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Performance Analysis of X-Band Microstrip Antennas under Superstrate Thickness and Dielectric Constant Variations

Nour Alhuda Khamaj [1], Nafaa Shebani [2]

[1] Department of Computer Technology, Faculty of Information Technology, University of Zawia, Zawia, Libya
[2] Electric and Electronic Engineering Department, Engineering Faculty, Sabratha University, Sabratha, Libya
[1]ORCID: 0009-0006-5916-2049
[1]n.khamaj@zu.edu.ly, [2]nafaa.shebani@sabu.edu.ly

Abstract
In this paper a compact dual-band microstrip patch antenna operating in the X-band is proposed and analysed for radar and satellite communication applications. The antenna is designed on a low-loss Teflon substrate with a relative permittivity of 2, thickness of 1.58 mm, and loss tangent of 0.000194, and is simulated using the Advanced Design System (ADS) Momentum solver. This study investigates the effect of introducing a dielectric superstrate layer on antenna performance by systematically varying its dielectric constant and thickness. The results show that the superstrate significantly influences key parameters such as resonant frequency, bandwidth, gain, directivity, and efficiency. Increasing the dielectric constant enhances directivity but causes a descending frequency shift and reduced efficiency, whereas a low dielectric constant ($\varepsilon r \approx 1.3$) with increased thickness improves impedance bandwidth and maintains stable radiation characteristics.
Keywords: X band, Superstrate, dual band, dielectric constant, height of superstrate.

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تحليل أداء هوائي شريطي يعمل في النطاق التردد X تحت تأثير تغيّر سمك وثابت العزل الكهربائي للمادة الفوقية

نور الهدى اخماج[1]، نافع الشيباني[2]

[1]قسم تقنيات الحاسوب، كلية تقنية المعلومات، جامعة الزاوية، الزاوية، ليبيا

[2]قسم الهندسة الكهربائية والإلكترونية، كلية الهندسة، جامعة صبراتة، صبراتة، ليبيا

[1]n.khamaj@zu.edu.ly, [2]nafaa.shebani@sabu.edu.ly

الملخص

في هذه الورقة، تم اقتراح وتحليل هوائي رقعي شريطي(Microstrip Patch Antenna) مدمج ثنائي النطاق يعمل ضمن نطاق X، وذلك لتطبيقات الرادار والاتصالات عبر الأقمار الصناعية. تم تصميم الهوائي على ركيزة من مادة التفلون منخفضة الفقد، ذات ثابت عزل نسبي مقداره 2، وسمك 1.58 مم، ومعامل فقد يساوي 0.000194، وتمت محاكاته باستخدام برنامج Advanced Design System (ADS). تهدف هذه الورقة لدراسة تأثير إضافة طبقة عازلة علوية (Superstrate) على أداء الهوائي الشريطي، من خلال تغيير كل من ثابت العزل وسمك هذه الطبقة بشكل منهجي.

أظهرت النتائج أن الطبقة العلوية تؤثر بشكل كبير على المعلمات الأساسية مثل التردد الرنين، وعرض النطاق، والكسب، والتوجيهية، والكفاءة؛ حيث يؤدي زيادة ثابت العزل إلى تحسين التوجيهية لكنه يتسبب في إزاحة التردد نحو القيم الأقل مع انخفاض في قيمة كفاءة الهوائي؛ ومن جهة أخرى فإن استخدام ثابت عزل منخفض ($\varepsilon r \approx 1.3$) مع زيادة السمك يؤدي إلى تحسين عرض النطاق المعاوقي مع الحفاظ على استقرار خصائص الإشعاع.

الكلمات المفتاحية :نطاق X، الطبقة الفوقية(Superstrate) ، ثنائي النطاق، ثابت العزل الكهربائي، سمك الطبقة الفوقية.

1. Introduction

The antenna is considered a fundamental component that links the communication system to free space, serving as an essential element

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in wireless communication systems by providing a direct interface with the signal propagation medium. [1]

There are various types of antennas, including the microstrip patch antenna, the cone-shaped antenna, and the helical antenna …etc. [2] Microstrip Patch Antenna (MPAs) are considered fundamental components in modern wireless communication systems. [3] These antennas have attracted significant attention since the 1970s, although the first patent was granted in 1955. [4]

They have been widely utilized in various wireless and mobile communication applications since 2002, following their authorization for civilian use by the Federal Communications Commission (FCC). [3]

A microstrip patch antenna consists of a dielectric substrate, on one side of which a conductive patch is mounted, while a conductive ground plane is placed on the opposite side. The substrate acts as a separating layer between the patch and the ground plane, and it plays a crucial role in determining the electrical characteristics and overall performance of the antenna. [5][4]

There are various feeding techniques for microstrip antennas, which are mainly classified into two categories. The first is contact feeding, where a microstrip feed line is directly connected to the radiating patch, such as microstrip line feeding and coaxial probe feeding. The second is non- contact feeding, where power is transferred through electromagnetic field coupling between the feed line and the radiating element, such as aperture coupling and proximity coupling. [4][2]

The rapid growth of modern wireless communication systems has led to a significant increase in the demand for antennas with desirable performance characteristics. [1] Compared to conventional antennas, microstrip patch antennas (MPAs) are considered an ideal choice for modern devices owing to their numerous advantages, including light weight, low- profile thickness, planar structure, low fabrication cost, and ease of integration with microwave integrated circuit technologies. [3][5] Furthermore, these antennas offer straightforward scalability for forming large arrays and exhibit superior performance at higher frequencies, thereby contributing to a considerably more compact overall system size. [6]

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Due to these characteristics, microstrip antennas are widely used in wireless communication systems, radar systems, and satellite communications. They can also be easily integrated into various platforms such as aircraft, satellites, vehicles, and portable devices. [3][5][4]

However, microstrip antennas suffer from several limitations, including low gain, low efficiency, narrow bandwidth, limited power – handling capability, narrow impedance bandwidth, and excessive radiation from the feed lines.[3][7] There are various methods to overcome the disadvantages, few of them are: Array configuration , multi-layered structure, change in shape of patch and adding different shaped slots in patch in proper position, using low dielectric constant of substrate or increase the thickness of substrate, proper feeding, using metamaterial structure, use different structure like photonic band gap (PBG), substrate integrated waveguide (SIW), and Defective Ground Structure (DGS). [7]

Multilayer microstrip antennas, characterized by their stacked configuration of dielectric substrates and radiating elements, represent a promising solution for overcoming the limitations associated with single – layer microstrip antenna designs, particularly in terms of narrow bandwidth and reduced radiation efficiency. [8]

The multilayer microstrip antenna structure involves the addition of a superstrate layer over the substrate,[9] a technique that has attracted significant research attention due to its key advantages, including design simplicity, and the ability to enhance between and gain, as well as compatibility with microwave and millimetre- wave frequency bands. [10][2] However, the addition of a superstrate layer affects the fundamental antenna characteristics, such as resonant frequency, gain, and bandwidth, which may degrade system performance if not carefully designed. Conversely, by optimally selecting the thickness of both the substrate and the superstrate layer, a significant improvement in gain can be achieved, making this structure suitable for practical application. For this reason, it is essential to analyze the effects of the superstrate to determine appropriate parameters that enhance both gain and radiation efficiency. [9]

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The bandwidth of a microstrip antenna increases with an increase in substrate thickness and decreases in the dielectric constant also, the bandwidth of the antenna increases when multi-resonators are coupled in planar or stacked configurations. [11] The gain can be increased by using the microstrip antenna array structure but this again increases the antenna size. Hence the bandwidth and gain of microstrip antenna is increased by slightly increasing the dimensions of multilayer structure. [5]
The X band is a segment of the microwave radio region of the electromagnetic spectrum. In radar engineering, the frequency range is specified by the IEEE at 8.0 to 12.0 GHz. [12] The X band is also utilized in military application, weather radar, air traffic monitoring, marine radar, and remote sensing systems. [1] The X band frequencies have the advantage that it is less affected by rain fade, where it provides higher rain resilience compared to other higher frequency band like Ku and Ka used for satellite communication. This allows extremely high link availability. [13]

2. Research Contribution and Gap

Previous studies have shown that dielectric superstrates can significantly alter the performance of microstrip patch antennas. Gupta and Singh [9] investigated the effects of superstrate permittivity and thickness on microstrip antenna characteristics, including resonant frequency, gain, directivity, and efficiency. Saidulu and Rao [14] experimentally examined the effects of dielectric superstrates on resonant frequency, bandwidth, gain, and radiation characteristics. More recently, Ajewole et al. [3] used an I-shaped metamaterial superstrate to enhance gain and bandwidth and achieve multiband operation.
However, these studies mainly focused on specific superstrate configurations or engineered structures for performance enhancement, while the combined effects of superstrate permittivity and thickness on the lower and upper resonances of a compact dual-band X-band antenna have not been systematically characterized in terms of their operating regimes and performance trade-offs. The novelty of this work lies in establishing a performance-based design map that relates superstrate permittivity and thickness to resonant-frequency shift, bandwidth, directivity, gain, and efficiency, while

distinguishing the behavior of the lower and upper resonances. The study further classifies the resulting operating regimes, from stable X-band operation to lower-resonance migration toward the C-band, and identifies the associated trade-offs among bandwidth, directivity, gain, and efficiency. This provides practical design guidelines for selecting superstrate properties according to the required performance priorities.

3. Antenna geometry and simulation method

This section presents the geometric structure of the proposed antenna and its electromagnetic simulation methodology, as follows:

3.1. Geometric Structure

Figure 1, illustrates the geometry of the proposed antenna, which is a compact dual-band antenna; the antenna structure lies in the (x, y) plane, and the main radiation beam (broadside) is directed along the positive z-axis.

The substrate consists of a Teflon insulating layer with a relative permittivity of $\varepsilon_r = 2.0$, a thickness of $h = 1.58$mm, and a loss tangent of $\tan\delta = 0.000194$. Both the conducting patch and the ground plane are modeled as copper layers with a standard thickness of 35 µm and an electrical conductivity of $\sigma = 5.8 \times 10^7$ S/m. The feed structure comprises a 50 Ω microstrip line with a width of W_7= 2.599mm and a length of L_7 = 15.855mm connected directly to the multi-slotted radiator. Table (1) presents the detailed dimensions of the radiating patch and the slots.

Table 1. Dimensions of The Proposed Antenna.

Parameter	Value (mm)	Parameter	Value (mm)
W1	25.154	L1	2.929
W2	2.500	L2	16.324
W3	5.263	L3	2.628
W4	1.794	L4	0.390
W5	2.480	L5	1.130
W6	8.797	L6	5.416
W7	2.599	L7	15.855

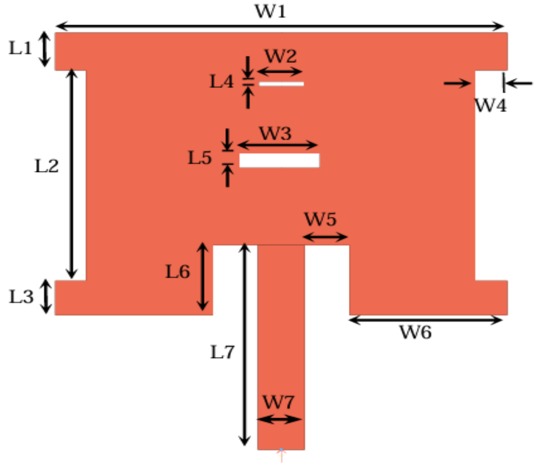

Figure 1: Configuration of a proposed Antenna.

3.2. Numerical Simulation Setup

Full-wave electromagnetic simulations were performed using Keysight Advanced Design System (ADS) Momentum solver. ADS Momentum employs the Method of Moments (MoM) to solve open-boundary 3D planar electromagnetic problems. The boundary conditions were defined as infinite free space above and below the multilayer stack-up. The substrate and superstrate dielectric layers were defined as homogeneous, isotropic planar layers.

4. Simulation Results

The simulated results of the variation of return loss versus the frequency of the proposed antenna is illustrated in Figure 2. From the figure, it can be observed that two resonant frequencies are located at the values of 8.201 GHz with return loss of -19.96 dB and 10.82 GHz with return loss -25.073 dB. Based on -10 dB return loss, at the first resonant frequency 8.201 GHz, 3.323% impedance bandwidth is obtained, in the frequency range 8.05 – 8.322 GHz; and 3.96 % impedance bandwidth is obtained at the second resonant frequency 10.82 GHz in the frequency range 10.63-11.06 GHz.

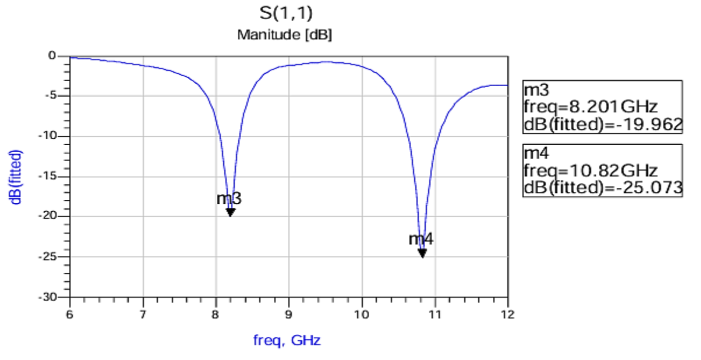

Figure 2: Simulated return loss for the proposed antenna.

The variation of the input impedance of the proposed antenna with frequency is plotted on the Smith chart as shown in Figure 3. From the figure, it can be seen that the simulated results give the acceptable impedance matching at the resonant frequencies, where the impedance at 8.201 GHz is 52.836+j 9.982 Ω, and it is 46.070+j3.646 Ω at 10.82 GHz. The simulated results of VSWR versus the frequency for the proposed antenna is shown in Figure 4, the VSWR is 1.223 at 8.201 GHz, and it is 1.118 at 10.82 GHz. For VSWR less than 2, the single layer antenna can cover the frequency range of 8.05 GHz to 8.322 GHz for lower band of the antenna, and it can cover the frequency range of 10. 63 GHz to 11.06 GHz for upper band.

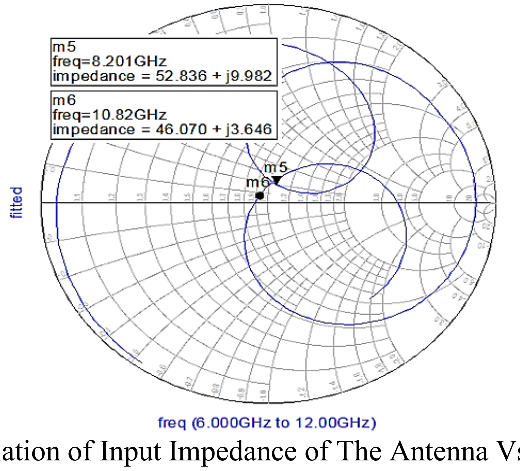

Figure 3: Variation of Input Impedance of The Antenna Vs. Frequency.

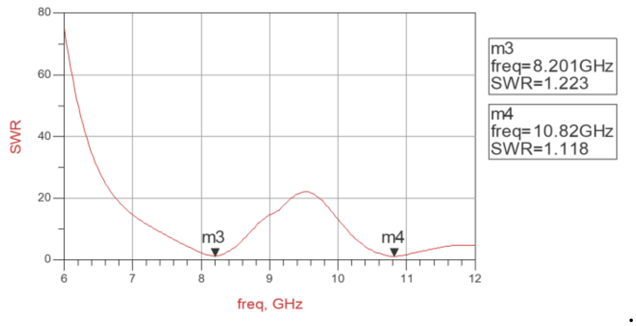

Figure 4: VSWR vs. Frequency for the dual-band antenna.

At 8.201 GHz the 3D representation of the radiation pattern of the proposed antenna is shown in Figure 5.

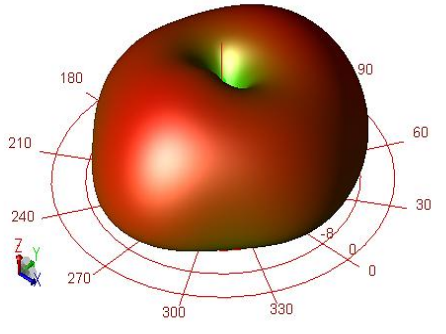

Figure 5: 3D Radiation pattern of the antenna at 8.201 GHz.

The parameters of the proposed antenna at 8.201 GHz are tabulated in Table 2.

Table 2: Parameters of the antenna at 8.201 GHz.

Parameter	Value
Power Radiated (mW)	1.886
Directivity (dBi)	7.490
Gain (dBi)	6.313
Efficiency (%)	76.209

At the resonant frequency of 8.201 GHz, the two-dimensional field patterns of the (Eθ) with Ø = 0° (E-plane) in elevation cut (x-z plane)

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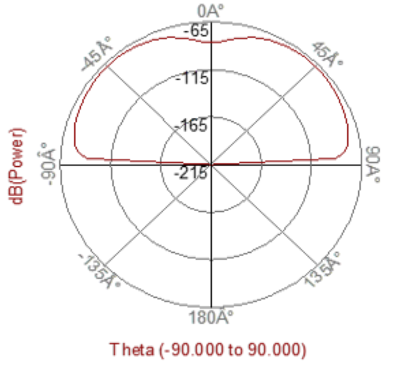
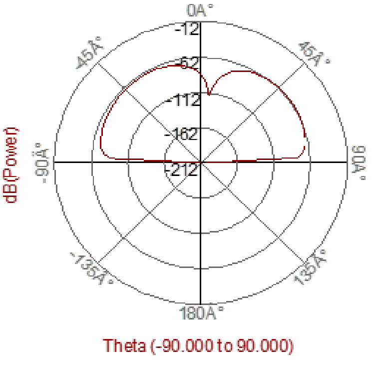
is shown in Figure 6a, and in elevation cut (y-z plane) with Ø = 90° is shown in Figure 6b.



(a)



(b)

Figure 6: Field pattern at 8.201 GHz in (a) x-z plane (b) y-z plane.

The parameters of the proposed antenna at 10.82 GHz are tabulated in Table 3.

Table 3: Parameters of the Antenna At 10.82 GHz.

Parameter	Value
Power Radiated (mW)	1.839
Directivity (dBi)	6.970
Gain (dBi)	5.630
Efficiency (%)	73.442

The 3D representation of the radiation pattern of the proposed antenna at 10.82 GHz is shown in Figure 7, The two-dimensional field patterns at the resonant frequency of 10.82 GHz, of the E_θ with Ø = 0° (E-plane) in elevation cut (x-z plane) is shown in Figure 8a, and in elevation cut (y-z plane) with Ø = 90° is shown in Figure 8b.

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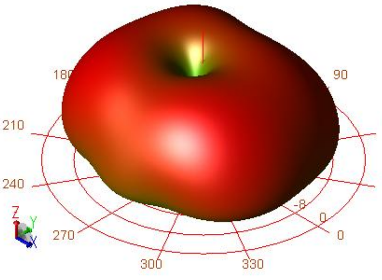

Figure 7: 3D Radiation pattern of the antenna at 10.82 GHz.

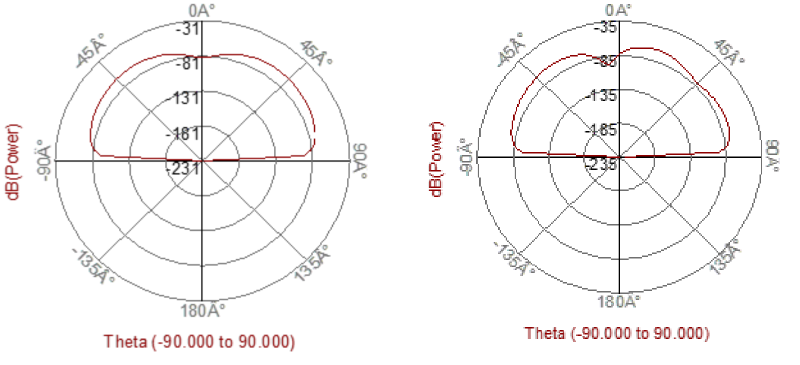

Figure 8: Field pattern at 10.82 GHz in (a) x-z plane (b) y-z plane.

With adding a superstrate layer with 1.58 mm thickness over a substrate of a proposed antenna; the effect of changing the dielectric constant of the superstrate on the return loss and impedance bandwidth of the antenna is presented in Figure 9.

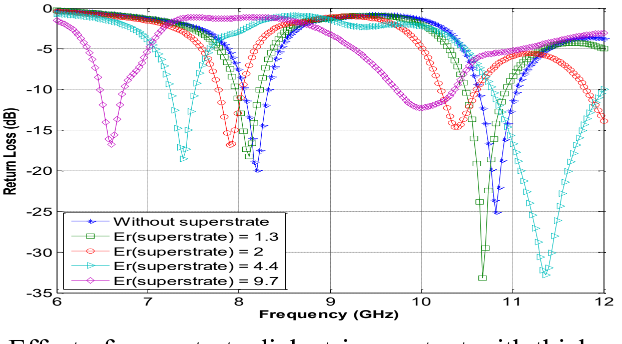

Figure 9: Effect of superstrate dielectric constant with thickness of 1.58 mm on the return loss and impedance bandwidth of antenna.

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Based on the simulated results that shown in Figure 9 and the far field results of the antenna, the variation of the antenna parameters based on the changing of the superstrate dielectric constant with thickness of 1.58 mm at the lower resonant frequency are summarized in Table 4, and at the upper resonant frequency the antenna parameters are summarized in Table 5.

Table 4: Effects of superstrate dielectric constant on the antenna parameters at lower resonant frequency.

Thickness of the superstrate is 1.58 mm					
Superstrate dielectric constant	-	1.3	2	4.4	9.7
Resonant frequency (GHz)	8.201	8.111	7.900	7.387	6.603
Return Loss (dB)	- 19.96	-18.20	-16.82	-18.53	-16.80
Impedance BW (%)	3.320	3.220	3.240	3.700	3.890
Radiated Power (mW)	1.886	1.659	1.463	1.404	1.584
Directivity (dBi)	7.490	7.693	7.863	8.075	7.853
Gain (dBi)	6.313	5.965	5.627	5.632	5.963
Efficiency (%)	76.209	67.172	59.753	56.970	64.704

From Table 4, it is illustrated that the lower resonant frequency of the proposed antenna is shifted to left in the frequency scale and the antenna operates in C band. And, it is seen that at the dielectric constant of the superstrate is greater than the dielectric constant of the substrate of the antenna; the multilayer structure has the impedance bandwidth greater that the antenna without superstrate layer. When the dielectric constant of the superstrate less than or equal the dielectric constant of the substrate, it noted that the impedance bandwidth of the multilayer stricture is less than the impedance bandwidth of the antenna without superstrate. The parameters, return loss, radiated power, gain, and efficiency decrease with covered the substrate with a superstrate layer. In addition, it can be observed the directivity of the antenna increases with increase the value of dielectric constant of the superstrate and it greater than the directivity of the antenna without superstrate.

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Table 5: Effects of superstrate dielectric constant on the antenna parameters at upper resonant frequency.

Thickness of the superstrate is 1.58 mm					
Superstrate dielectric constant	-	1.3	2	4.4	9.7
Resonant frequency (GHz)	10.82	10.67	10.40	11.37	10.01
Return Loss (dB)	-25.07	-33.21	-14.66	-32.84	-12.25
Impedance BW (%)	3.96	4.49	3.75	5.38	6.57
Radiated Power (mW)	1.839	1.652	1.502	0.981	0.821
Directivity (dBi)	6.970	7.279	7.635	9.464	10.260
Gain (dBi)	5.630	5.475	5.556	5.407	5.688
Efficiency (%)	73.442	66.010	61.960	39.300	34.900

From Table 5, it is illustrated that the upper resonant frequency of the proposed antenna is shifted according to the value of dielectric constant of the superstrate within the X-band. It is seen that the impedance bandwidth, directivity, and gain of multilayer antenna are changed; at the superstrate dielectric constant is 9.7, the best values of impedance bandwidth, directivity, and gain are 6.57%, 10.260 dBi, and 5.688 dBi respectively. The radiated power, and efficiency decrease with covered the substrate with a superstrate layer.

The effect of changing the thickness of the superstrate on the antenna parameters with the dielectric constant of the superstrate of 1.3 is presented in Figure 10. Based on the simulated results that shown in Figure 10 and the far field results of the antenna, the variation of the antenna parameters based on the changing of the superstrate thickness with dielectric constant of 1.3 at the lower resonant frequency are summarized in Table 6, and at the upper resonant frequency are summarized in Table 7.

From Table 6, it is illustrated that the lower resonant frequency of the proposed antenna has a small shift with changing the thickness of the superstrate within the X-band. It is seen that the impedance bandwidth, and directivity are increased, the best values of impedance bandwidth, and directivity are 3.53%, and 7.833 dBi respectively, when the superstrate thickness is 3 mm. The radiated

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power, gain and efficiency decrease with increase the thickness of the superstrate layer, the best value of them at the antenna without superstrate layer.

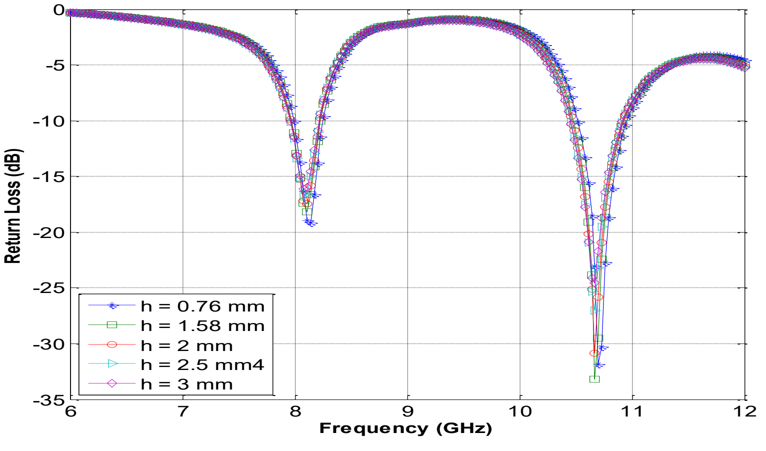

Figure 10: Effect of superstrate thickness with dielectric constant of 1.3 on the return loss and impedance bandwidth of antenna.

Table 6: Effects of superstrate thickness on the antenna parameters at lower resonant frequency.

Dielectric constant of the superstrate is 1.3					
Superstrate thickness (mm)	0.76	1.58	2	2.5	3
Resonant frequency (GHz)	8.141	8.111	8.111	8.080	8.080
Return Loss (dB)	-19.16	-18.20	-17.47	-16.68	-16.12
Impedance BW (%)	3.15	3.22	3.22	3.53	3.53
Radiated Power (mW)	1.770	1.659	1.603	1.550	1.504
Directivity (dBi)	7.591	7.693	7.772	7.764	7.833
Gain (dBi)	6.141	5.965	5.913	5.785	5.732
Efficiency (%)	71.610	67.172	65.184	63.389	61.635

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Table 7: Effects of superstrate thickness on the antenna parameters at upper resonant frequency.

Dielectric constant of the superstrate is 1.3					
Superstrate thickness (mm)	0.76	1.58	2	2.5	3
Resonant frequency (GHz)	10.70	10.67	10.67	10.67	10.67
Return Loss (dB)	-31.85	-33.21	-30.83	-27.06	-24.53
Impedance BW (%)	4.00	4.49	4.49	4.21	4.21
Radiated Power (mW)	1.735	1.652	1.622	1.594	1.574
Directivity (dBi)	7.119	7.279	7.477	7.455	7.531
Gain (dBi)	5.525	5.475	5.477	5.487	5.501
Efficiency (%)	69.280	66.010	64.758	63.573	62.658

The upper resonant frequency is remains constant within X-band range with change the thickness of superstrate as shown in Table 7. It is seen that the impedance bandwidth, and directivity are increased, the best values of impedance bandwidth, and directivity are 4.21%, and 7.531 dBi respectively when the superstrate thickness is 3 mm. The best value of the radiated power, gain and efficiency at the antenna without superstrate layer, where they decrease with increase the thickness of the superstrate layer.

Figure 11, shows the effect of changing the thickness of the superstrate on the antenna parameters with the dielectric constant of the superstrate of 9.7.

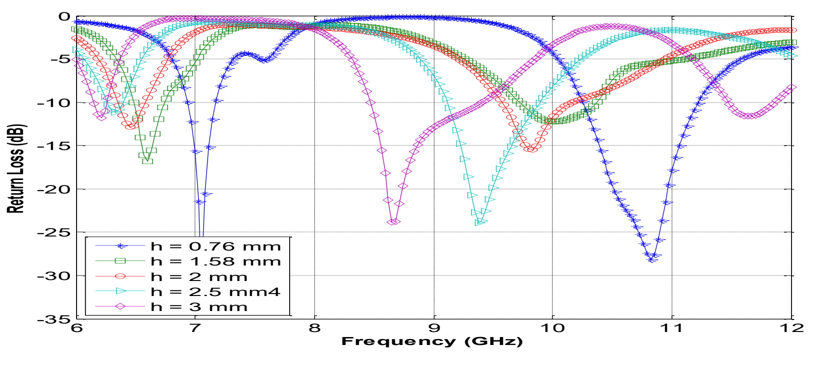

Figure 11: Effect of superstrate thickness with dielectric constant of 9.7 on the return loss and impedance bandwidth of antenna.

Table 8, presents the variation of the antenna parameters based on the changing of the superstrate thickness at the lower resonant frequency with the dielectric constant of the superstrate of 9.7, and at the upper resonant frequency are summarized in Table 9.

As shown in Table 8, the lower resonant frequency is shifted to C band range with change the thickness of superstrate. From the Table, it is seen that all parameters are changed, where the best values of impedance bandwidth are 3.89 at the thickness of the superstrate is 1.58 mm; directivity is 10.205 dBi at the thickness of the superstrate is 2 mm; and gain, radiated power and efficiency are 7.602 dBi, 2.253 mW and 97.575% respectively when the superstrate thickness is 2.5 mm.

Table 8: Effects of superstrate thickness on the antenna parameters at lower resonant frequency (8.2GHz).

Dielectric constant of the superstrate is 9.7					
Superstrate thickness (mm)	0.76	1.58	2	2.5	3
Resonant frequency (GHz)	7.055	6.603	6.452	6.332	6.211
Return Loss (dB)	-31.246	-16.80	-12.86	-11.17	-11.78
Impedance BW (%)	3.28	3.89	3.73	2.07	1.77
Radiated Power (mW)	1.661	1.584	1.078	2.253	1.810
Directivity (dBi)	7.380	7.854	10.205	7.709	8.467
Gain (dBi)	5.607	5.963	6.757	7.602	7.364
Efficiency (%)	66.469	64.704	45.203	97.575	77.566

From Table 9, it seen that the upper resonant frequency is shifted to left within X-band range with change the thickness of superstrate. It is seen that the best values of impedance bandwidth, the directivity, gain, is 10.46% at thickness of the superstrate is 3 mm, 10.260 dBi at thickness of 1.58 mm; and 6.859 dBi at thickness of the superstrate is 2 mm, respectively. At 0.76 mm thickness of the superstrate, the best values of radiated power and efficiency are 1.661 mW, and 66.469%.

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Table 9: Effects of superstrate thickness on the antenna parameters at upper resonant frequency (10.82GHz).

Dielectric constant of the superstrate is 9.7					
Superstrate thickness (mm)	0.76	1.58	2	2.5	3
Resonant frequency (GHz)	10.820	10.010	9.829	9.377	8.653
Return Loss (dB)	-28.13	-12.25	-15.46	-23.89	-23.83
Impedance BW (%)	3.28	6.57	6.00	8.03	10.46
Radiated Power (mW)	1.661	0.821	1.203	1.403	0.718
Directivity (dBi)	7.380	10.260	9.911	9.244	9.208
Gain (dBi)	5.607	5.688	6.859	6.748	3.807
Efficiency (%)	66.469	34.894	49.522	56.288	28.788

5. Conclusion

This study investigated the effect of dielectric superstrate permittivity and thickness on a compact dual-band microstrip patch antenna using full-wave MoM simulations. The results show that low-permittivity superstrates ($\varepsilon r = 1.3$) maintain X-band operation while providing improved bandwidth, reaching 3.53% at the lower resonance and 4.49% at the upper resonance. In contrast, high-permittivity superstrates ($\varepsilon r \geq 4.4$) produce a stronger downward shift of the lower resonance toward the C-band, reaching 6.21 GHz for $\varepsilon r = 9.7$ and $t = 3$ mm, while increasing directivity up to 10.26 dBi and upper-band bandwidth up to 10.46%. The optimum superstrate thickness depends on the required performance objective, since bandwidth, directivity, gain, and radiation efficiency do not vary monotonically with thickness. Overall, the study provides practical design guidelines for selecting superstrate permittivity and thickness according to the desired balance between frequency stability, bandwidth, directivity, and efficiency.

6. Limitations and Future Research

This study is limited to full-wave electromagnetic simulations using the Method of Moments (MoM), without experimental validation. Future work should include antenna fabrication and experimental

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measurements to validate the simulated results, investigate a wider range of superstrate materials and thicknesses, and evaluate the effects of material losses, fabrication tolerances, and superstrate spacing on antenna performance.

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