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Design and Implementation of X-Band Patch Array Antenna for Medium-Range Radar Applications

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***Abstract*—** In this work, the design, implementation and testing of a 4×4 patch array antenna for X-band radar applications at a center frequency of 10 GHz are discussed. Several studies have been made in designing patch array antennas. The objective of this paper is to design a 4x4 patch array antenna with improved performance for radar application by investigating the patch elements spacing distance so as to develop a patch antenna array with compact size, low volume, and efficient target detection. The antenna was designed via empirical equations and numerical modeling using Computer Simulation Technology (CST) Microwave Studio. The antenna performance was verified through experimental measurements with high gain of 15.48 dBi, bandwidth impedance of 510 MHz (9.69-10.20 GHz), and radiation efficiency of 86.17%. A solid and light-weight antenna was fabricated on RT/Duroid 5880 copper board and mounted in a radar system for medium-range applications. Field testing proves the potential of the antenna for radar applications with a percentage range error measurement of 4.21%, showing that it can be used in ground-based light-weight surveillance radar systems.

***Keywords*—** Patch antenna; X-band radar; Bandwidth; Radiation pattern; Field tests; Radar applications.

1. INTRODUCTION

Radio Detection and Ranging (RADAR) technology is an extremely effective tool in numerous applications, including surveillance [1], navigation [2], and tracking [3], since it can sense and determine the range, velocity, and direction of targets with great accuracy. Medium-range radar systems employ directive and high-gain antennas to detect and track the target at a range of several kilometers. The X-band range (8-12 GHz) is used widely in radar systems due to their freely adjustable range and resolution. In recent years, additional interest has been evoked for designing radar systems for specific applications, such as ground surveillance [4], air traffic control [5], and weather monitoring [6]. The antenna is also regarded as one of the most critical components of a radar system and is employed to send and receive electromagnetic waves [7].

The Patch antenna is particularly trendy due to its attributes such as low volume [8], light weight [9], low cost and easy manufacture [10], and easy integration to non-planar and planar surfaces. Patch antenna structure is made up of a radiating patch element, dielectric substrate and ground plane. Patch element geometry is elliptical, rectangular, square, and circular. Contacting or non-contacting feeding techniques are applied in patch antennas design. Patch

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antennas have numerous applications in radar [11], communication systems [12], and navigation [13] but designing a patch antenna for radar involves numerous difficulties, such as achieving high gain [14], low side lobe levels [15], and wide impedance bandwidth [16].

Several researchers have proposed various designs and techniques to improve the performance of microstrip patch antennas for radar applications. Studies by [17] present a wideband 4×4 patch array antenna for radar-based obstacle detection in railway transportation. The antenna exhibits an impedance bandwidth from 9.13 GHz to 9.76 GHz (6.3%) and a gain of 18.15 dBi at the center frequency of 9.55 GHz with 17° 3-dB beamwidth in the E-plane and 16° in the H-plane and simulated radiation efficiency of 85%. Another study by [18] investigated a patch antenna with broad bandwidth and narrow antenna beam width for radar application in non-contact signs detection. The antenna was designed using a substrate with a thickness of 1.6 mm, dielectric constant of 4.3, center frequency at 7.5 GHz and loss tangent (tan δ) of 0.02, achieving a gain of 6 dBi, bandwidth of 10.7% and 40 degrees beamwidth at vertical plane and 50 degrees at the horizontal plane. Similarly, a study by [19] designed an array of 2×2 patch antenna with 9.6 GHz center frequency of operation for radar applications, achieving a return loss of -4.487 dB. Recent studies have also explored the use of advanced materials and techniques to enhance the performance of patch antennas. A study by [20] presents application of metamaterials for performance enhancement of planar antennas. Another study by [21] presented characteristics of antenna fabricated using additive manufacturing technology and the potential applications.

This research builds upon the existing body of work to design, develop, and test an X-band patch antenna array for medium-range radar applications. Many studies have been made in designing patch array antennas. The objective of this paper is to design a 4×4 patch array antenna with improved performance for radar application by investigating the effect of element spacing on the antenna's beamwidth. Each antenna designer focuses on a specific purpose and areas of potential applications, tailoring the design towards the identified application. The studied patch array antenna was fine-tuned to operate in the X-band at a center frequency of 10 GHz for ground target surveillance radar systems. Specifically, arbitrary patch element spacing that leads to spurious radiation and grating lobes, degrading radio signals in radar operation is identified in many existing studies on patch array antennas for radar systems. The research aimed to develop a compact size, low weight, high gain, and high directivity antenna for target detection and tracking radar applications.

In this study, the design and development of a 4×4 patch array antenna for X-band radar applications is presented. The array antenna is designed to meet the main requirements such as low side-lobe level, high gain, high directivity, compact size, and high bandwidth suitable for radar systems. The antenna was implemented on a low-loss RT/Duroid 5880 substrate. A commercial EM software CST Microwave Studio was used in [22] to simulate and fine-tune the antenna array. The antenna was fabricated and experimentally characterized in an anechoic chamber, where antenna radiation patterns are measured within X-band (8–12 GHz) frequency range.

The proposed antenna operates at a center frequency of 10 GHz with a bandwidth of 512 MHz and beamwidth of 10°, making it suitable for medium-range radar systems. The antenna's measurement results show that it achieves a high gain of 15.48 dBi and a reflection coefficient of -18.85 dB. Finally, the patch array antenna was tested for range measurement at an out-house field experimental setup to determine its suitability for radar application. The studied antenna offers a promising solution for ground-based lightweight surveillance radar systems. This article consists four Sections. Section one presents study's introduction; Section Two reports the design material and methodology; the results obtained from the adopted research methodology and the corresponding analyses and discussions are presented in Section Three; finally, Section Four concludes the study.

2. METHODOLOGY

2.1. The Patch Antenna Substrate Material

Patch antennas can be designed using various types of substrates, which significantly influence their radiation characteristics. The antenna bandwidth increases by increasing the substrate thickness. To achieve the radar antenna's bandwidth of 500 MHz (5% of 10 GHz central operating frequency) and appropriate radiation efficiency, an RT5880 substrate with minimum substrate thickness h of approximately 1.58 mm and dielectric constant of 2.2 is required. Finally, the substrate thickness of 1.6 mm was selected to compensate for bandwidth loss due to fabrication errors. For this 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 chosen. Rogers RT/Duroid 5880 substrate is found to be most suitable due to its qualities, such as high gain, minimal return loss, uniform electrical characteristics over the frequency of operation, and cheaper cost of the substrate material [23].

2.2. Antenna Design

The design of the single element patch antenna was done prior to the design of planar array; it serves as the base antenna used to form the patch antenna array structure. Though patch can be of any shape, a rectangular shape was selected due to its simple form of analysis, low manufacturing cost and their distinctive radiation characteristics. The patch antenna radiating element is designed using the transmission line model [24]. The patch dimensions are calculated using the following equations [24]:

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

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

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

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

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

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 radiating patch were obtained by Eqs. (6-7):

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

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

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

Fig. 1 shows the single patch antenna designed for the formation of patch array antenna in this study. The characteristic impedance of quarter wave matching feed line was obtained by Eq. (8). The quarter wave feed line and 50 Ω feed line dimensions were optimized using microstrip line equations for 50 Ω characteristic impedance. The optimized dimensions of the single element patch antenna are presented in Table 1.

$$Z_0 \text{ (quarter wave transformer)} = \sqrt{Z_0 \text{ (feedline)} \times Z_0 \text{ (patch)}} \quad (8)$$

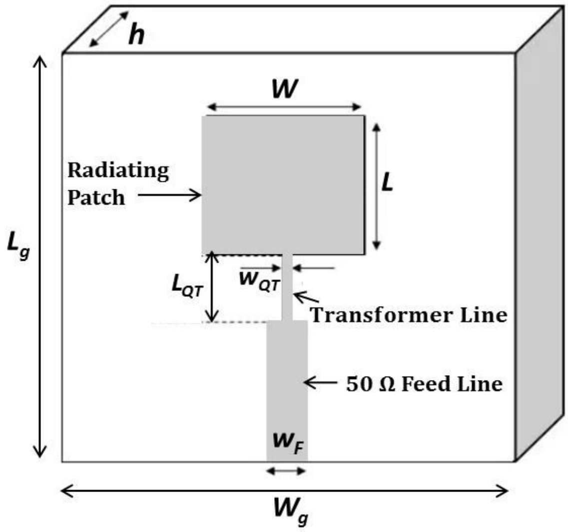

Fig. 1. Single Patch Antenna fed with a 50 Ω feed line with quarter-wave transformer matching.

Table 1. The optimized dimensions of the single element patch antenna.

S/No.	Parameter	Value
1.	L	9.05 mm
2.	W	11.85 mm
3.	ε_{eff}	1.98
4.	W_g	21.45 mm
5.	L_g	18.65 mm
6.	W_F	2.4 mm
7.	W_{QT}	1.6 mm
8	L_{QT}	3.86 mm

2.3. Design of Patch Antenna Array

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 radiation that can lead to increase side lobe which, otherwise, causes low antenna gain. 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. The antenna was projected to exhibit a HPBW value of 10° which gives a competitive radar resolution. The 3 dB illumination beamwidth of 10° requirement emerged based on the relevant recommendations for radar systems operation [25, 26]. The 3 dB illumination beamwidth of a uniform amplitude broadside array is given by [27], as:

$$\theta_{n\times m} = \left[\pi - 2cos^{-1}\left(\frac{1.391\lambda}{\pi N d}\right)\right] \quad (9)$$

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

Fig. 2 shows the sixteen elements patch array antenna placement with patch element spacing distance, *d*. The 4×4 patch array antenna configuration with feed lines is shown in Fig. 3. The impedance line of 100 Ω was matched to the impedance line of 50 Ω using a quarter-wavelength transformer of 70.7 Ω. To achieve an azimuth beamwidth (Δθ) of approximately 10°, the inter-element separation distance between patch antenna elements was iterated using Eq. (9).

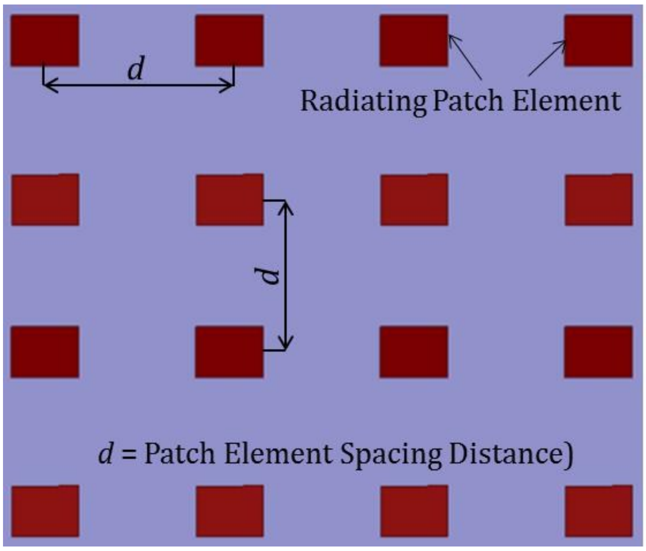

Fig. 2. The 4×4 patch array antenna placement with patch element spacing distance.

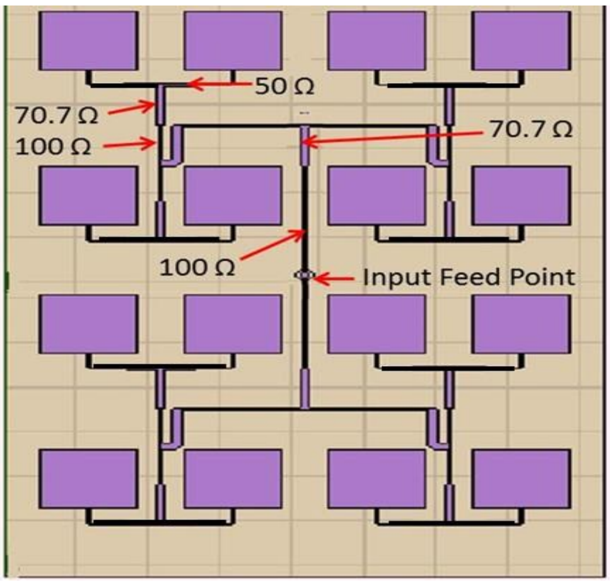

Fig. 3. The 4×4 patch array antenna structure with feed lines.

The results of this computation are presented in Table 2, which shows the illumination beamwidth for various inter-element spacing. As the spacing increases, the beamwidth decreases. Specifically, an inter-element spacing of 0.32λ (9.525 mm) yields an illumination beamwidth of 9.92°, meeting the design requirement of 10°.

A 4×4 patch array antenna with 16 elements and an inter-element spacing of 9.525 mm was designed and simulated using CST Microwave Studio. The antenna elements are fed using a corporate microstrip feed network [28], with a source impedance of 50 Ω.

Table 2. 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 final design configuration parameters are summarized in Table 3. The simulation results confirm that the estimated illumination beamwidth and other radiation performance parameters meet the design specifications for radar applications.

Table 3. 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

2.3.1. Simulation Analysis

The performance of the designed patch array antenna was simulated and studied using Computer Simulation Technology (CST) microwave studio software prior to fabrication [29, 30]. The simulation results show that the 4×4 patch array produces an illumination beamwidth of 10.37° with minimal side lobe as shown in Fig. 4. The radiation pattern, gain, directivity, and front-to-back ratio were analyzed to determine the antenna's efficiency at 10 GHz. The simulation results indicate a directivity of 19.35 dBi, F/B of 27.28 dB, and an antenna gain of 17.23 dBi. The array antenna radiation efficiency is 89.01% at the center frequency of operation as presented in Fig. 5. 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 of the 4 × 4 array antenna were carried out (see Fig. 6). The bandwidth of the patch array antenna appears broad at element spacing between 0.32λ to 0.54λ, which decreases with increase in the inter-element spacing above 0.54λ. The final simulation output of $|S_{11}|$ plots for the patch array is as shown in Fig 7. It is the $|S_{11}|$ simulation at inter-element spacing of 9.525 mm (0.33λ) which presents a wider bandwidth of 530 MHz, S_{11} value of -21.23 dB, and meets the set performance requirements of the array antenna for radar application in this study. From the graph in Fig. 7, the designed patch array antenna resonates at the operating frequency of 10 GHz, with a S_{11} of -21.23 dB, which is below -10 dB minimum return loss for wireless communication application, and good value for radar system applications.

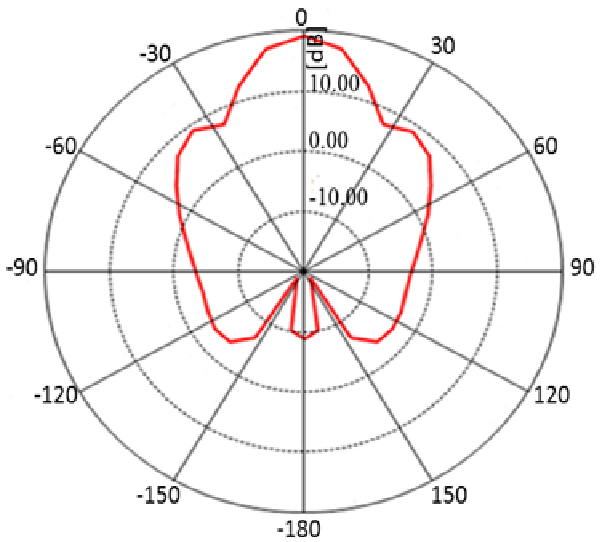

Fig. 4. Simulation plots of radiation pattern of the patch array antenna.

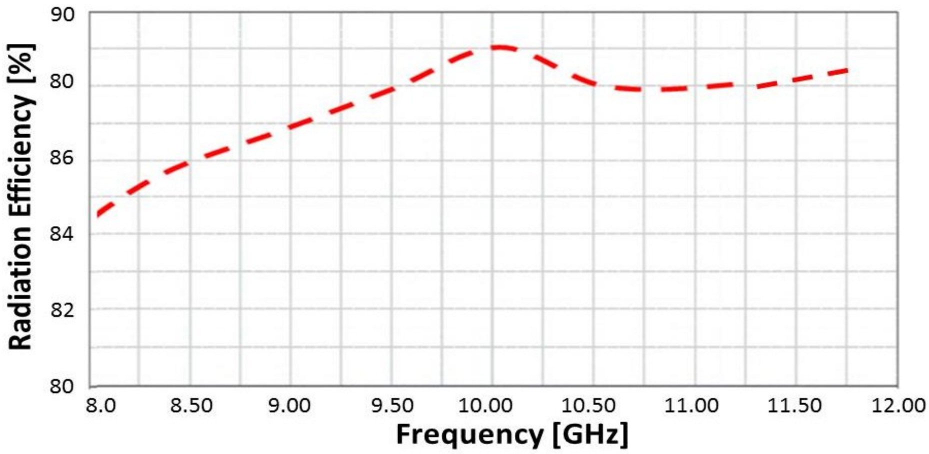

Fig. 5. Simulation plots of radiation efficiency of the patch array antenna.

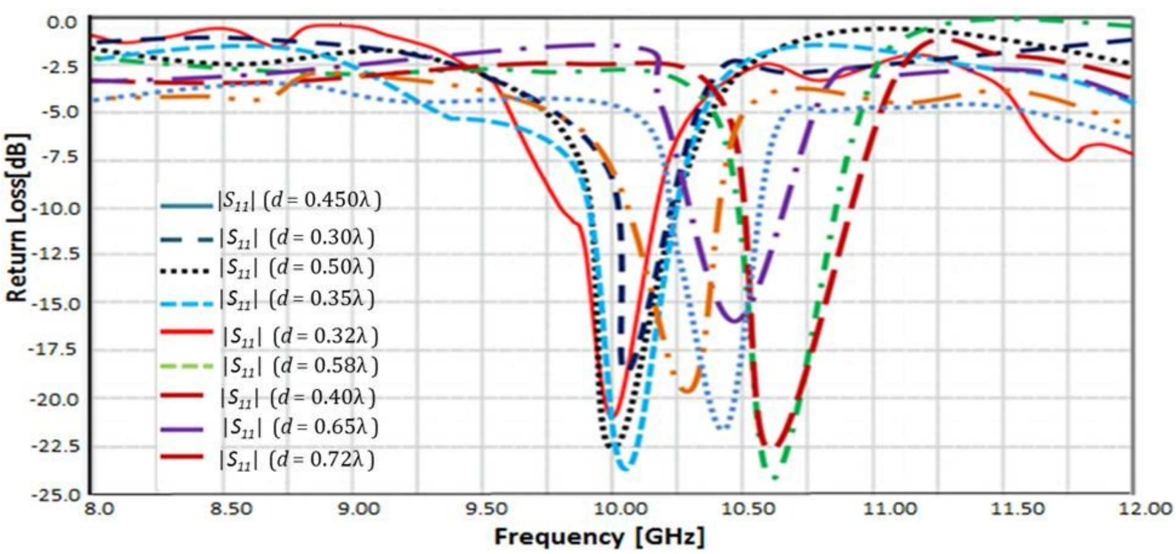

Fig. 6. Parametric analysis for feed point.

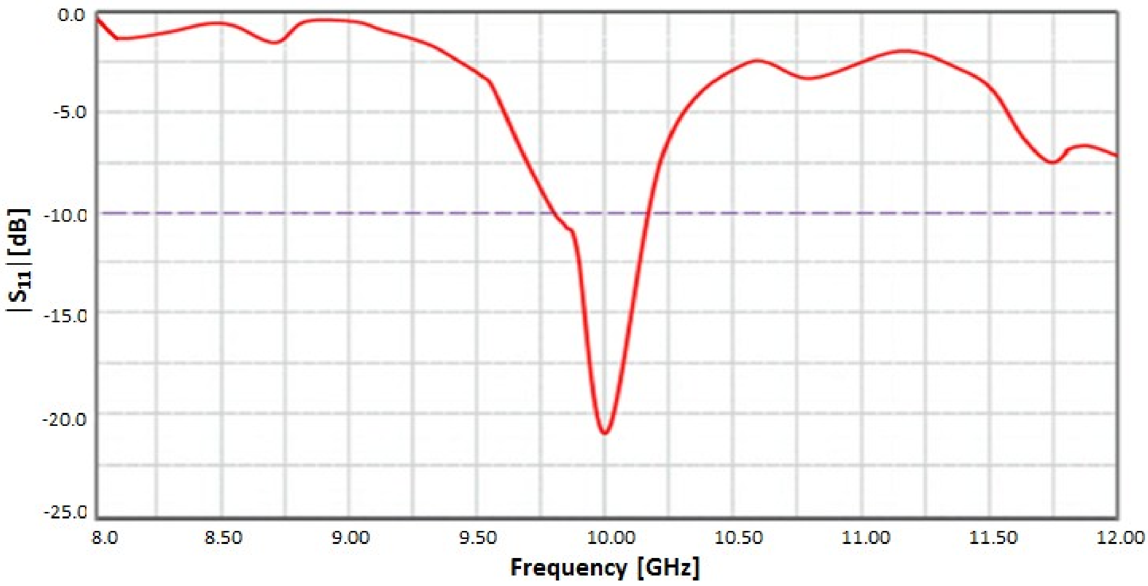

Fig. 7. Simulated $|S_{11}|$ at best inter-element spacing distance.

2.3.2. The Antenna Prototyping

The 4×4 patch antenna array was fabricated by employing local technique using precision photoengraving and chemical etching process on a copper board. Chemical etching is a process in which the unwanted metal region of the metallic layer is removed so that the intended design is obtained. A double-sided RT/Duroid 5880 copper board was used for prototyping. The main input is a 50 Ω coaxial cable male version, with a sub-miniature version A (SMA) female RF connector. The fabrication of patch antenna array at X-band was a challenging task. The wavelength (which is within the range of 25 to 37.5 mm in this project) determines the patch antenna structural size. The antenna fabrication becomes very challenging due to high fabrication tolerance of the microstrip lines within the patch elements. The patch elements and the microstrip lines of designed antenna were printed repeatedly using an ink jet printer to ensure the antenna footprint was thick and dark enough during toner transfer to the copper cladded board. The adopted printing and toner transfer methodology protected the microstrip feed lines as well as the patch elements during the copper etching procedure. The designed antenna transfer to the RT/5880 copper board starts by printing the black footprint of the antenna on a photo-resist transparent film with controlled dimensions.

Two chemicals were used, one for developing (Sodium Bicarbonate) and the other chemical (ferric chloride solution) for copper etching. The two chemicals were poured inside the appropriate baths. The etching chemical was heated for 20 minutes. The transparent film was cut a bit larger than the size of the ground plane of the antenna. Marks were drawn on both side of the copper-cladded substrate (double sided Rogers RT/Duroid 5880 in this project). Thereafter, the Rogers RT/Duroid 5880 material was cut at the marked dimensions. When the Rogers RT/Duroid 5880 was cut, the sticker was removed from one layer. The film was carefully attached to the top of the Rogers RT/Duroid 5880 dielectric material. The black section of the transparent film acted as a protective mask throughout the photo-exposure procedure. The masked area would retain its photoresist qualities and would shield the copper region from etching. The 'masked' Rogers RT/Duroid 5880 was exposed to UV-Light with the surface facing the light. The UV-light exposure lasted for approximately 2 minutes. The sticker was then removed from the ground plane of the substrate. The chemical process began by inserting the UV-light exposed RT/Duroid 5880 board in the bath that contains the developing chemical for 1 minute. The developed RT/Duroid 5880 board was washed under running tap water and thereafter inserted into the etching chemical to remove unwanted copper area exposed light rays.

The copper etching based on the design specifications took about 10 minutes. The etched RT/Duroid 5880 board was washed under running tap water as well to remove the photoresist from copper. Finally, after air drying, an RF SMA Connector was soldered at the feed point on the ground plane of the PCB; this was to be used as the connector to a network analyzer and feeder network (radar system).

The antenna was ready for measurements and performance tests to compare the measurements outcome with computer simulations. The weight of the fabricated antenna prototype was measured by a digital weight measuring balance/scale and the antenna weight of 0.13 kg was achieved. The fabricated prototype antenna is as shown in Fig. 8.

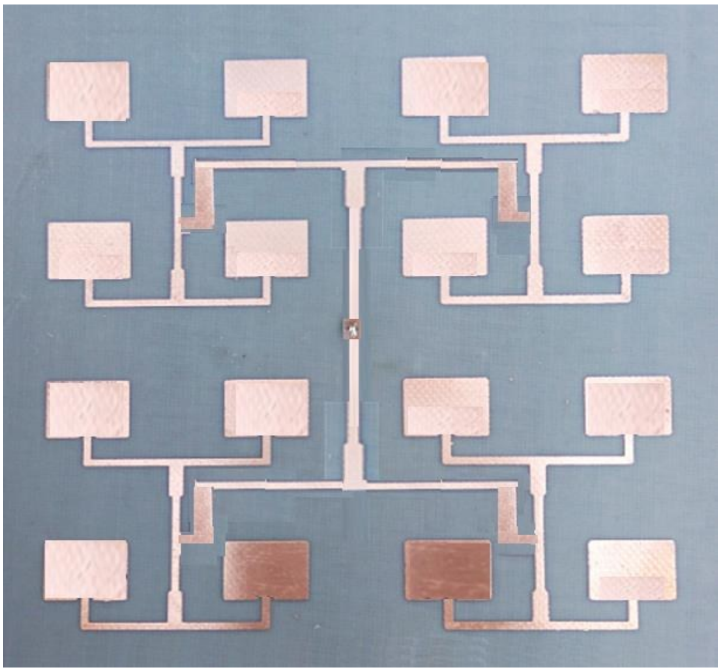

Fig. 8. Photograph of the Fabricated Prototype Antenna

2.4. Experimental Measurement

The validation of simulated antenna performance parameters though experimental measurement is a standard practice in antenna design. This verification is crucial to ensure the antenna performance accuracy, reliability, and actualization of the simulated design before the antenna fabrication and deployment.

The developed antenna prototype was subjected to relevant measurements. Its reflection coefficient, $|S_{11}|$ was measured with a vector network analyzer, VNA as shown in Fig. 9. The antenna reflection coefficient measurement was carried out at a center frequency of 10 GHz within the X-band.

The 4×4 patch array antenna operates with reflection coefficient value below -10 dB as indicated by Fig. 10. The photography of the radiation pattern measurement of the 4×4 array is shown in Fig. 11, and the measured and simulated plot is as shown in Fig. 12.

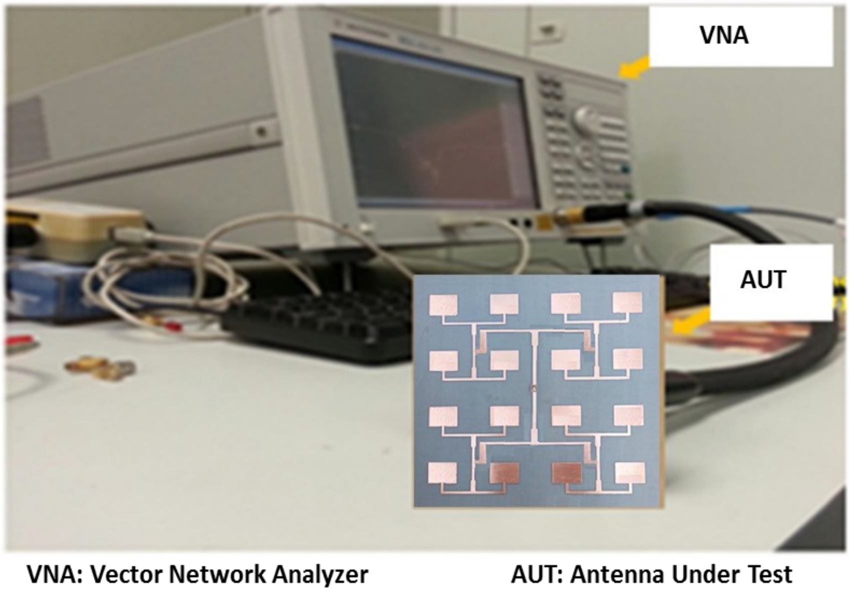

Fig. 9. Photograph of $|S_{11}|$ measurements.

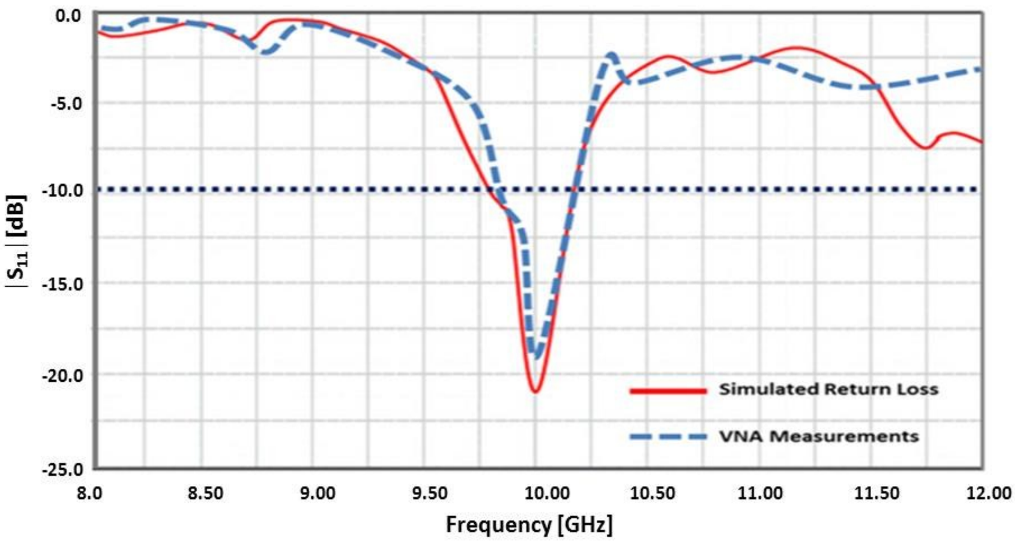

Fig. 10. Simulated and measured |S11|.

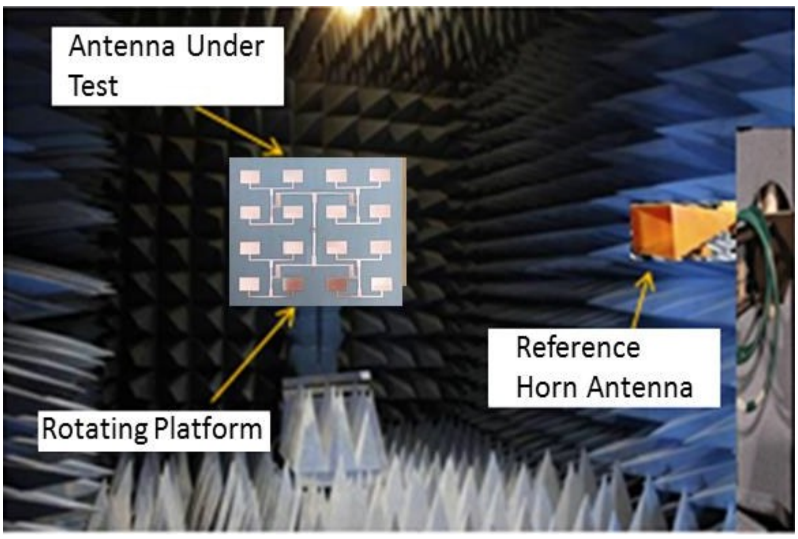

Fig. 11. Photograph of radiation pattern.

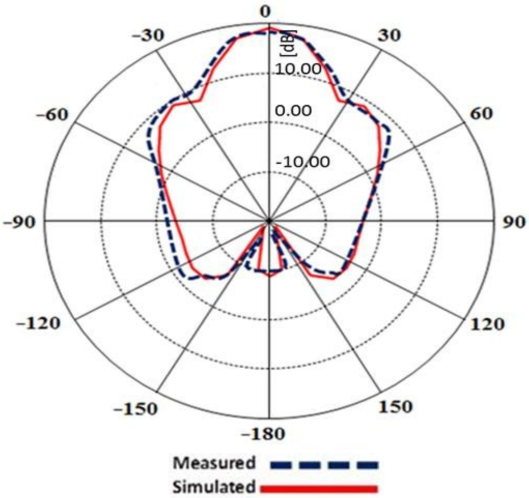

Fig. 12. Simulated and measured radiation pattern.

2.5. Field Test

This section presents the testing of the fabricated patch antenna array for radar system applications. The fabricated antenna was finally incorporated into the computer-controlled linear continuous-wave frequency modulated radar system. The fabricated radar antenna was experimentally tested for radar applications by monitoring ground distance covered by a moving car from outdoor experiments conducted 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 units: antenna stand, saloon car which has a size of 2.0 m × 1.5 m × 1.0 m, laptop computer, and the fabricated patch 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. In this experiment, the radar antenna was placed 1.3 m high pointing at the car to record the range as the car moved and stopped every 10 m over a coverage distance of 100 m. The scenario starts with the car moving at 25 km/h toward the antenna and stopped for 8 seconds at every coverage distance of 10 m toward the radar antenna until the car was 10 m toward the antenna as illustrated in Fig. 13.

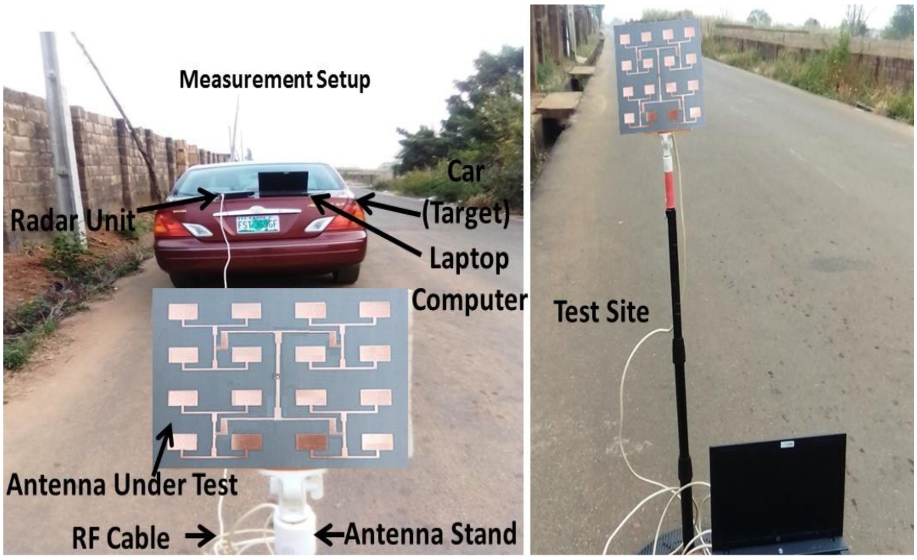

Fig. 13. Photograph of the field test.

3. RESULTS AND DISCUSSIONS

The designed 4×4 patch array antenna for X-band radar applications has been successfully simulated, fabricated, and tested, demonstrating its excellent performance characteristics. Table 4 shows a comparison of the simulated and measured results. These results make the antenna suitable for accurate target detection and tracking in radar systems. The observed numerical differences between the simulated and measured values could be due to fabrication errors, measurement and simulation settings, or cable loss in the measuring process. However, both simulation and measured results are in good comparison.

Table 4. The proposed 4×4 patch array antenna performance parameters.

Parameter	Simulated Value	Measured Value
Frequency Range	8 GHz – 12 GHz	8 GHz – 12 GHz
Resonant Frequency	10 GHz	10 GHz
Directivity	19.35 dBi	17.96 dBi
Beamwidth (HPBW)	10.37°	11.02°
Gain	17.23 dBi	15.48 dBi
-10 dB bandwidth	530 MHz	510MHz
S_{11}	-21.23 Db	-18.85 dB
Front-to-Back Ratio(F/B)	27.28 dB	26.03 dB
Radiation Efficiency	89.02%	86.17%

3.1. Simulated Results and Discussion

The gain of the simulated antenna is 17.23 dBi, and the directivity is 19.35 dBi. The gain and directivity enable efficient signal transmission and reception, and therefore the antenna can be used in radar systems. The gain and directivity are important parameters for antenna design since they influence the detection and tracking ability of the antenna. The antenna's radiation efficiency is 89.02% when simulated at 10 GHz, indicating effective power radiation. High radiation efficiency is required in radar applications such as precise detection and tracking of targets. Efficiency in radiation is an indication of the antenna's effectiveness in converting electrical power into power to be radiated.

The antenna has a broadside radiation direction pattern whose main lobe is oriented in the broadside direction (0°). The simulated 10.37° 3 dB beamwidth is suitable for radar applications where there is a need for high resolution and accuracy. The low side lobe level reduces interference and enhances the radar system's performance. The radiation pattern is a critical parameter for radar systems as it determines the ability of an antenna to detect and track targets.

The reflected simulated reflection coefficient (S_{11}) of -21.23 dB at 10 GHz indicates good impedance matching of the feed network and antenna. The S_{11} below -10 dB indicates the good performance of the antenna, and the wide bandwidth renders the antenna effectively operational within a wide range of frequencies. Reflection coefficient is an important parameter in designing an antenna because it affects the efficiency and bandwidth of the antenna. The simulated and measured value of F/B of the array antenna is 27.28 dB and 26.03 dB respectively. The Antenna Front-to-Back Ratio (F/B) is one of the metrics that are very critical in radar systems. The F/B is a measure of ability of the antenna to radiate energy in the forward direction while reducing radiation in the opposite direction. It can be expressed as the ratio of the power density in the broad forward direction to the power density in the backward direction. A typical F/B value for long-range directional antenna is between 15 dB to 30 dB [31, 32]. A high F/B indicates the radar system can detect and track targets more effectively and reduce unwanted interference or signal noise.

3.2. Measured Results and Discussion

Experimental findings support the antenna performance with good conformity with simulated values. -18.85 dB reflection coefficient and impedance bandwidth of 510 MHz measured clearly show the capability of the antenna to radiate and receive electromagnetic waves efficiently. The reading of -18.85 dB for S11 measured is better than the minimum required of -10 dB for most wireless applications. Measured 3 dB beamwidth was 11.02° (Horizontal-plane), gain and directivity was 15.48 dBi and 17.96 dBi respectively. The measured value of F/B of the array antenna was 26.03 dB, while radiation efficiency of the developed antenna model is 86.17%. Differences from the measurement and simulation results, if observed, can be caused due to simulation parameters, tolerance in fabrication and X-band alignment required. Experimental confirmation is an important element in the process of designing antennas as it confirms how the antenna behaves in real-life environments.

The small beamwidth, high directivity, and high gain of the antenna ensure precise target detection and tracking, while its low S_{11} ensures effective transmission and reception of the radio wave. The developed antenna is found to be deployable in car-speed detection and monitoring radar use.

3.3. Field Test Results and Discussion

The range of the ground covered by the car in motion was measured against time and the record graph is as shown in Fig. 14. Results of range measurements are presented in Tables 5 to 13. The field measurements conducted validate the applicability of the antenna in radar purposes with results showing a percentage error in measuring range of 4.21%. This relatively low percentage error shows the capability of the antenna for effective target detection and tracking in real-world implementation.

Field test result is a critical part of antenna design as it depicts the performance of the antenna when employed in real-life conditions. The outcome of this research proves the effective design, development, and testing of an X-band radar 4×4 patch array antenna. The antenna's performance parameters can be used for accurate detection and tracking of targets in radar systems.

The findings of this study have significant applications to the design of compact and lightweight radar systems, and subsequent studies can try to further optimize the design of the antenna and explore the possibility of using it in other fields.

The percentage measurement error was determined by the actual distance and distance covered by the vehicle if as shown in Eq. 10.

$$\text{Measurement Error (\%)} = \frac{\text{Actual Distance} - \text{Measured Distance}}{\text{Actual Distance}} \times 100 \tag{10}$$

The mean percentage range measurement error was arrived at by calculating the means of measurement error within the experiment as shown in Eq. 11.

$$\text{Range Measurement Error (\%)} = \frac{\text{Total Measurement Error}}{\text{Number of marked distance at every 10 meters}} \times 100 \quad (11)$$

$$\text{Range Measurement Error (\%)} = \frac{2.27+2.37+2.90+1.97+3.42+3.77+4.8+4.9+10.5}{9} = 4.21\%$$

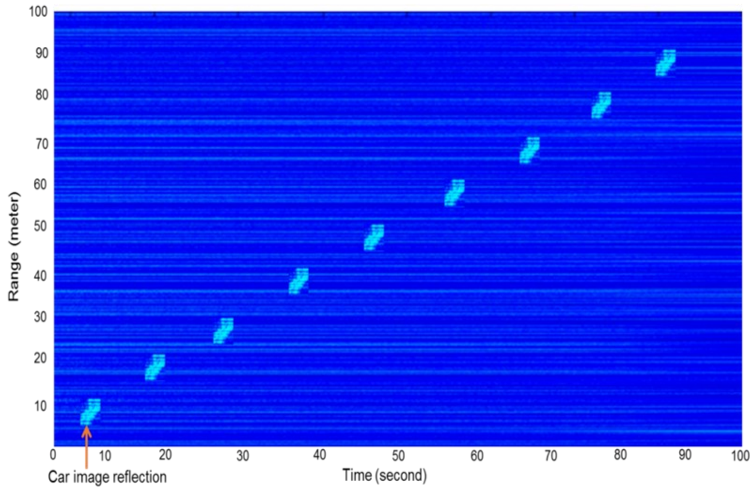

Fig. 14. Range measurement plot.

Table 5. The car at 90 meters toward the radar antenna.

Attempt	Actual Distance [m]	Measured Distance [m]	Measurement Error [%]
1st	90	87.94	2.29
2nd	90	88.11	2.10
3rd	90	87.81	2.43

Table 6. The car at 80 meters toward the radar antenna.

Attempt	Actual Distance [m]	Measured Distance [m]	Measurement Error [%]
1st	80	77.83	2.71
2nd	80	77.81	2.74
3rd	80	78.67	1.66

Table 7. The car at 70 meters toward the radar antenna.

Attempt	Actual Distance [m]	Measured Distance [m]	Measurement Error [%]
1st	70	68.07	2.76
2nd	70	68.01	2.84
3rd	70	67.83	3.10

Table 8. The car at 60 meters toward the radar antenna.

Attempt	Actual Distance [m]	Measured Distance [m]	Measurement Error [%]
1st	60	58.79	2.02
2nd	60	59.00	1.67
3rd	60	58.68	2.20

Table 9. The car at 50 meters toward the radar antenna.

Attempt	Actual Distance [m]	Measured Distance [m]	Measurement Error [%]
1st	50	48.54	2.92
2nd	50	48.04	3.92
3rd	50	48.30	3.40

Table 10. The car at 40 meters toward the radar antenna.

Attempt	Actual Distance [m]	Measured Distance [m]	Measurement Error [%]
1st	40	38.39	4.03
2nd	40	38.19	4.53
3rd	40	38.90	2.75

Table 11. The car at 30 meters toward the radar antenna.

Attempt	Actual Distance [m]	Measured Distance [m]	Measurement Error [%]
1st	30	28.97	3.43
2nd	30	28.50	5.00
3rd	30	28.21	5.97

Table 12. The car at 20 meters toward the radar antenna.

Attempt	Actual Distance [m]	Measured Distance [m]	Measurement Error [%]
1st	20	18.99	5.05
2nd	20	19.18	4.10
3rd	20	18.88	5.60

Table 13. The car at 10 meters toward the radar antenna.

Attempt	Actual Distance [m]	Measured Distance [m]	Measurement Error [%]
1st	10	8.87	11.30
2nd	10	9.02	9.80
3rd	10	8.92	10.80

4. CONCLUSIONS

In this research, a 4×4 patch array antenna in the X-band have been developed, experimentally characterized, and successfully tested for real-world medium-range target detection radar application. The proposed antenna attained a high gain, impedance bandwidth, and radiation efficiency. The experimental measurements and field test data have validated the target detection and tracking capability of the antenna with 4.21% measurement error. The low measurement error demonstrates the effectiveness of the proposed antenna for accurate target detection and tracking in real-world applications. The array antenna thus designed can be employed in surveillance, navigation, tracking and detection of the target. High gain and directivity of the antenna enable efficient transmission and reception of the signal, and hence are employed in radar applications where precise detection and tracking of the target needs to be done.

The Future research could investigate and develop strategies to mitigate any adverse effects of environmental factors, such as humidity, rainfall, atmospheric pressure, and on the antenna's performance. Advanced feed network design can also be considered to improve the antenna's impedance matching and reduce losses. Further study can also focus on reconfigurable patch antenna array in other frequency bands to enhance its versatility and functionality for emerging radar and communication systems.

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