Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 12, No. 2, June 2024, pp. 307~318
ISSN: 2089-3272, DOI: 10.52549/ijeei.v12i2.5512

A 76 GHz Millimeter-Wave Marine Radar Antenna Design

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Article Info

Article history:

Received Mar 25, 2024
Revised May 5, 2024
Accepted May 14, 2024

Keywords:

Antenna array
Dolph-Chebyshev
Millimeter-wave
Microstrip antenna
Radar

ABSTRACT

In this work, a 76 GHz microstrip antenna array is proposed for usage in the mm-wave Marine radar application. Millimeter-wave radars are commonly used in automotive applications and a lot of effort is made in this way but it is also can be used in marine applications as they work robustly in bad weather conditions such as fog, dust, smog, smoke, and water vapor. So, it will be very helpful in marine applications. The proposed array antenna is a corporate Series feed 24×8 antenna array that has achieved a return loss of -26.4 dB, a gain of 23.5dBi, bandwidth of 5.2 GHz, and sidelobe levels of -21.4 dB in H-plane and -14 dB in E-plane. This antenna array's 3dB angular width equals 10.9 ° in the H-plane and 5.9 ° in the E-plane. That makes it a suitable choice for the mm-wave marine radar antenna. The final design of the antenna is acceptable compared with another previous work, making this design more considerable as will be shown. Also, an antenna array with 3 transmitters and 4 receivers is presented. Each antenna is a 24-element. the Dolph-Chebyshev technique is utilized to taper the patches. The antenna has been manufactured, and the results of the simulation are confirmed by the experimental measurements.

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1. INTRODUCTION

Applications for millimeter wave technology in communications and sensing have grown recently [1, 2]. most efforts in the mm-wave radar application were in Automotive applications for collision detection and avoidance systems in vehicles. Automotive Long-Range Radar (LRR) is designated to operate in the frequency between 76 to 77 GHz, while Medium Range Radar (MRR) and Short-Range Radar (SRR) are to operate in the frequency range between 77 to 81 GHz. They are used for blind-spot detection (BSD), adaptive cruise control (ACC), and cross-traffic alert (CTA) [3, 4]. The main advantage of short-range E-band (76 GHz) marine radar is the complete absence of a blind spot. It can be used as collision avoidance radar that can precisely measure the radial distance and velocity of closed vessels. it will be a very effective assisting tool in the mooring and towing of ships and tugs. E-band radars can be installed not only onboard ships but also on port berths for vessel traffic service operated by the harbor or port authorities. This will allow 24×7 monitoring of port area waters for the position of ships in the harbor, and movements of vessels when approaching the berths, including assisting in the mooring and towing of ships and barges. Because of all the last reasons we chose to present an mm-wave antenna that can be used in marine applications. The resolution of E-band (76 GHz) marine radar is much better than existing S-band (3 GHz) and X-band (9 GHz) marine radar systems and even better than the latest K-band (24 GHz) radars in terms of range and angle resolution for the near obstacles. Designing antennas in the millimeter wave band is a big challenge [5], it requires careful consideration of a variety of factors, including frequency, attenuation, beamwidth, and sensitivity to fabrication tolerances.

2. ANTENNA DESIGN

2.1. Single Element Patch Antenna Design

This work aims to construct an antenna array suitable for integration into a low-profile mm-wave naval radar application operating at 76 GHz. Because its features are suited for high frequency, thick Rogers RO3003 with ε_r = 3 and height h = 0.13 mm was chosen as a suitable substrate. Copper with a thickness of 0.035mm is used for the ground and radiating patch. For this system antenna array with a low SLL, Flat gain along the required band, high gain, low cost for mass production, and narrow beam width is considered to be a good choice. Therefore, the series feed microstrip antenna array is still the most important solution in mm-wave radar applications. The technique transmission line model was used to design the microstrip rectangular patch antenna as it has high accuracy and perfect numerical efficiency. By the following classical equations [6] the antenna patches are designed using CST software.

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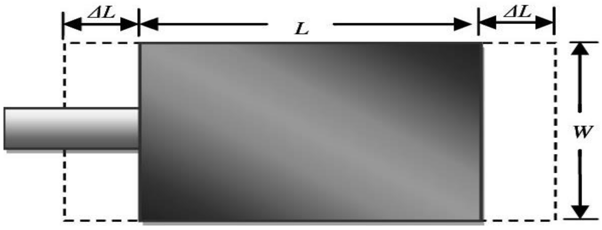


Figure 1. The Physical and effective lengths of a rectangle patch antenna

First, determine the patch width (W_p):

$$W_p = \frac{C}{2fo\sqrt{\frac{\varepsilon r+1}{2}}} \tag{1}$$

Where C = 3×10^8 m/s, εr = 3 is the relative permittivity, and f_o=76 GHz is the resonance frequency. To get the patch antenna's length, we must first determine the effective dielectric constant εr_{eff} and the length extension ΔL. εr_{eff} can be calculated using the next formula:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} * \frac{1}{\sqrt{1+\frac{12h}{Wp}}} \tag{2}$$

Where W_p is the patch width and h is the substrate thickness. ΔL_P is obtained by the next formula:

$$\Delta L_P = 0.412h\left[\frac{(\varepsilon_{reff} + 0.3)(\frac{W_P}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W_P}{h} + 0.813)}\right] \tag{3}$$

Now we can find the patch antenna's length (L_p)

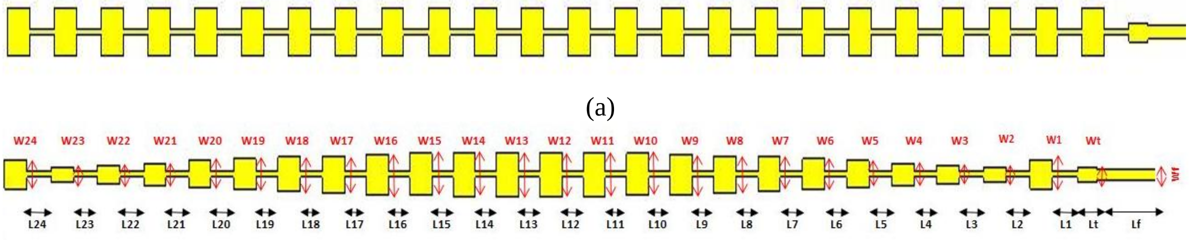
$$L_p = \frac{C}{2fo\sqrt{\varepsilon_{reff}}} - 2\Delta L_P \tag{4}$$

2.2. Series Feed Linear Antenna Array Design

In this design, the number of elements increased to 24 patches to obtain high gain and HPBW with narrow value. To keep up the radiation in the broadside direction, the series-fed array elements should be in progressive phases, therefore the distance between adjacent patches must be around one guided wavelength (λg) at 76 GHz. According to equation (5), the λg is 2.28 mm. The final dimensions of the sub-array are given in Table 1.

$$\lambda_g = \frac{C}{f\sqrt{\varepsilon_r}} \tag{5}$$

An antenna array can obtain low SLL if array elements are excited with a specified amplitude distribution. The amplitude coefficients can be controlled by altering the widths of patches, space between patches, or both together. In this design, the widths of patch elements (*W1- W24*), the inter-element spacing (*L1- L24*), and the impedance transform size (W_t, L_t) will be optimized to obtain the required results. As shown in Figure 2.



(a)

(b)

Figure 2. The proposed antenna design (a) Conventional design (b) Design with -25 dB Dolph-Chebyshev

By applying the -25 dB Dolph-Chebyshev distribution [7] in the array magnitude coefficients. The amplitude distribution is derived as 1: 0.983: 0.951: 0.904: 0.843: 0.772: 0.693: 0.609: 0.522: 0.436: 0.352: 0.645. The width of patches is designed nearly according to the choice of the above amplitude distribution. In the beginning, the width of the central patch is calculated according to the working frequency and the dielectric constant Then the width of the other patches is varied due to the derived amplitude distribution before. The tapering of the patches affects the radiation of the element [8]. Moreover, the power passing through the element is decreased with the increase in distance between the element and the source. So amplitudes of symmetrical patches are not equal even if the widths of patches are the same.

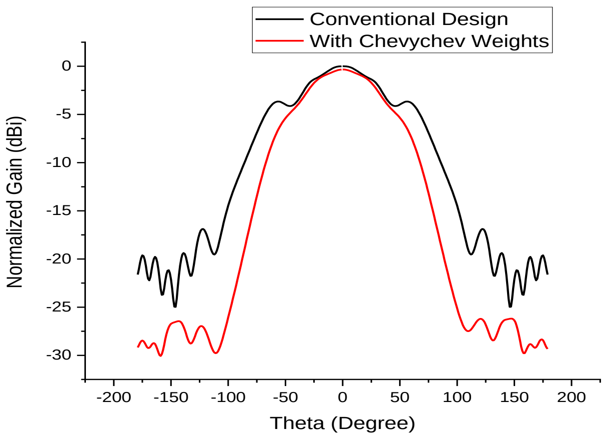


Figure 3. The significant effect of Chebyshev Distribution on the side lobe level reduction

the parametric sweep optimization tool in CST simulation software was used to optimize and tune the excitation amplitude coefficients of the patches to obtain a perfect radiation pattern. Finally, to obtain a good impedance matching a Quarter-Wavelength transformer is added. The significant effect of Chebyshev Distribution on the side lobe level reduction is shown in Figure 3.

Table 1. Dimensions of the proposed antenna element (Units: mm).

Par.	Value	Par.	Value	Par.	Value	Par.	Value
W1	0.867	*W24*	0.867	*L1*	1.25	*L24*	1.23
W2	0.47	*W23*	0.47	*L2*	1.2	*L23*	1.18
W3	0.586	*W22*	0.586	*L3*	1.2	*L22*	1.18
W4	0.701	*W21*	0.701	*L4*	1.14	*L21*	1.13
W5	0.818	*W20*	0.818	*L5*	1.14	*L20*	1.13
W6	0.93	*W19*	0.93	*L6*	1.1	*L19*	1.09
W7	1.04	*W18*	1.04	*L7*	1.1	*L18*	1.09
W8	1.13	*W17*	1.13	*L8*	1.09	*L17*	1.08
W9	1.214	*W16*	1.214	*L9*	1.07	*L16*	1.06
W10	1.277	*W15*	1.277	*L10*	1.05	*L15*	1.045
W11	1.32	*W14*	1.32	*L11*	1.05	*L14*	1.045
W12	1.343	*W13*	1.343	*L12*	1.05	*L13*	1.045
Wt	0.44	*Lt*	0.95	*lp*	1.1	*Wf*	0.321

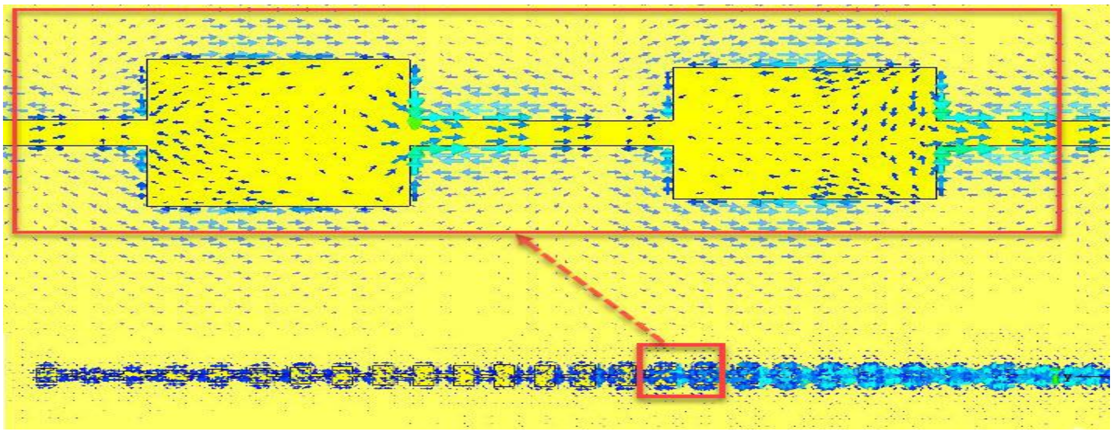


Figure 4. The current surface of the proposed antenna at 76 GHz

The current distribution for the presented array antenna at an intended frequency 76 GHz is shown in Figure 4 From these results, the current distributions are collected around the radiating elements which confirms its responsibility for the radiation.

2.3. Applying Side Reflector for Results Enhancement

The values obtained in terms of SLL, Gain, and angular width need some optimizations to be suitable for use as mm-wave Radars As these parameters are very important in the antenna design in radar systems. Antenna Reflectors can be added as shown in Figure 5 to improve the design in terms of gain, SLL, and angular width at the H-plane as shown in Table 2.

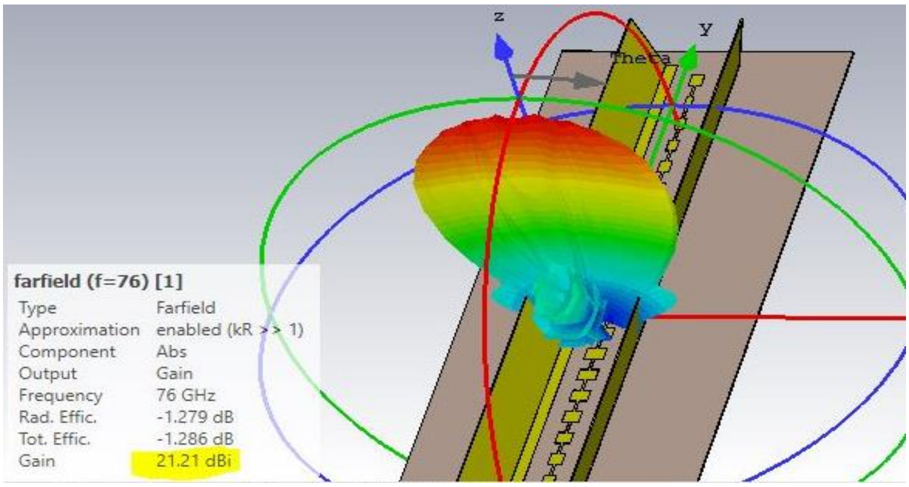


Figure 5. Adding a reflector to improve gain and SLL

Table 2. Comparison between the conventional design and with reflectors at different angles

	Without reflector	With Reflector at Angle 30	With Reflector at Angle 15	With Reflector at Angle 45
S_{11} (dB)	-29 dB	-35 dB	-35 dB	-33 dB
Bandwidth	3 GHz	3 GHz	3 GHz	3 GHz
Gain	18.06 dBi	22 dBi	21.21 dBi	20 dBi
Angular width	5.2 ° in E-plane 68.2 ° in H-plane	5.1 ° in E-plane 26° in H-plane	5.2 ° in E-plane 33.6 ° in H-plane	5 ° in E-plane 50 ° in H-plane
SLL (dB)	-19.2 in E-plane -29.8 in H-plane	-19.8 in E-plane -32.4 in H-plane	-19.1 in E-plane -27.8 in H-plane	-19.8 in E-plane -32.5 in H-plane

As shown in Table 2, Adding a reflector can significantly improve Gain, SLL, and 3dB Angular width in the H-plane While maintaining S_{11}, bandwidth, and Angular width in the E-plane are nearly the same. There is a great change in the Angular beam width in the H-plane, The Reflector with an Angle of 30° gives the best one as shown in Figure 6.

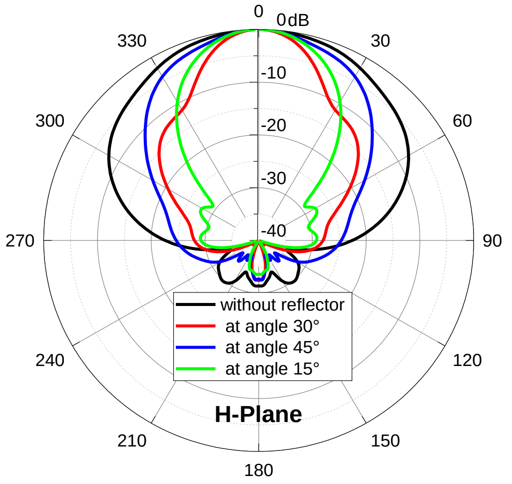


Figure 6. Beamwidth comparison at different angles of antenna reflectors

We Can also see the SLL Comparison in H-plane at different reflector angles in Figure 7.

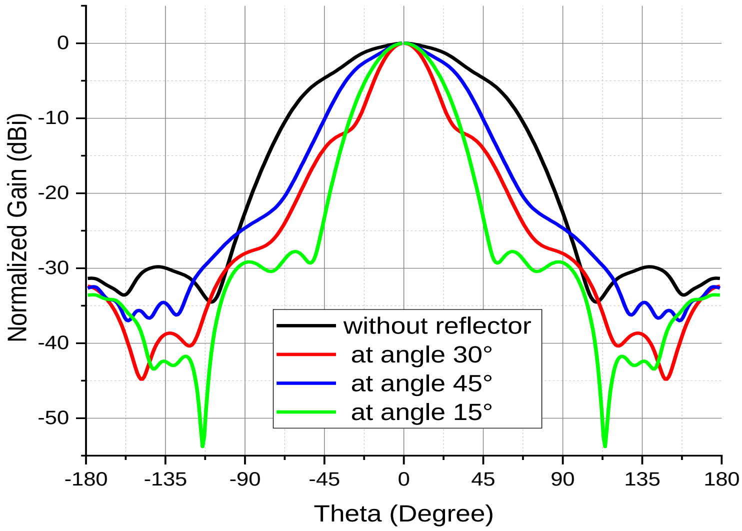


Figure 7. SLL comparison at different angles of antenna reflectors

A design of the array antenna with a reflector of Angle 30° gives the best angular beam width in the H-plane, the best gain, and acceptable SLL, this antenna can be used in FMCW radar to measure the range, velocity, and angle of arrival of objects. Also, it can be used within a Radom and motorized system to scan 360 degrees to obtain objects' angles according to the radar position.

3. CORPORATE SERIES FEED 8×24 ANTENNA ARRAY DESIGN

3.1. Feeding Network Design

To install the Corporate Series feed 24x8 Antenna Array, a full-corporate feeding network must be designed. The designed eight-way series feeding network is explained in Figure 8 where P donates power flow. To decrease the SLL in the H-plane, unequal power distribution is applied in the feeding network. The power ratio of 0.125:0.25:0.5:1:1:0.5:0.25:0.125 can be achieved Through an equal cascading power divider, which is sufficient to make the value of SLL less than -20 dB at 76 GHz. The output ports feeding network also has a progressive phase they also should be spaced about one λg.

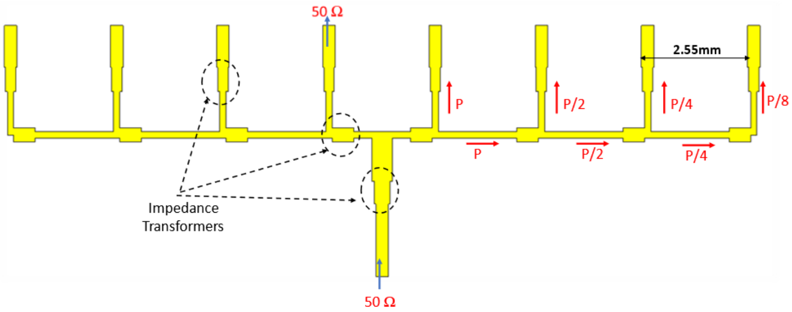


Figure 8. The geometry of the designed eight-way series feeding network

3.2. Antenna Array Design

Radars in the mm-wave band are generally small in size because of the high frequency, in the marine industry because of the huge size of the vessels and marine boats, the limitation on radar size is less than in the automotive. So, in this study, the 24×8 corporate feed series tapered antenna array for LRR mm-wave marine radar has been adopted as shown in Figure 9 there is a good bandwidth Enhancement and sidelobe suppression. This antenna can achieve a gain of 23.5 dBi, and sidelobe levels of -21.4 dB in the H-plane and -14dB in the E-plane. The 3dB angular width of this antenna is equal to 10.9 ° in the H-plane and 5.9 ° in the E-plane as shown in figure 10 (a). The results of the simulated reflection coefficients in the CST and HFSS simulation programs are reasonably similar and satisfied as shown in Figure 10 (b) with a -10 dB bandwidth of 5.2 GHz. There is a good enhancement in -10dB impedance bandwidth in comparison with the series feed 1×24 antenna design.

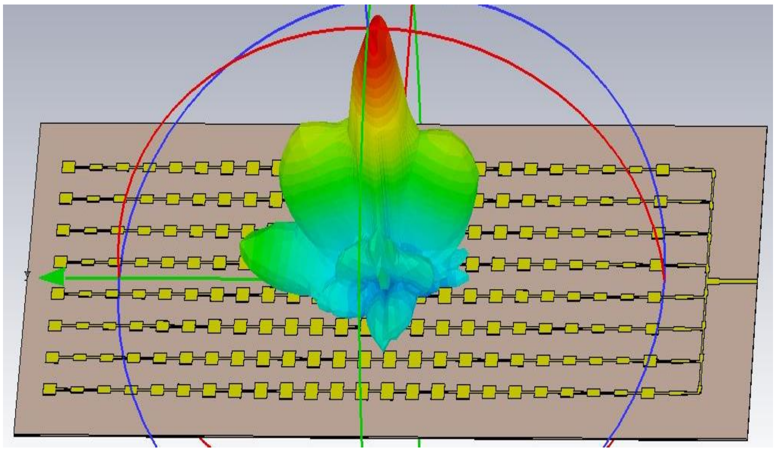
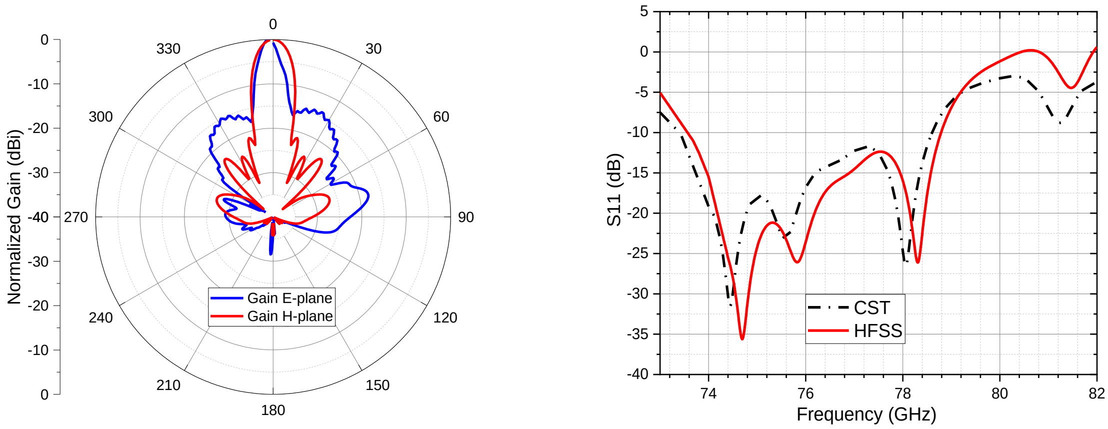


Figure 9. Designed Corporate Series feed 24×8 Antenna Array 3D Radiation Pattern



(a) (b)

Figure 10. The designed Corporate Series feed 24×8 Antenna Array (a) Normalized Gain at H-plane and E-plane (b) S_{11} in both CST and HFSS simulation programs

The great enhancement in the beamwidth is observed in Figure 11 between the series 1×24 array and Corporate Series feed 24×8 array design even by adding a reflector. The beam width in the H-plane optimized from 68.2° to 10.9° which is a critical parameter in mm-wave radar antenna, also the gain increased from 18.06 dBi to 23.5dBi.

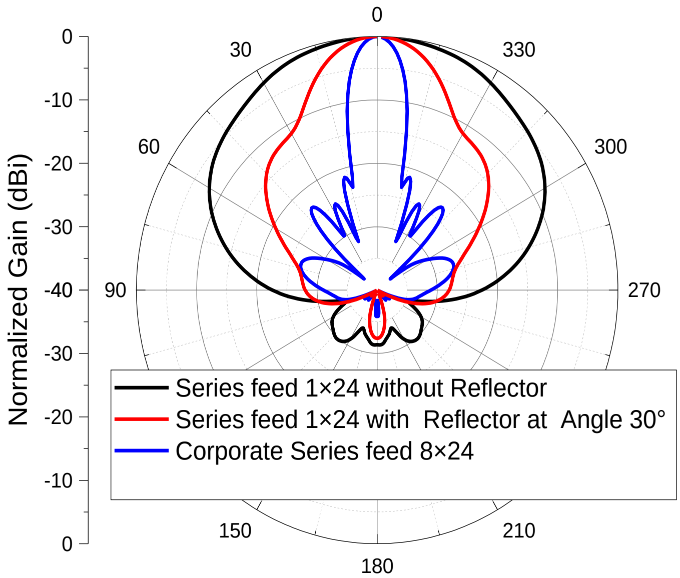


Figure 11. Beamwidth comparison between series feed 1×24 and corporate series feed 8×24 array design

4. ANTENNA FABRICATION AND MEASUREMENTS

4.1. Series Feed Planar Antenna Array Design

Mm-wave radar with Frequency-modulated continuous wave (FMCW) requires at least 2 receivers for the angle of arrival estimation. When two antennas are placed *d* distances apart, the largest field of view is $\theta^{max}=sin^{-1}(\lambda/2d)$, and when d equals $\lambda/2$ results in the largest field of view (±90˚).

Measuring the angle of arrival of many objects at the same range and velocity requires an array of *N* receive antennas, the angle resolution increased by increasing the number of elements. Angle resolution is given by $\theta^{res}=\lambda/Ndcos(\theta)$. the space between receive and transmit antennas is all $0.5\lambda_0$, where λ_0 is the free space wavelength at 76 GHz as shown in Figure 12. This model is very common in the mm-wave antenna design so, it has been chosen for the fabrication process.

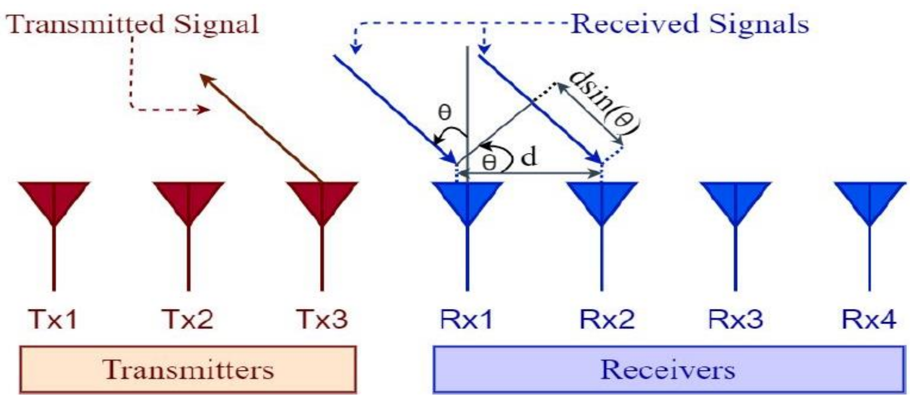


Figure 12. Mm-wave Angle of arrival estimation [8]

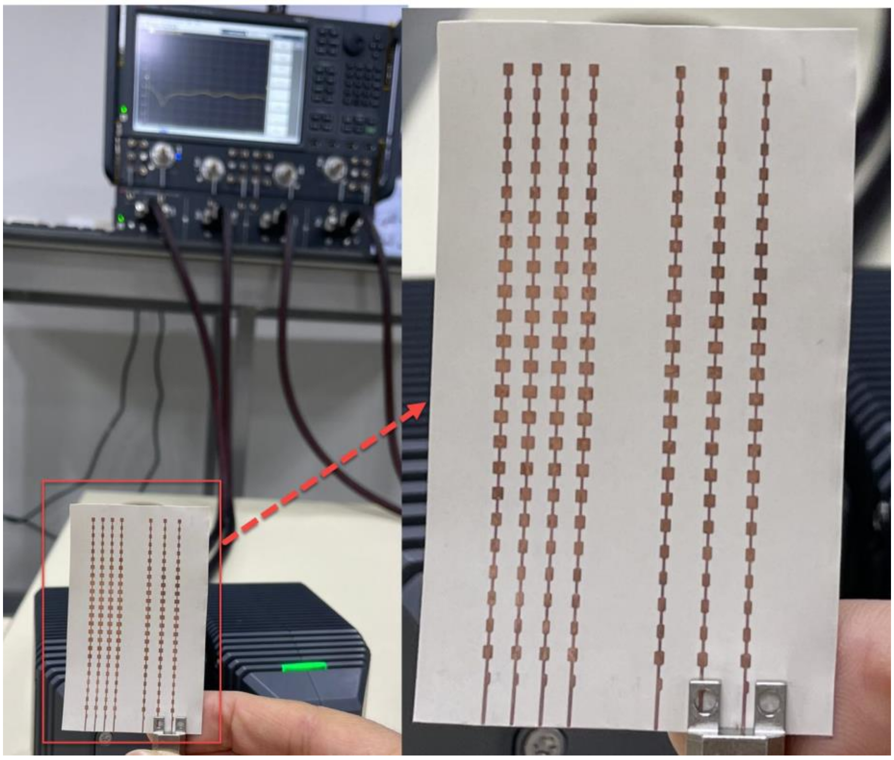


Figure 13. The fabricated antenna in the vector network analyzer (VNA)

The photograph of the fabricated antenna is shown in Figure 13. From left to right, marked as Rx4, Rx3, Rx2, Rx1, Tx3, Tx2, Tx1.

4.2. Return Loss

The launcher connector is used with the vector network analyzer (VNA) model (N5244B) for measuring the performance of the fabricated antenna as shown in Figure 13. Figure 14 shows the measured and simulated results of the S_{11} for Tx1 as a sample of measurement. There is a slight shift of the 76 GHz resonant frequency. The experimentally measured bandwidth is wider than the simulated, which may be due to the huge of the measuring connector compared with the antenna size, improper measurement, fabrication processes, connector losses, or material quality, but finally, the results of the measured and simulated reflection coefficients are reasonably similar as satisfied.

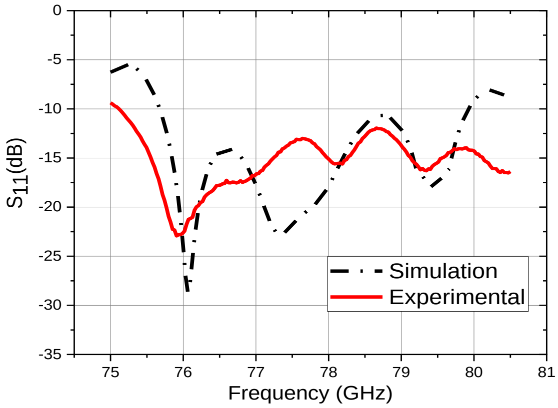


Figure 14. The measured and simulated S_{11} of the proposed array antenna

4.3. Radiation Patterns

The far-field radiation pattern of the fabricated antenna is measured experimentally by using a vector network analyzer (keysight N5244B) with the broadband frequency extender (keysight N5293AX01)and horn antenna (LB-12-20-C-1.0F) inside anechoic chamber size 2x2x2 mts as shown in Figure 15.

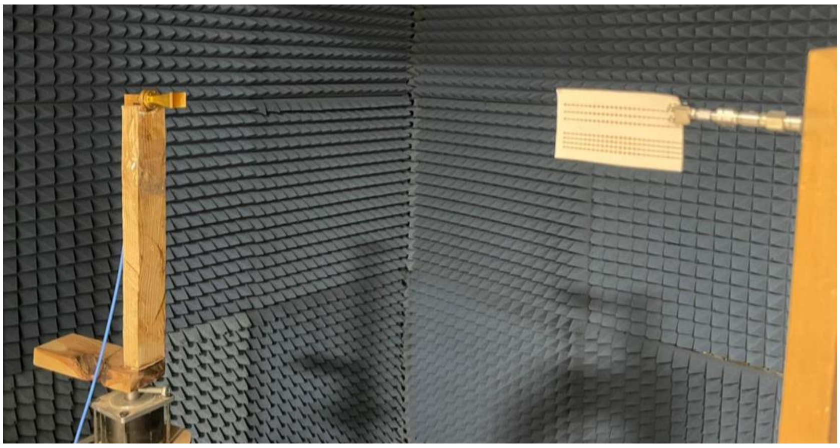


Figure 15. Experimental setup for the far-field radiation pattern of the fabricated antenna

The antenna maximum gain is measured experimentally as in Figure 16 and compared with the simulated gain showing good agreement with the simulation results.

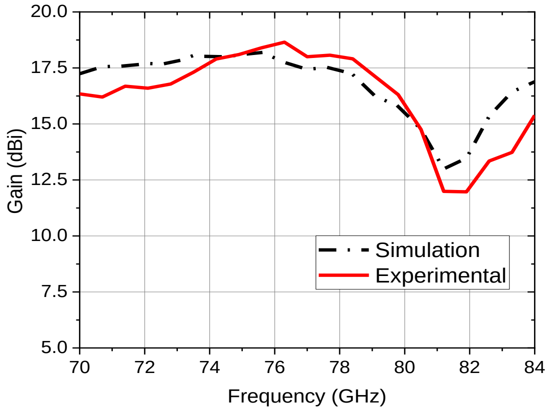
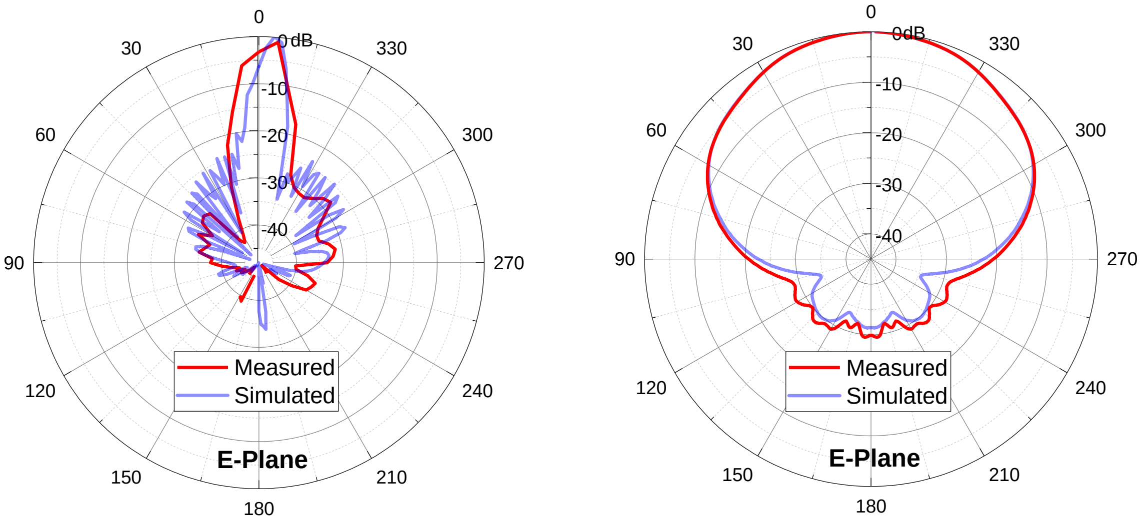


Figure 16. The measured and simulated gain versus frequency

Also, the two principal plane radiation patterns are measured and compared to the ones calculated numerically using the CST. Figure 17 shows a good agreement and ensures results.



(a) (b)

Figure 17. Measured and simulated patterns of the far-field radiated (a) E-Plane and (b) H-Plane

5. DISCUSSION

Radars in the mm-wave band are generally common in automotive applications, but it is rare to find them in marine applications published in research. So the novelty of this paper is to explain the variety of applications of the mm-wave radar in marine and design a radar antenna with superior characteristics in comparison with others used in automotive as shown in Table 3 also with good characteristics in comparison to the commonly industrial marine radars that work in X-band as shown in Table 4.

Table 3 compares this work with other published work of microstrip patch antenna arrays in the same band, it is considerable to obtain high gain while maintaining other parameters such as -10 dB bandwidth, angular width, and SLL with satisfied value. The design in [9]with same high gain as the proposed design but it uses a pyramidal horn and a dielectric lens to obtain this high gain also our design is best in terms of SLL and gain at h-plane. In [14] the SLL with good values in the two planes and the other results are accepted but the -10 dB bandwidth is not confirmed and the return loss is a weak value equal to -12.5 dB. The 79 GHz linear array described in [11] has good performance in terms of gain, SLLand wide bandwidth by using parasitic patches on the top layer to achieve a broader bandwidth, but this method is not accepted for usage in radar antenna.

The comparison shows that the quality of the proposed design in terms of the beam width in the H-plane and E-plane at the same time is better than others, So the designed antenna is very suitable for radar sensor applications.

Table 3. Comparison with the previous work

Ref.	No of Elements	Size (MM)	Freq (GHz)	-10 dB Band Width	Gain dBi	Angular width		SLL (dB)	
						E-plane	H-plane	E-plane	H-plane
[9]	20×8	19×47	77	4 GHz	23.5	4.5 °	16 °	-16.3	-18.8
[10]	12×4	-	77	-	19.1	8 °	25 °	-18	-
[11]	6×8	21×31	79	4.41 GHz	22	13.22 °	10.17 °	-19	-17
[12]	10×6	-	79	3 GHz	21	-	-	-24	-23
[13]	10×6	-	77	4.85 GHz	20	-	-	-15	-
[14]	18×8	58×23	77	-	19.67	4.36 °	15.26°	-25.08	-20.19
[15]	6×8	50×30	77	5.91GHz		15.63°	13.6 °	-20.15	-15
This work	24×8	60×25	76	5.2 GHz	23.5	5.9 °	10.9 °	-14	-21.4

Also, our antenna design is compared with already existing X-band common industrial marine radars in Table 4 which shows a good antenna result.

Table 4. Comparison with the already existing X-band common industrial marine radar

MAKER	This work	FURUNO (JAPAN) [16]	ICOM (JAPAN) [17]	SIMRAD (Norway) [18]
MODEL		DRS4D-NXT	MR-1010	HALO20
Frequency (GHz)	76 GHz (E-band)	9 GHz (X-band)	9 GHz (X-band)	9 GHz (X-band)
-10 dB Bandwidth	5.2 GHz	60 MHZ	60 MHZ	48 MHZ
Gain	23.5 dBi	-	-	-
Beam Width (3dB) Vertical	10.9 °	25 °	22 °	25 °
Beam Width (3dB) Horizontal	5.9 °	3.9 °	4 °	4.9 °
SLL(in E plane)	-21.4 dB	-24 dB	-22 dB	-23 dB

6. CONCLUSION

A 24-element series feed microstrip patch array has been designed at 76GHz.the design optimized by Appling -25 dB Dolph-Chebyshev distribution significantly increases the reduction on the side lobe level. Adding reflectors significantly improved Gain, SLL, and 3dB Angular width in the H-plane. the design with 3 transmitters and 4 receivers is presented to be used as an FMCW radar for Angle of arrival estimation. the proposed antenna has been fabricated for verification of the S_{11} and radiation pattern in the E-plane and H-plane. Finally Corporate Series feed 24×8 Antenna Array is presented to achieve a gain of 23.5 dBi, bandwidth of 5.2 GHz, and sidelobe levels of -21.4 dB in H-plane and -14dB in E-plane, 3dB angular width of 10.9 ° in H-plane and 5.9 ° in E-plane. These attractive features allow this enhanced design to be used as a millimeter-wave radar antenna in marine applications.

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