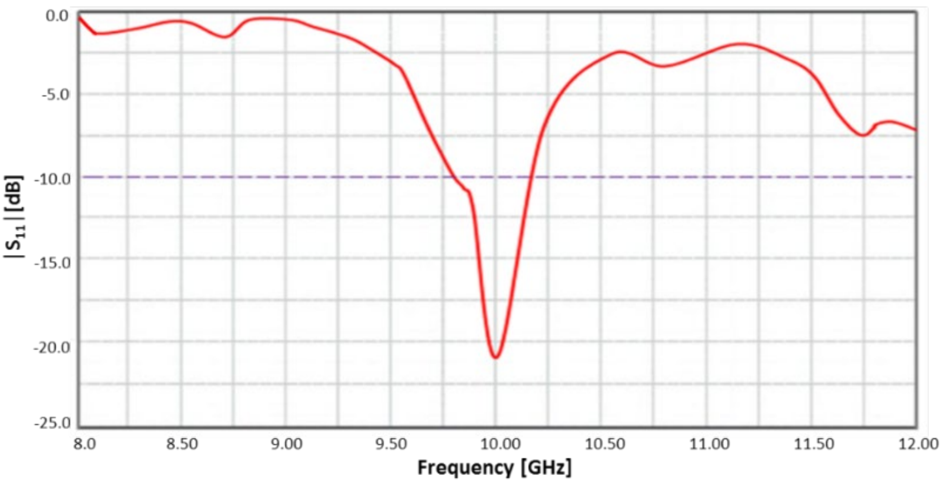


Fig. 13 *Simulated |S_{11}| of 4×4 array at best feed point*

2.4.5.3 Radiation Efficiency Simulation of 4×4 Patch Array Antenna

Fig. 14 is the 4×4 Planar Array 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. The antenna radiation efficiency of 89.01% indicates that the patch array antenna is good and acceptable for practical application since it is greater than 70% minimum radiation efficiency required for most practical purposes. Thus, the designed antenna is relatively suitable for radar system applications.

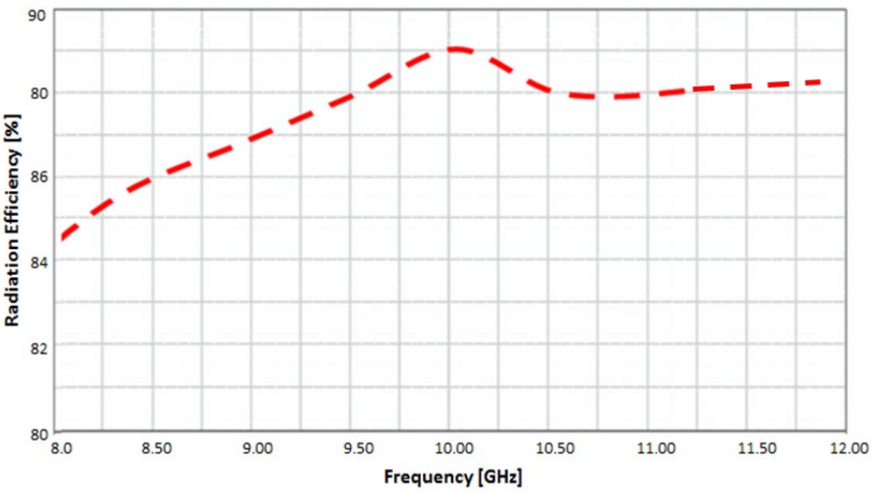


Fig. 14 *Simulated |S_{11}| of 4×4 array at best feed point*

2.5 Experimental Characterization

Following the antenna design, the prototype of patch antenna array was fabricated and experimentally characterized as shown in Fig. 15. The realized antenna prototype has been evaluated through experimental measurements and the achieved results are in good comparison with simulation results obtained before the antenna fabrication. Its reflection coefficient |S_{11}| was measured with a vector network analyzer (VNA) as shown in Fig. 16. A comparison of the simulated and measured plots is as presented in Fig. 17. The array antenna operates with reflection coefficient value below the minimum required value of -10 dB. Fig. 18 shows the measured radiation patterns recorded at 10 GHz along the X-band. The radiation patterns of the realized patch array antenna are presented in Fig. 19.

(a) (b) (c)

Fig. 15 *Realized antenna array prototype: (a) Top view; (b) Back view; (c) Cross sectional view*

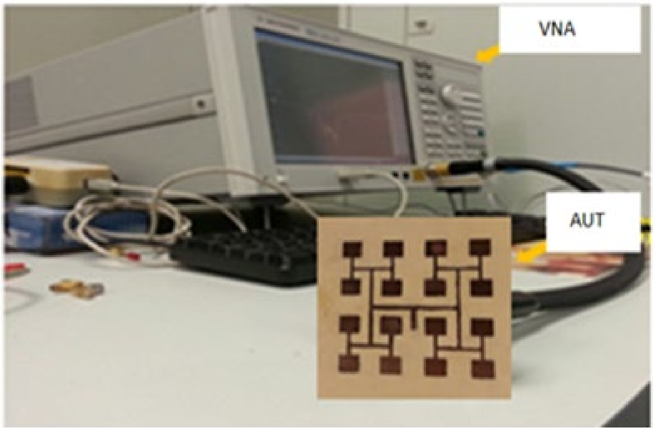


Fig. 16 *Photograph of |S_{11}|measurements*

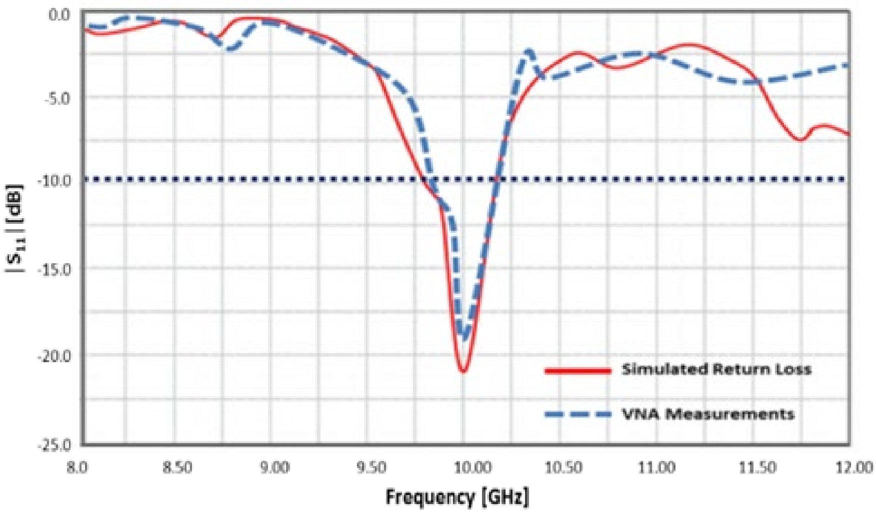


Fig. 17 *Simulated and measured |S_{11}|*

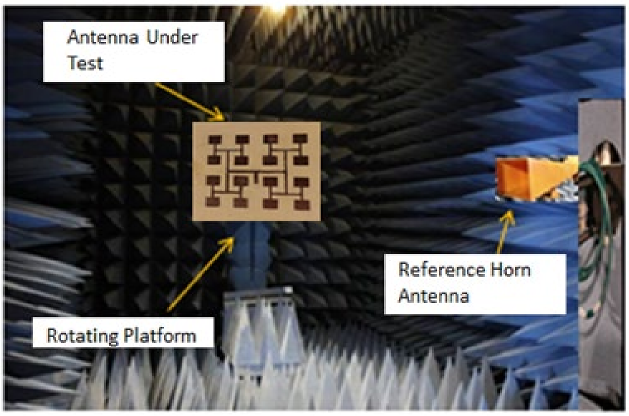


Fig. 18 *Radiation pattern setup*

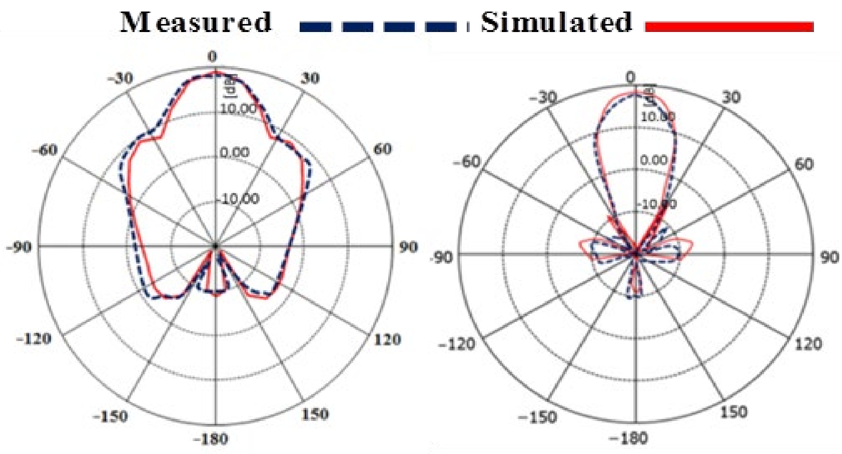


Fig. 19 *Simulated and measured radiation patterns*

2.6 The Prototype Antenna's Deployment for Car-Speed Detection Radar Application

The studied array antenna's deployment for real-world application was actualized by incorporated the antenna into a computer-controlled linear continuous-wave frequency modulated radar system. The prototype radar patch array antenna was practically tested for radar applications by monitoring speeds of a moving car a moving car in outdoor experiments carried out in Ilorin (8.5°N latitude and 4.55°E longitude). The field test was conducted under environmental condition with humidity of 43%, pressure of 1013.9 mb, temperature value of 19^{o} C, and under clear atmosphere. The experimental setup consist a radar sensor device [21], saloon car which serves as the target being monitored with physical dimensions of 2.0 m ×1.5 m × 1.0 m, antenna stand, laptop computer, and the fabricated patch array antenna under test. The RF radar device was powered by 12V battery packs. The experiment started with the car moving toward the antenna at a speed of 25 km/h. The car moved past the antenna at an initial controlled speed of 25 km/h from a distance of 100 m away from the antenna test setup. The car-speed was controlled using an on–board diagnostics (OBD2) scanner in the car. The experiment was repeated at a set of 50 km/h and 70 km/h respectively. Figs. 20 and 21 show photographs of the test site and the experimental setup. The measured speeds of the monitored car were recorded and compared with the actual set speeds of the saloon car. Figs 22 to 24 show the measured speed plots for the car-speed detection radar application.

(a) **(b)**

Fig. 20 *Simulated and measured radiation patterns*

(a) **(b)**

Fig. 21 *Field test photographs: (a) Antenna connection to the radar via RF feeder cable; (b) Experimental setup*

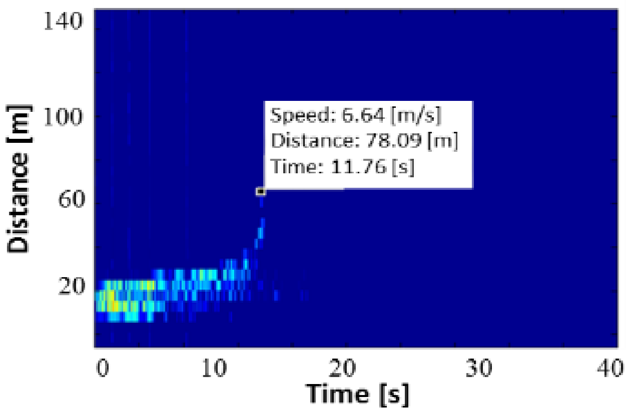


Fig. 22 *Measured speed plot of the: (b) 25 km/h*

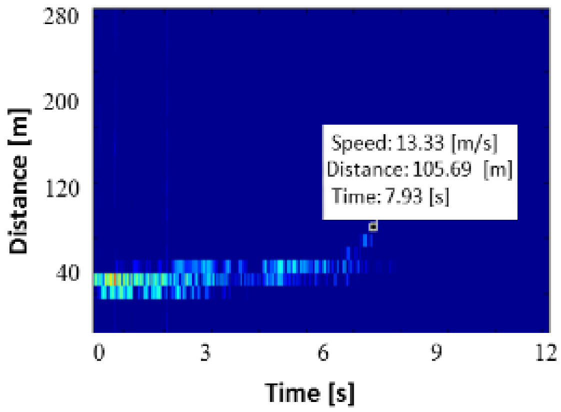


Fig. 23 *Measured speed plot 50 km/h*

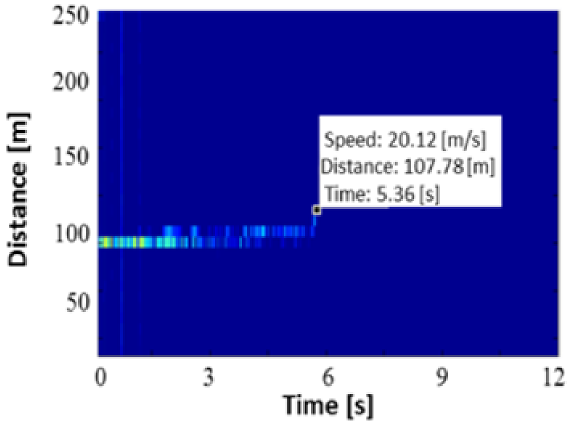


Fig. 24 *Measured speed plot at 75 km/h*

3. Results and Discussions

The simulation results of the designed 4×4 patch array antenna for car-speed detection and monitoring radar systems are presented and discussed in this section. The antenna's performance is evaluated in terms of its radiation pattern, gain, directivity, reflection coefficient (S_{11}), and radiation efficiency. Table 7 depicts the summary of the simulation results at 10 GHz. The simulation results show that the designed patch array antenna achieves a gain of 19.35 dBi, directivity of 16.5 dBi, and S_{11} of -21.23 dB. The measured and simulated antenna performance parameters are presented in Table 6.

Table 7 *The performance parameters of the studied 4x4 patch array antenna*

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%

3.1 Radiation Pattern

The simulated radiation pattern of the 4×4 patch array antenna at 10 GHz is shown in Fig. 11. The antenna exhibits a directional radiation pattern with a main lobe directed towards the broadside direction (0°). The 3 dB beamwidth of the antenna is 10.37°, which is suitable for radar applications that require a narrow beamwidth to achieve high resolution and accuracy. The side lobe level is also minimized, which reduces interference and improves the overall performance of the radar system.

3.2 Reflection Coefficient (S_{11})

The simulated reflection coefficient (S_{11}) of the 4×4 patch array antenna is -21.23 dB at 10 GHz, which indicates good impedance matching between the antenna and the feed network. The S11 value is below -10 dB, which is a common criterion for good antenna performance. The reflection coefficient plot shows a wide bandwidth, which enables the antenna to operate effectively over a range of frequencies.

3.3 Radiation Efficiency

The simulated radiation efficiency of the 4×4 patch array antenna is 89.02% at 10 GHz, which indicates that the antenna is efficient in radiating power. The high radiation efficiency of the antenna is essential for radar applications that require accurate target detection and tracking. The radiation efficiency value obtained in this study is comparable to or better than those reported in previous studies [47, 48].

3.4 Gain and Directivity

The simulated gain and directivity of the 4x4 patch array antenna are 17.23 dBi and 19.35 dBi, respectively. The high gain and directivity of the antenna enable it to transmit and receive signals efficiently, which is essential for radar applications that require accurate target detection and tracking. The gain and directivity values obtained in this study are better than those reported in previous studies [49, 50].

3.5 Comparison with Existing Studies

The performance of the designed 4×4 patch array antenna is compared with existing studies [47, 48] as presented in Table 8. The results demonstrate the good performance of the designed patch array antenna, making it suitable for car-speed detection and monitoring radar applications. The antenna's narrow beamwidth, high gain and directivity enable accurate target detection and tracking, while its low S_{11} ensures efficient transmission and reception of radio signals. The comparison shows that the designed patch array antenna's performance is comparable and better than some existing studies, highlighting its potential for car-speed detection and monitoring radar applications.

Table 8 *Comparison with existing studies*

Parameter	Simulated Value	Measured Value	Minimum Standard
[47]	15	16	-20
[48]	12	14	-18
This study	17.23	19.35	-21.23

3.6 Measured Results Analysis

The prototype of the patch antenna for the radar applications in X-band was subjected to appropriate performance tests in a standard antenna measurement environment. A measured reflection coefficient of -18.85 dB is achieved, with impedance bandwidth extending from 9.69 to 10.20 GHz, and measured illumination beamwidth of 11.02°. Also, the measured antenna directivity of 17.96 dBi and gain of 15.48 dBi are obtained in the X-band at a center operating frequency of 10 GHz for the 4×4 array patch antenna.

The prototype antenna shows good radiation properties with measured radiation efficiency of 86.17 % and an antenna total weight of 0.13 kg. The antenna satisfied the weight and volume restriction required for wireless communication and radar system. The total mass of the antenna array prototype, approximately 0.13kg, is negligible when compared to a range of 1 kg to 10 kg of convectional microwave antennas. The numerical and measured S_{11}, directivity, gain, radiation patterns and efficiency represent adequate performances. Therefore, the results of these tests compared favorably well and are in close agreement with the computer simulations. They also showed that the prototype patch antenna array is indeed a competitive small size and light weight antenna for radar system applications. The observed slight discrepancies from the results obtained through CST computer simulation and that of experimental measurements could be as a result simulation and measurement settings, SMA soldering effect, and cable loss in the measuring process. However, both measured and simulation results are in good comparison.

The fabricated antenna was tested to determine its suitability for radar applications. The prototype antenna was deployed to measure a moving car's speed to determine the antenna accuracy for radar applications. The antenna, when integrated with radar device, achieved acceptable results for car-speed monitoring and monitoring test with an average measurement error of 3.97%. The percentage measurement error was computed by comparing the set speed of the car with the measured speed as shown in Eq. (9)

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

The practical tests show a close correlation between measured and set speed of the car. The studied antenna offers a compact, lower cost and lightweight antenna for car-speed monitoring radar system. The observed slight differences between the set speed and measured speed results could be attributed to factors such as non-ideal radar system characteristics, system settings, radar system thermal noise and interference, processing rounding errors, several other environmental conditions.

Table 9 *Car speed detection results at 25, 50, and 75 km/h*

Set Speed (km/h)	Measured Speed (km/h)	Measurement Error (%)
25	23.89	4.44
50	47.98	4.04
75	72.42	3.44

4. Conclusion

This study presents the design, simulation, and performance analysis of a high-performance X-band 4×4 patch array antenna for car-speed detection and monitoring radar systems. The antenna's performance is evaluated in terms of its radiation pattern, gain, directivity, reflection coefficient (S_{11}), and radiation efficiency. The antenna demonstrates good performance, with a high gain, good directivity, and efficient radiation characteristics. The antenna's narrow beamwidth and low side lobe level also reduce interference and improve the overall performance of the radar system. The studied antenna's performance is better than some existing studies, highlighting its potential for practical applications in car-speed detection and monitoring radar systems. The antenna's compact size, high gain, and good radiation efficiency make it an attractive option for radar systems that require accurate target detection and tracking. The antenna's potential applications extend beyond car-speed detection and monitoring radar systems. Its high gain, directivity, and radiation efficiency make it suitable for various radar applications, including surveillance, tracking, and navigation. The antenna's compact size and good performance also make it an attractive option for integration with other radar systems, such as synthetic aperture radar (SAR) and ground-penetrating radar (GPR). The study's findings contribute to the existing body of knowledge on patch antenna design and radar systems, and highlight the potential of patch antennas for automotive radar applications.

In general, the antenna demonstrates acceptable performance for radar target detection applications at the desired center frequency of 10 GHz. The measured speed of the car being monitored is compared with actual controlled speed of the car. The results demonstrate the antenna's capability in real-world radar applications for car-speed detection and monitoring with a percentage measurement error of 3.97%.

In conclusion, this studied demonstrates a high-performance X-band 4×4 patch array antenna for car-speed detection and monitoring radar systems. The antenna's good performance, compact size, and potential for practical applications make it an attractive option for various radar applications. Future research on this topic could consider exploring advanced different dielectric substrate materials, implementing adaptive or reconfigurable array elements, and other patch shapes and geometry.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Author 1, Author 2;* ***data collection:*** *Author 1;* ***analysis and interpretation of results:*** *Author 1, Author 2, Author 3;* ***draft manuscript preparation:*** *Author 1, Author 2, Author 3. All authors reviewed the results and approved the final version of the manuscript.*

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