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Performance analysis of a proximity-coupled triangular slot microstrip patch antenna for ship radar applications

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ABSTRACT

Microstrip patch antennas are extensively utilized in modern communication systems because of their small size and simple fabrication process. Among the different patch geometries, triangular patches offer size reduction compared to their rectangular and circular counterparts, making them suitable for space-constrained applications. This study focuses on the design and analysis of an equilateral triangular microstrip antenna (ETMSA) using proximity coupled feed with a triangular slot, targeting optimal performance at 2.2 GHz. The antenna is constructed using two FR4 substrates of identical permittivity but different thicknesses (h_1 and h_2), with a 50-ohm microstrip line feed positioned between them. The aim is to determine the optimal values of patch surface area, slot dimensions, and upper substrate thickness to achieve maximum bandwidth, minimal return loss, and ideal voltage standing wave ratio (VSWR). Simulations and measurements confirm that the antenna achieves a 120 MHz bandwidth achieving a return loss of –42 dB and a VSWR of 1.03, demonstrating excellent agreement. These results confirm the antenna's effectiveness for fixed-beam applications in wireless communication systems, highlighting its potential for efficient and compact antenna solutions.

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1. INTRODUCTION

Radar systems, by their very nature, have a central core component known as the antenna, which ensures transmission and reception of electromagnetic waves to detect, locate and track objects. Radar works by sending an electromagnetic wave in a narrow beam which bounce off the target being observed, then captures the reflected signals. In most cases, the received signal power is very low because of strong attenuation, but due their high gain, radar systems are capable of detecting such low signal [1], [2].

With the increasing demand for small antennas in personal communication equipment, microstrip antennas have become essential for wireless communication applications, satellite communication and radar [3]. Nearly all significant wireless applications operate within the 900 MHz to 5.8 GHz band, with particular emphasis on broadband microstrip antennas operating at 2.2 GHz. Their flat design, low profile, lightweight, reasonable efficiency, and ease of integration with microwave integrated circuits (MIC) make them more suitable compared to conventional antennas like helical, parabolic, and horn antenna [4]–[6]. Usually, antennas are in strictly dimensional structure with large size making them not suitable for wireless devices. Furthermore, microstrip antennas suffer from capabilities like low bandwidth, poor efficiency and gain. To overcome these drawbacks, numerous solutions can be assumed. A notable method for improving microstrip antenna parameters, such as return loss, bandwidth, voltage standing wave ratio (VSWR) and impedance [7]–[10] is the use of appropriate feeding techniques. Various techniques have been extensively studied by researchers, including coaxial feed, microstrip line feed, proximity-coupled feed, and aperture-coupled feed [4].

In this paper, the appropriate feeding method is selected based on its reported advantages and disadvantages outlined in [4] and used in accordance with the aim of improving specific parameters. The investigated typical microstrip antenna consists of one or more dielectric substrates, a ground plane, and a conducting patch [7]. The designs become highly versatile regarding operating frequency by selecting the shape and operating patch mode. The patch may have rectangular and circular shape reported in [11]–[16], respectively. The length of the microstrip patch antenna is crucial for determining the resonance frequency. The proposed microstrip antenna operate at the frequency of 2.2 GHz which requires a bandwidth greater than 100 MHz, to increase bandwidth, decrease return loss (S11), and eliminate spurious radiation, the proximity-coupled feeding technique is among the most effective methods for achieving these enhancements [8], [14], [17]–[21].

Conventional equilateral triangular microstrip antennas (ETMSAs) were studied in [7], [13], [22]–[29]. Most of these studies use coaxial cable feeding. Recently, to improve antenna performance, some studies have employed proximity-coupled feeding for triangular microstrip antenna [7], [13]. The ETMSA has been analyzed using a genetic algorithm (GA) [24]. Achieving dual-band operation of the ETMSA has been demonstrated through various methods, including stacked patches [28], incorporating a V-shaped slot studied in [29].

In this paper, the triangular microstrip antenna is proposed. Because of its smaller dimensions compared to rectangular and circular patches. The aim of this work is to change some of antenna dimensions, such as the upper substrate thickness h_2, the patch antenna surface and slot surface. Optimal values of these parametres will ensure the maximum bandwidth, the minimum return loss, and ideal matching between the patch and transmission line represented by VSWR parameters.

The paper is divided in to five sections. Introduction in section 1, section 2 represents design and configuration with the dimensions of the proposed antenna. Then, in section 3 are presented the simulated results and discussion of proposed antenna operating at 2.2 GHz, but also the parametric analysis determining the influence of each one on the antenna's performance. Fabrication and measurement results are presented in section 4. Finally, our conclusions are given in section 5.

2. ANTENNA DESIGN AND CONSTRUCTION

The proposed ETMSA is designed for the frequency of 2.2 GHz. Geometry of the proximity-coupled ETMSA is shown in Figure 1. The structure consists of two FR4 dielectric substrates of different thicknesses (h_1, h_2) stacked above a ground plane. A 50-ohm microstrip feed line is placed between the two substrates. Figure 1(a) shows conventional triangular patch antenna without slot. Figure 1(b) shows proposed antenna with a central isosceles triangular slot, and slot angle θ, introduced in the upper triangular metal patch to improve impedance matching and bandwidth. The value of “a” is obtained from (1) [14]:

$$a = \frac{2.c}{3\ f_0\sqrt{\varepsilon_r}} \quad (1)$$

whare: f_r is operating frequency, and ε_r is relative dielectric constant. A microstrip line feed with length L_f and width W_f is etched onto the top surface of substrate 1, which is positioned beneath substrate 2 [17].

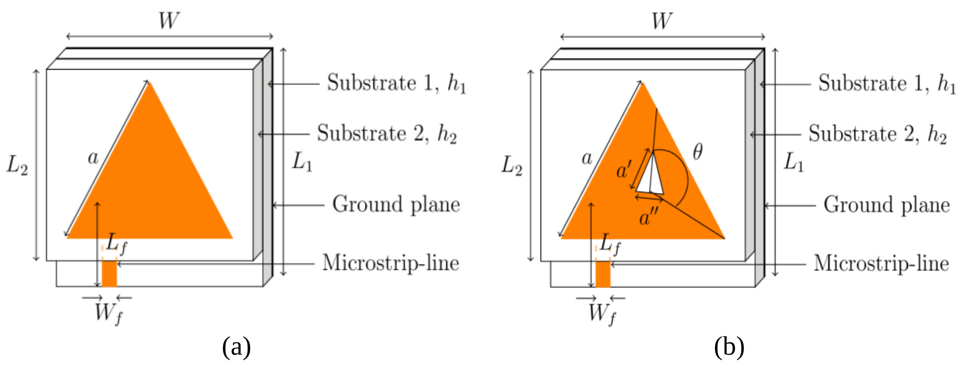


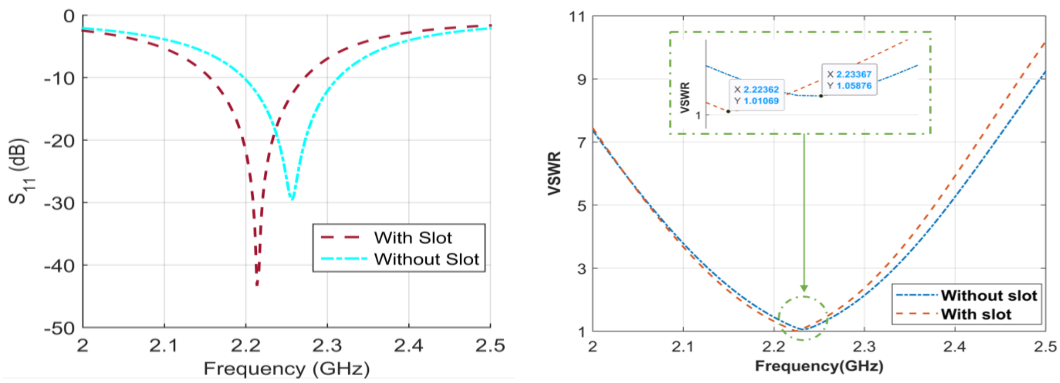
Figure 1. Triangular microstrip antenna; (a) design of antenna without slot and (b) proposed antenna (with slot)

The feeding technique, electromagnetic coupling scheme, which employs two dielectric substrates, is as shown in Figure 1. The feed line is arranged between the substrates, while the radiating patch is placed on top of the upper substrate. Some of the major advantages of this method include the capability for spurious feed radiation to be completely eliminated and for bandwidths as high as 13% to be achieved with increased thickness of the microstrip patch antenna. In this configuration, different dielectric materials can be chosen for the patch and the feeding line to individually optimize their performance characteristics. The optimized geometric parameters of the proposed antenna are given in Table 1.

Table 1. Geometrical parameters of proposed antenna

Antenna dimension	Value (mm)
a	39.91
L_1	43.3749
L_2	47.4410
W	48.6763
L_f	16.7608
W_f	1.9
h_2	1.6
h_1	1.6
a'	11.6
a''	7.5

The structures in the inset of Figure 1 have been designed and simulated using a soft high frequency structure simulator (HFSS) software to verify the friability of the suggested method; the outcome is displayed in Figure 2(a). The two antennas are made with comparable sizes for easier comparison. A simple antenna is found to have a resonance around 2.25 GHz, whereas the developed antenna with the triangular slot shows a resonance at 2.21 GHz. Figure 2(b) illustrates the VSWR comparison between the two antennas where the proposed antenna has VSWR=1.01 at 2.22 GHz while the simple antenna gives VSWR=1.06 at 2.23 GHz.



(a) (b)

Figure 2. Simulated; (a) return loss and (b) VSWR

3. RESULTS AND DISCUSSION

There are multiple factors that affect the antenna response. Using HFSS, a parametric study of various parameters was conducted in order to enhance the suggested antenna's bandwidth and reflection coefficient.

The main element in the proposed antenna is the triangular slot added to the top metallic of the antenna to change the surface currents distribution, and therefore the area of this slot and its position play a very important role in the proposed improvement ratio. The impact of varying the rotation angle of the triangular slot on the return loss characteristics is illustrated in Figure 3 for different angles, including $\theta=90^0$, 110^0, 130^0, and 150^0. The return loss reaches its optimal value of -42 dB at the resonant frequency when θ is set to 130^0.

If $\theta=130^0$ yields the lowest S_{11}, this may indicate that:

– Surface currents are evenly distributed, with no parasitic or cancelling components.
– The radiated field is well directed, enhancing transmission efficiency.

– The feed line and input impedance are effectively matched resulting in reduced reflection.

Changing the thickness of the substrate has a direct effect on the value of dielectric losses as well as on the width of the microstrip feed value, which in turn is important in the impedance matching. The effect of variation in thickness of upper substrate h_2 on the return loss characteristics is illustrated in Figure 4. It is observed that the best performance is achieved when $h_2=h_1=1.6$ mm at the resonant frequency.

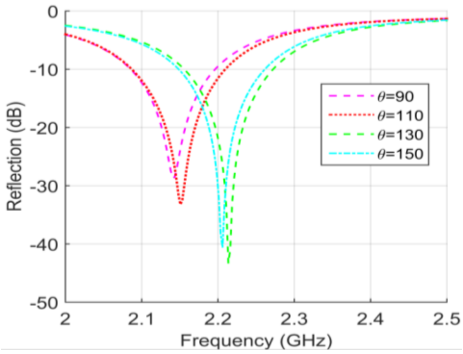


Figure 3. Simulated return loss for various values of θ (degree)

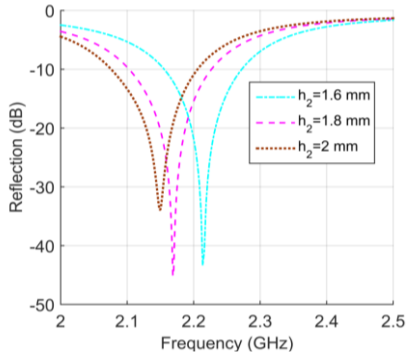


Figure 4. The proposed antenna's simulated return loss for various values of h_2

To examine the effect of the triangular slot's surface area on the antenna's return loss response, we increased its size by a factor of x_1, where $S_{n1}=x_1*S_1$ and $S_1=76.03$ mm^2 is the triangle slot's original surface area and S_{n1} is the new triangle slot's surface area. Figure 5 illustrates the return loss simulation results for different values of x_1. When $x_1=1$, the ideal return loss of -42 dB is reached.

To investigate the impact of the surface area of the upper copper triangle on the antenna response, we changed its area by a factor of x_2, where $S_{n2}=x_2*S_2$, $S_2=1383.60$ mm^2 is the initial value of the surface area of the upper triangle copper and S_{n2} is the new surface area of the upper triangle copper. Figure 6 shows the simulated return loss for factor of x_2. The optimal return loss of -42 dB is achieved when $x_2=1$.

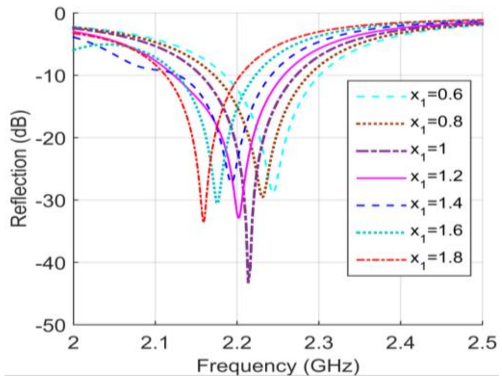


Figure 5. The simulated return loss for various triangular slot surface areas

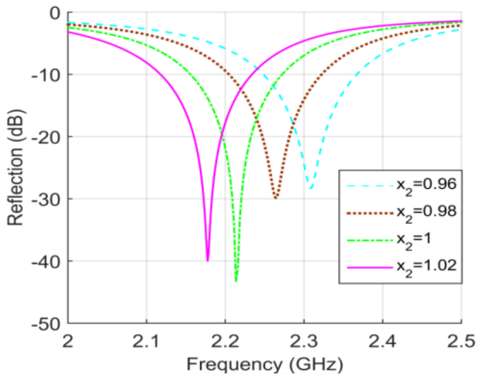


Figure 6. Simulated return loss for different surface areas of triangular patch

At the resonant frequency of 2.2 GHz, the color near the feedline in Figure 7 suggests 20 to 30 A/m, suggesting high magnetic field intensity in that location. Compared to an antenna without a slot, which shows roughly 7 A/m, the current distribution at the top of the antenna is centered on the left portion of the patch, the bottom right edge of the triangular slot, which shows 20 to 30.8 A/m. This explains why antennas with slots perform better than those without.

At the resonant frequency (2.2 GHz), the normalized radiation pattern of the proposed antenna is depicted in Figure 8. From this Figure, a directional radiation pattern with stable radiation characteristics is observed in the two plans (E-plan and H-plan). The main lobe is centered in the 0° with symmetrical diagram for ensuring the orientation of antenna. Concerning the side lobes, it is observed that the absence of side lobes ensuring a minimal radiation in the undesired direction. The radiation pattern of the proposed antenna demonstrates good performances in terms of directivity and stability.

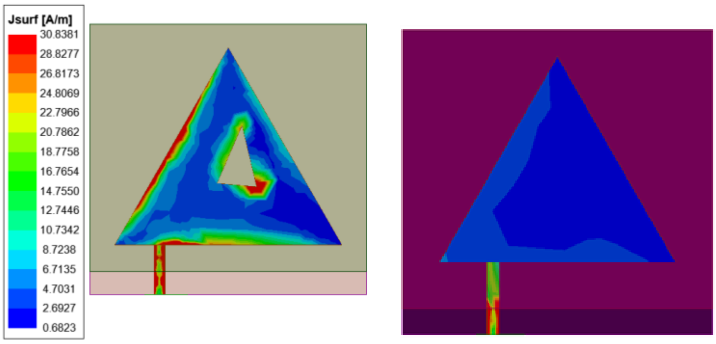


Figure 7. Surface current distribution of proposed antenna

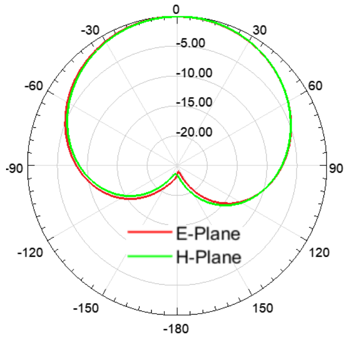


Figure 8. Radiation pattern of the proposed antenna

4. FABRICATION AND MEASUREMENT RESULTS

A prototype was created utilizing the printed circuit board (PCB) chemical etching method in order to verify the suggested design and analysis that were discussed in the parts that came before it. The caption of Figure 1 and Table 1 gives the antenna's measurements dimensions. We employed a FR4 substrate that was 1.6 mm thick, with tan δ=0.02 and ε=4.4. Figure 9 shows a picture of the antenna measurement configuration. The LibreVNA vector network analyzer was used to conduct measurements at room temperature. A typical short-open-load-thru (SOLT) approach was used to calibrate the VNA over a frequency range of 1 to 4 GHz.

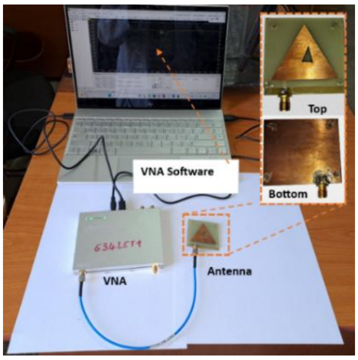


Figure 9. Fabricated prototype of the proposed antenna with VNA software

As seen in Figure 10, the antenna's reflection response was measured and contrasted with the full-wave electromagnetic response. The resonance frequency in the measurement result is 2.216 GHz, which is 2.7% different from the simulated result of 2.21 GHz. Among other things, the influence of SMA connectors and fabrication tolerance are to blame for this minor discrepancy. A comparison between the proposed design presented in this work and the other antennas reported in literature is presented in Table 2.

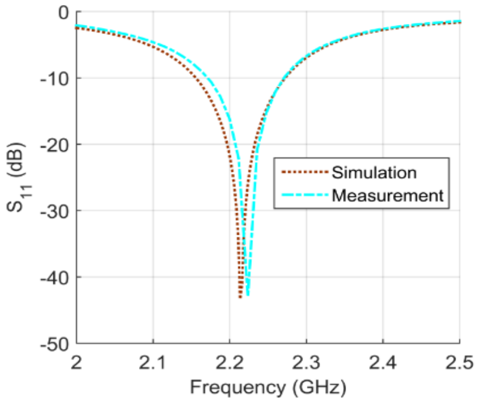


Figure 10. Simulated and measured return loss comparison

Table 2. Comparison between the proposed antenna and various literature works

Previous works for S-band (2.2-2.4) GHz	Simulated return loss S11 (dB)	Simulated VSWR	Bandwidth (simulation) (MHz)	Measurement
[7] single element	-31.955	1.0518	84	S11=-51.913 dB, VSWR=1.005
Dual element	-24.367	1.1288	111	S11=-48.213 dB, VSWR=1.007
[30]	-33.945	1.0409	200	S11>-60 dB
[1]				
Single patch	-13.934	1.502	61	----
1*2 array	-20.371	1.211	83	----
2*2 array	-18.086	1.284	83.6	----
Proposed antenna	-42	1.01	120	S11=-41.7 dB, VSWR=1.003

Table 2 demonstrates that our antenna has a greater bandwidth and, for the most part, a better matched VSWR value for the recommended antenna. The suggested antenna is very appealing for S band radar applications because of these features.

5. CONCLUSION

This work presented the design, simulation, and experimental validation of a proximity-coupled triangular slot patch antenna intended for S-band applications, particularly in ship radar and mobile satellite systems. The primary objective was to optimize the antenna's geometric parameters—specifically the triangular slot and substrate thickness to achieve high bandwidth, low return loss, and ideal impedance matching. The antenna operates at 2.2 GHz and demonstrates a measured bandwidth of 120 MHz, a return loss of –42 dB, and a near-ideal VSWR of 1.003. These results confirm excellent agreement between simulation and experimental validation using Ansys HFSS and fabricated prototypes. The compact structure and fabrication simplicity make it highly suitable for integration in space-constrained radar and communication systems. However, the current study is limited to single-frequency operation and fixed-beam performance. In future work, we aim to explore bandwidth enhancement through multilayer structures or metamaterials, as well as beam steering capabilities using array configurations. Additionally, testing the antenna performance under real environmental conditions, such as on moving platforms or in marine environments, is suggested to validate robustness and reliability.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ismahene Ikhlef	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Karima Chemachema		✓				✓	✓	✓	✓		✓	✓	✓	✓
Farouk Grine	✓		✓	✓			✓		✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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