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Analysis and Design of 79 GHz Patch Antenna Array for Radar Applications

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ABSTRACT

Nearly 10 years ago, the 79 GHz band was utilized in automotive radar applications. In difficult conditions, this frequency band improves the ability and accuracy of target detection. This work presents a good design for a key component of the radar sensor. It maintains the performance parameters needed for mm-wave radar and Internet-of-Things applications (IoT). We present a single patch antenna, 1x4 and 1x8 series feed patch antenna array that operates at the 79 GHz band by using an inset-feed line feeding technique that is one of the most popular techniques for perfect matching. The simulated results were obtained by two different software programs CST microwave studio 2020 and Ansys HFSS 2021. These software packages are basically different and used for confirming the results. these results include the return loss, voltage standing wave ratio, Band Width, Gain, Directivity, and Efficiency. A new technique has been used to optimize the bandwidth and overcome one of the most popular weaknesses of the series array microstrip antenna. The proposed design's good results make it appropriate for medium-range and short-range radar in the 77-81 GHz frequency band. The antenna is fabricated, and the simulated results are validated by the experimental measurements.

1. Introduction

Microstrip patch antennas have played an important role in wireless communication due to their advantages like as low fabrication cost, low profile, simplicity of integration with the integrated circuit, and Antenna-In-Package (AIP) technology. As shown in Fig 1, it is made up of a radiating patch of a conducting material such as copper on one side of a dielectric material(substrate) and a ground plane on the other. Microstrip array antennas are in high demand in a variety of communications and radar systems. They're employed to create a pattern that can't be accomplished with just one element [1]. They're also utilized to scan an antenna system's beam, boost directivity, and do a variety of other tasks that would be difficult with a single element. These elements can be fed with a single line which is known as a series-feed arrangement or fed by multiple lines in a feed network arrangement which is known as a corporate-feed arrangement [2].

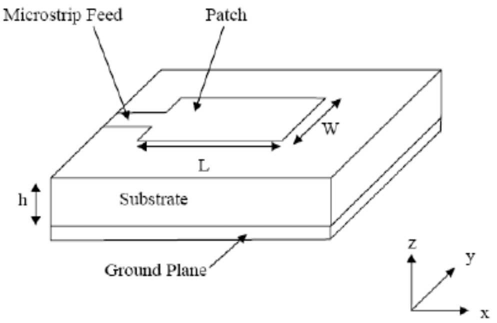

Fig. 1. Geometry of microstrip patch antenna [1]

The remainder of the paper is laid out as follows:
The second section defines all of the equations that were used to obtain the results, Clarify the different techniques of feeding and feeding network types.

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In Section three single-element patch antenna with its parameter such as return loss, bandwidth, gain and directivity will be clarified. In section four Series fed antenna array design 1x4 will be presented and compared with the results of the single patch design. Also, bandwidth optimization will be presented and compared with results without optimization. In Section five 1x8 Series fed antenna array design will be presented with more satisfactory results. In section six the proposed antenna has been fabricated for verification. Finally, in conclusion, we analyze the results and explore the benefits of this solution.

2. Antenna Calculations

The goal of this paper is to build an antenna array that can be integrated into a low-profile radar that operates at 79 GHz and is used in mm-wave radar applications. Because its features are suited for high-frequency, a thick Rogers RO3003 with $\varepsilon_r = 3$ 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.

2.1. Width calculations:

We use numerous formulas [2] to calculate the dimensions of this antenna. First, determine the width (Wp):

$$W_p = \frac{c}{2fo\sqrt{\frac{\varepsilon r+1}{2}}}\frac{c}{2fo\sqrt{\frac{\varepsilon r+1}{2}}} \qquad (1)$$

where:

- c: is the speed of light in free space, $c = 3\times10^8$ m/s
- ε_r: relative permittivity, $\varepsilon_r = 3$
- f_o: The resonance frequency, f_o=79 GHz.

As seen below, the ground plane width W_g is related to the patch width W_p:

$$W_g = W_p + 6*h \qquad (2)$$

2.2. Length calculations:

To get the patch antenna's length, we must first determine the effective dielectric constant ε_{reff} and the length extension ΔL. ε_{reff} can be calculated using the next formulas:

- if $(\frac{Wp}{h} < 1)$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2} * \frac{1}{\sqrt{1+\frac{12h}{Wp}}} + 0.04\left(1-\frac{Wp}{h}\right)^2 \qquad (3)$$

- otherwise, if $(\frac{Wp}{h} \geq 1)$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2} * \frac{1}{\sqrt{1+\frac{12h}{Wp}}} \qquad (4)$$

where:

- W_p: the patch width.
- h : the substrate thickness.

ΔL_P is get by the next formula:

$$\Delta L_P = 0.412h\left[\frac{(\varepsilon_{reff}+0.3)(\frac{W_P}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{W_P}{h}+0.813)}\right] \qquad (5)$$

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

$$L_p = \frac{c}{2fo\sqrt{\varepsilon_{reff}}} - 2\Delta L_P \qquad (6)$$

Similarly, the ground plane's length L_g will be:

$$L_g = L_p + 6*h \qquad (7)$$

2.3. Different feeding methods:

Patch antennas can be fed in a variety of ways. In general, there are two main types of feeding techniques as shown in the next figure.

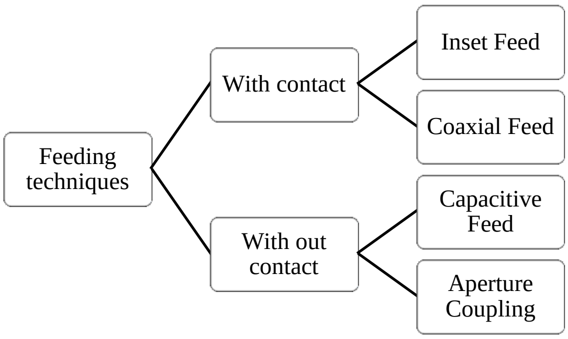

Fig. 2. Different feeding techniques [3]

We use Microstrip line feeding with the inset feeding method, which includes two gaps' notches for matching, to feed the suggested antenna.

2.4. Feeding Network:

A single line or numerous lines in a feed network arrangement can feed elements in a microstrip array [2]. The following are the several types of feeding methods:

- Series feed arrangement.
- Corporate feed arrangement.
- Corporate-series feed arrangement.

As shown in the next figure:

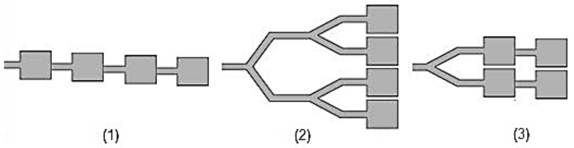

Fig. 3. (1) Series feed (2) Corporate feed (3) Series-Corporate feed [2]

3. Single Element Design

A printed copper patch with a height of 0.035mm is layered over a Rogers substrate RO3003 with relative permittivity ε_r =3 and height h = 0.13 mm to form a single-element patch antenna. Fig.4 illustrates a single patch antenna with a 50-ohm input impedance, it has been designed to operate at a frequency of 79 GHz.

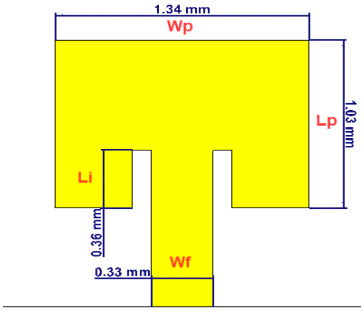

Fig. 4. Rectangular patch antenna of Single element

The patch's size is 1.3426 mm x 1.0345 mm with an inset feed at 0.357 mm, The transmission line width is 0.32679 mm. the simulation parameters are presented in the next table.

Table 1. Single Patch antenna simulation parameters

Parameter	symbol	Value
relative permittivity	ε_r	3
Roger thickness	h	0.13 mm
Copper thickness	t	0.035 mm
Resonance frequency	f_o	79 GHz
Ground width	W_g	2.643
Ground length	L_g	2.335
patch width	W_p	1.3426
Patch length	L_p	1.0345 mm
inset feed length	L_i	0.357 mm
inset feed width	w_i	0.1
Feed line width	W_f	0.33mm
Feed line length	L_f	0.611

3.1. Return Loss (S11)

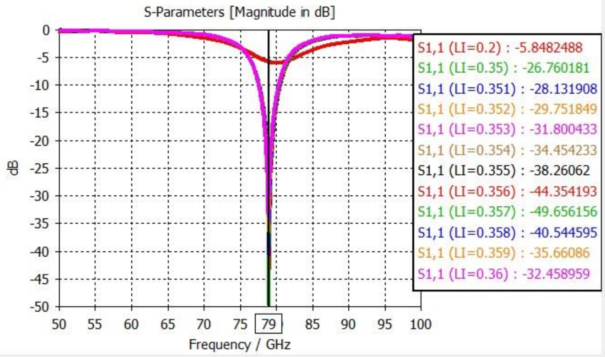

Fig. 5. S11 Different values according to inset feed values

According to Fig.5, it was observed that with the variation of the length of the inset feed, the return loss parameter S_{11} shows a high considerable change. This antenna resonates at a wideband from 77.628 to 80.391 GHz. We can observe that the S_{11} at 79.02 GHz is -60.7dB which is a good obtained value.

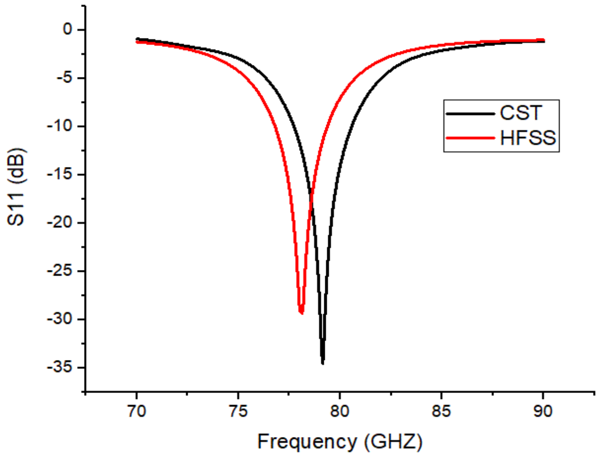

Fig. 6. S11 comparison by using two different ways of simulations

As the importance of the return loss value S11, the results are obtained by two different simulation programs as shown in Fig.6. The two simulation programs are CST and HFSS which are different where one of them depends on FIT “finite integrated technique” and the other depends on FDTD “finite difference time domain”. This result notes that there is a small difference between results due to the different analysis methods of each simulation program.

3.2. Efficiency

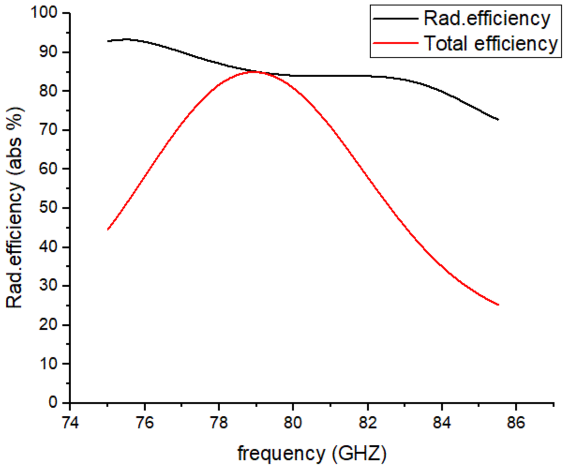

Fig. 7. Rad and Tot efficiency in percentage

Fig.7 shows the radiation and the total efficiencies of the proposed antenna.

3.3. Gain and Directivity

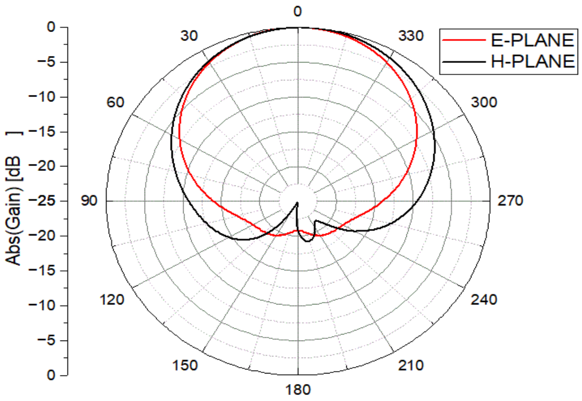

Fig. 8. Fairfield Gain at E-Plane and H-Plane

We get 7.327dBi of directivity at 79 GHz.The gain graph of this antenna at Phi=0° and Phi=90° with the variation of theta as shown in Fig.8.

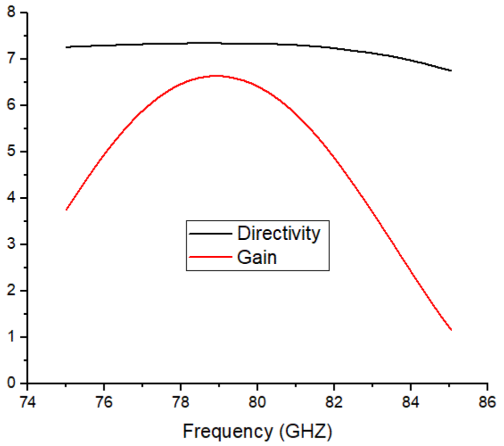

Fig. 9. Gain and Directivity Vs. frequency

Fig.9 illustrates the proposed antenna's simulated gain and directivity as a function of frequency. The gain has a good value across the working frequency range (77-81 GHz). also, the antenna's directivity grows in tandem with its gain.

4. 1x4 Series Feed Antenna Array Design

Series feed microstrip patch antenna array is typically used in millimeter-wave radar sensors due to its simple structure, excellent gain, and low fabrication cost. They do, however, usually have a limited impedance bandwidth [6].

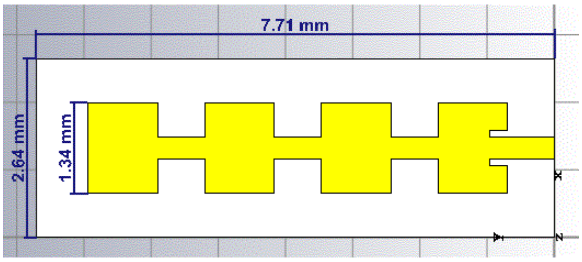

Fig. 10. 4*1 Series feed antenna array design

Here at Fig.10 the used 4 patches have the same dimensions as in single patch. The length of the inset feed will be changed to obtain the required matching.

4.1. Return Loss (S_{11})

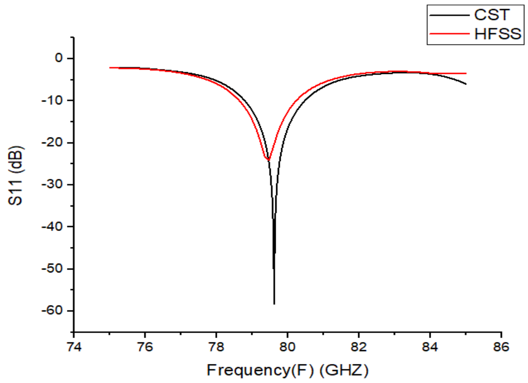

Fig. 11. Series feed array S11 comparison by using two different ways of simulations

As shown in Fig.11 this antenna resonates at a wideband [78.8-80.485] GHz. The value of reflection coefficient at 79.63GHz is -45.37 dB with -10dB bandwidth of 1.685 GHz. Again, the results are obtained by two different simulation programs. The next Fig.12 shows the radiation and the total efficiencies of the proposed array antenna.

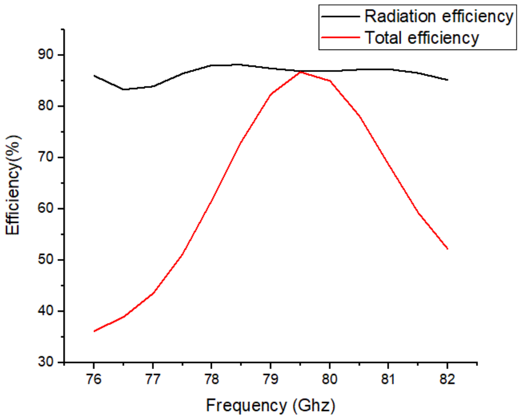

Fig. 12. Rad and Tot efficiency in percentage

4.2. Gain and directivity

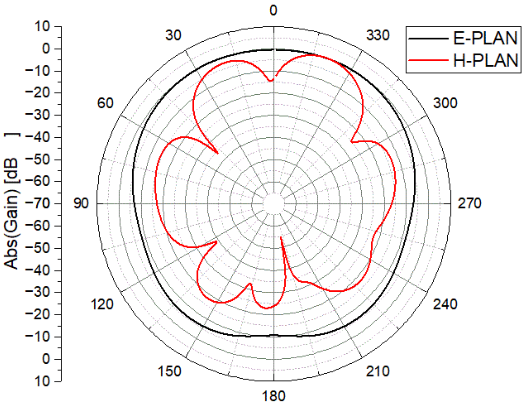

Fig. 13. Fairfield Gain at E-Plane and H-Plane

We get 10.83dBi of directivity at 79 GHz. The Fairfield Gain at E-Plane and H-Plane is shown in Fig.13.

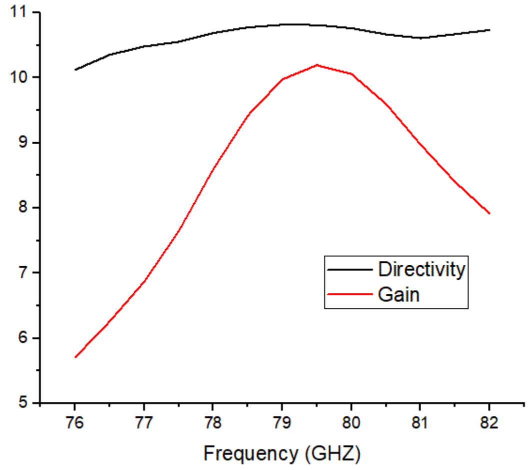

Fig. 14. Gain and Directivity Vs. Frequency

4.3. Single patch vs 1x4 series feed array antenna

Table 2. Parameter comparison between single and series feed array antenna

Parameter	Single patch	4 elements series array
Frequency (GHZ)	79.02	79.63
S11 (dB)	-60.7	-45.37 dB
-10 dB Band Width	2.763 GHZ	1.6847 GHZ
Gain	4.675 (6.697 dBi)	10.6 (10.5 dBi)
Directivity	5.404 (7.327 dBi)	12.11 (10.83 dBi)
Angular width (3dB)	74.9	23.5 deg
VSWR	1.006	1.63

From table 2 above, the gain and directivity of the 4x1 series feed array antenna are clearly superior to those of a single patch antenna. It is evident that a series feed array antenna's beamwidth is narrower than that of a single patch antenna, which is an important criterion in radar system design. Finally, we can observe that the series feed array antenna has superior characteristics to that of the single element antenna except the -10dB Band Width value that is a very important parameter for radar system design.

4.4. Series Feed Array 1x4 Antenna Bandwidth Optimization

The basic weakness of series fed microstrip patch antenna arrays is their small bandwidth, which arises from the naturally narrow bandwidth of microstrip patch antennas [4]. At this optimization, we need to increase the bandwidth while keeping its other good features.

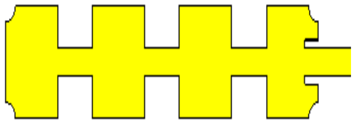

Fig. 15. 4*1 Series feed antenna array with inner round edges

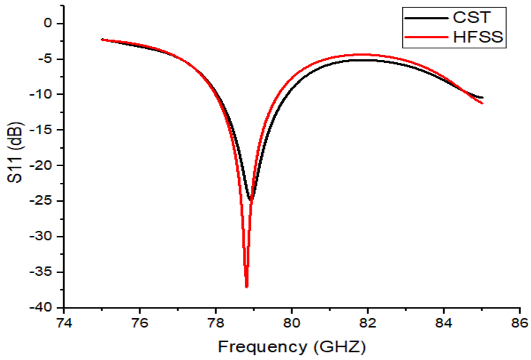

Fig. 16. S11 of the Series feed antenna array 1*4 with inner round edges

As observed at Fig.16 that there is a good optimization at the -10dB bandwidth parameter of the series feed microstrip patch antenna array with inner round edges design compared with the conventional design, there is a difference of 0.2367 GHz.Also, we can see that there is small shift at the resonant frequency due to the change at the geometry of the patches that can easily optimized by changing the patch length L_p parameter.

5. 1x8 Series Feed Antenna Array Design

The round edges technique will be applied to the next design to optimize the bandwidth also by increasing the number of patches we can get improved results for gain and directivity and other radiation parameters.

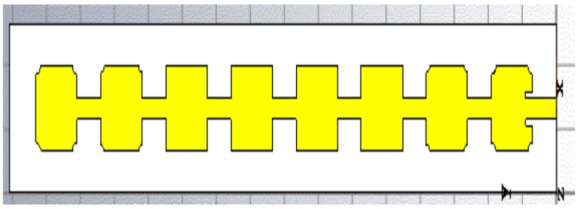

Fig. 17. 1*8 Antenna array with inner round edges

The round edges are applied at the first and the 8th patches at all corners by radius x1=0.14mm and also at the 2nd and 7th patches by radius x2=0.75*x1. the value of the round edge radius x1 and x2 are chosen by the parametric sweep method to obtain the widest bandwidth.

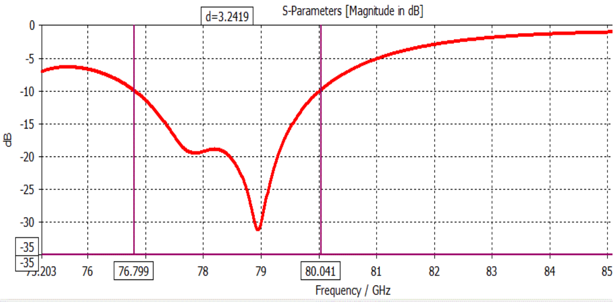

Fig. 18. S11 of 1*8 Antenna array with inner round edges

As observed in Fig.18 that there is a good value of the -10dB bandwidth parameter of this antenna compared with the previous results. It is equal to 3.242 GHz. In comparison to several antenna designs dedicated to mm-wave radar applications in the 77-81 GHz region, this result is very acceptable.

6. Experimental Results

As the limitation of the fabrication process dimensions the round edges have been canceled and the matching techniques have been changed from the inset feed method to the quarter wavelength transformation to enable the launcher connector. The new design will be as follow in Fig.19.

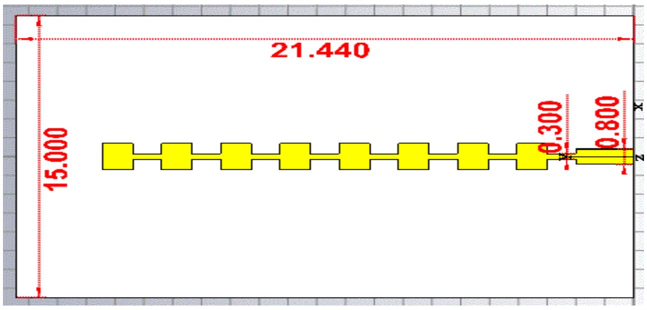

Fig. 19. Final 1*8 Antenna array design for fabrication

A prototype is fabricated as shown in the next figure to confirm the simulated results.

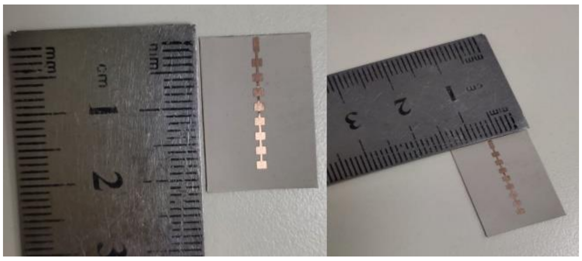

Fig. 20. Photograph of the of the fabricated antenna dimensions

The launcher connector is used for measuring the performance of the fabricated antenna using the vector network analyzer (VNA) model (N5244B) as shown at Fig.21 and Fig.22.

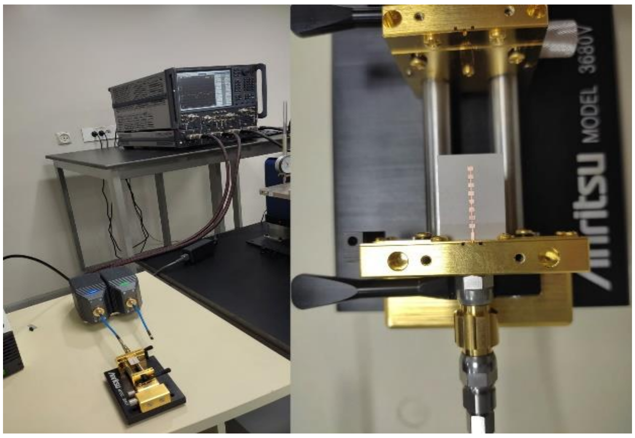

Fig. 21. Measuring setup of proposed antenna

Fig. 22. S11 value at the screen of VNA

The result of simulated S11 obtained by CST® 2020 simulator and measured S11 are shown in Fig. 23 shows good agreement at the resonant frequency.

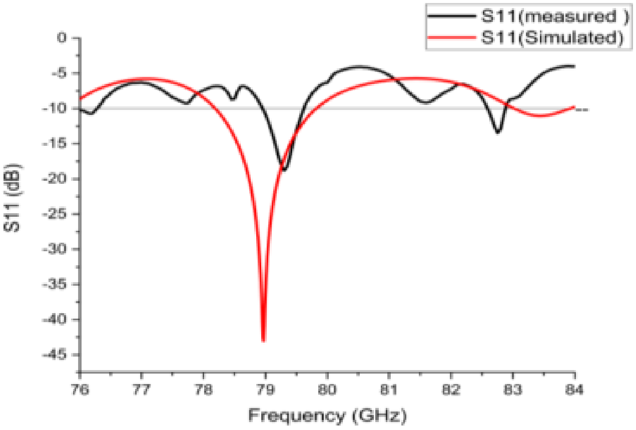

Fig. 23. S11 Comparison between simulated and measured

The results of the measured and simulated reflection coefficients are reasonably similar. The slight shift of the 79 GHz resonant frequency and one that appeared at 82.76 GHz may be due to the huge of the measuring connector compared with the antenna size or improper measurement, fabrication processes, connector losses, and material quality. The final design of antenna is acceptable compared with another previous work as shown in the next table.

Table 3. Comparison with the previous work

Parameters	This work	[12]	[13]	[14]	[15]	[16]
Element	8	4	10	10	10	5×4
Freq. (GHZ)	79	79.06	78	77	9	77
S11 (dB)	-42.5	-34.47	-20	-26	-35	-13.32
Bandwidth (GHZ)	1.71	1.21	2.5	1.5	N/A	1.51
Gain (dB)	15.12	12.34	15	16	14.5	18.7
HPBW (°)	11.7°	25°	N/A	10°	8.3°	14.3

7. Conclusion

In this paper, the Millimetre-wave microstrip patch antenna is successfully designed and enhanced at a resonant frequency of 79 GHz. This paper showed the design of single, 4-element, and 8-element series feed array antennas by using Roger RO3003 substrate. It is observed that by introducing a series feed array antenna we enhance its features in terms of gain, directivity, Angular width, and return loss. The gain optimization from 4.675 at single patch design to 10.6 in 4 element series Array and to a very acceptable value of 15.12 in 8-element series array antenna. optimization was introduced to widen the bandwidth which gave a good result to -10dB bandwidth from 1.6847 to 1.9214 GHz at the 4-element array design. This optimization was applied on the 8-element array to obtain a good value equal to 3.242 GHz, which makes this design more considerable compared with a lot of previous work as shown in table 3. the proposed antenna has been fabricated for verification of the S11 value.

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