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Performance Enhancement of Patch Antenna using Cut Slot Techniques for Dual-Band Applications

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Abstract

The microstrip patch antenna has been developed and analyzed to meet the increasing demand for cost-effective, low-profile antennas suitable for various wireless applications, such as mobile phones and communication devices. To improve performance, the proposed design integrates a cut-slot structure and an inset feed technique. The proposed antenna design uses a cotton, with a dielectric constant of 1.61 and a loss tangent of 0.01, as the substrate material, offering a low dielectric constant to minimize return loss. Simulations, conducted using CST (Computer Simulation Technology) software, demonstrate a dual-frequency operation at 1.76 GHz and 3.42 GHz, suitable for targeted S-band applications. The final antenna structure achieves a gain enhancement of 5.43 dBi, indicating a significant improvement in performance.

Keywords: CST, Gain, Patch Antenna, Inset Feed.

1. Introduction

A patch antenna [1] is a low-profile antenna and is widely utilized in communication systems due to its compact size, reliable performance, and ease of fabrication. While traditionally designed for single-frequency operation, patch antennas are well-suited for narrowband applications [2] [3]. However, the growing demand for multi-functional systems capable of operating across multiple frequency bands has driven the development of dual-band and multi-band antennas. Gain enhancement is essential for improving the performance of such antennas for applications in satellite communications, radar systems, wireless networks, and wearable devices.

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An effective approach for achieving dual-band performance in patch antennas is the implementation of cut-slot techniques [4]. By introducing strategically positioned cuts or slots in the conductive patch, the antenna can support multiple resonant frequencies, enabling operation in dual-band or multi-band modes. These modifications alter the current distribution on the patch, creating additional resonant modes without significantly increasing the antenna's size.

The cut-slot technique is particularly advantageous for modern communication systems requiring operation across various frequency bands, including Wi-Fi, Bluetooth, GPS, and cellular networks [5]. Designing a compact antenna that resonates at two or more distinct frequencies offers several benefits, such as saving space, reducing weight, and minimizing system complexity, making it ideal for portable and multifunctional devices.

Navpreet Kaur & Narinder Sharma et al. [6] designed a patch antenna featuring rectangular shapes and circular slots to enhance its gain. The FR-4 substrate was used for fabricating the antenna. It was observed that the gain improved with each iteration of the design. The final version of the patch antenna exhibited gains of "1.07 dB at 2.81 GHz, 2.53 dB at 5.81 GHz, 5.94 dB at 7.81 GHz, 6.20 dB at 8.00 GHz, and 9.30 dB at 8.72 GHz," respectively, and effectively resonated at five different frequencies ranging from 2 GHz to 9 GHz.

Ajay Singh & Sunil Joshi et al. [7] exhibited the construction of a rectangular slot Defected Ground Structure (DGS) patch antenna for 5G wireless communication applications that is fed by a microstrip line. Three distinct frequency bands—4.0 GHz, 4.9 GHz, and 5.5 GHz—are used by this antenna. The antenna's impedance bandwidths are 9%, 8.9%, and 5.1%, which convert to bandwidths of 443 MHz, 287 MHz, and 356 MHz, for the corresponding frequency bands, while its gains are 2.69 dBi, 11.37 dBi, and 7.27 dBi, . FR-4 is the substrate utilized in this design.

Maie A. Gaber et al. [9] designed a defective ground structure patch antenna featuring three U-shaped slots in the ground plane, utilizing a ceramic-filled PTFE composite as the substrate. The antenna operated across three frequency ranges: 2.93–3.07 GHz with a 0.14 GHz bandwidth, 6.07–6.21 GHz with a 0.14 GHz bandwidth, and 7.87 to 8.47 GHz with a 0.6 GHz bandwidth.

The reviewed literature highlights various slot designs and their effects on antenna performance. Researchers in [8], [10] have proposed several strategies to enhance the gain of patch antennas, such as increasing the patch height, increasing substrate thickness, and reducing substrate permittivity. However, increasing substrate thickness makes the antenna unsuitable for wearable applications, and using high-cost substrates like Rogers or nanofilms increases the overall expense. These challenges can be addressed by adopting lightweight, flexible substrates combined with a simple cut-slot design.

This research explores the design and development of a dual-band patch antenna using cut-slot techniques. The dual-band functionality is achieved by strategically introducing slots into the patch, allowing the antenna to resonate at two different frequencies.

Cotton [11] is employed as the substrate due to its lightweight, flexible, and eco-friendly nature, making it ideal for wearable and textile-based antenna applications. The substrate's characteristics, such as low relative permittivity and loss tangent, play an important role in enhancing the antenna's performance in terms of resonance, bandwidth, and radiation efficiency. Cotton-based antennas are well-suited for applications in wearable devices, healthcare monitoring, and IoT systems.

The major contributions of this research are to:

- Introduce cotton as a substrate for antenna design.
- Enhancing antenna performance through cut-slot techniques, enabling dual-band operation.

The research is structured as follows: Section 2 covers the antenna design, Section 3 presents the antenna simulation, Section 4 discusses the results, and Section 5 provides conclusions and future directions.

2. Antenna Design

The parameters of the antenna structure, such as the Length and width of the patch at a frequency of around 2.5GHz, are calculated using standard equations for patch antennas. A rectangular patch antenna is designed with various textile substrate materials, including jeans, cotton, felt, and polyester, using Computer Simulation Technology (CST) Studio Suite 2024 version [13]. The results are presented in Table 1.

Each substrate material (jeans, cotton, felt, and polyester) is used with the rectangular patch antenna at different frequencies, resulting in varying output values. Among the tested materials, the antenna with a cotton substrate demonstrated superior output parameters, such as VSWR, gain, return loss, and directivity, compared to the other substrate materials.

Table 1. Design of Rectangular Patch Antenna using Identified Textile and Non-Textile FR-4 Substrate Materials

Substrate material	**Dielectric constant, εr**	**Loss Tangent, tan σ**	**Frequency (GHz)**	**Return Loss, S11 (dB)**	**VSWR**	**Gain (dBi)**
Jeans	1.60	0.085	2.52	-8.4	1.9	-0.2
Cotton	1.61	0.010	2.65	-15.1	1.5	1.2
Felt	1.45	0.02	2.45	-12.6	1.2	3.7
polyester	1.90	0.0045	2.42	-10.1	1.3	0.3
FR-4	4.4	0.02	2.45	-8.4	1.7	0.72

In this work, cotton, with a dielectric constant of εr = 1.61 and a loss tangent of 0.01, is explored as a promising substrate for flexible antennas operating in the ISM band. Unlike rigid substrates such as FR4 (εr = 4.4), which introduce higher losses and reduce efficiency, cotton's lower dielectric constant minimizes surface wave losses and enhances radiation efficiency. This study represents an initial effort to demonstrate cotton as an effective material for flexible antenna applications.

The flexible microstrip patch antenna is designed using cotton as the substrate, taking advantage of its low dielectric constant, which helps achieve a low return loss. Copper is used for the ground plane, patch, and strip line. The cotton material is securely fixed onto the copper ground plane. A slot is introduced in the antenna design to reduce its size, which leads to improved gain. Both the patch and strip line are made of copper and are mounted on the cotton substrate.

2.1 Proposed Antenna

Using standard patch antenna equations [14] [15], the design parameters are calculated and summarized in Table 2. Both the patch and the stripline are made of copper. Since the patch has a square shape, each side measures 49 mm in length with a thickness of 0.1 mm.

Table 2. Proposed Antenna's Parameters

Parameters	Dimensions
Patch Length	47.50 mm
Patch Width	53.50 mm
Substrate	60 x 60 mm^2
Ground Plane	60 x 60 mm^2
Stripline and PatchThickness	0.03 mm
Thickness (Ground plane)	0.1mm
Thickness(Substrate)	1mm

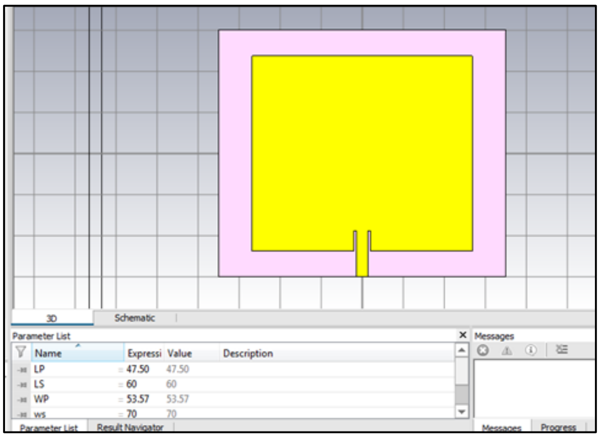

Figure 1. Structure of Rectangular Patch Antenna

The rectangular shaped patch designed is shown as in Figure 1. After optimization, the length and width of the patch is resized to 47.50 mm and 53.50 mm respectively. The thickness of stripline is 0.3mm. The substrate is 60 mm in length and 60 mm in breadth. The substrate has a thickness of 1 mm. The ground plane is made of copper. The width and length of the ground plane are the same as those of the substrate. The Ground Plane has 0.03 mm as the thickness.

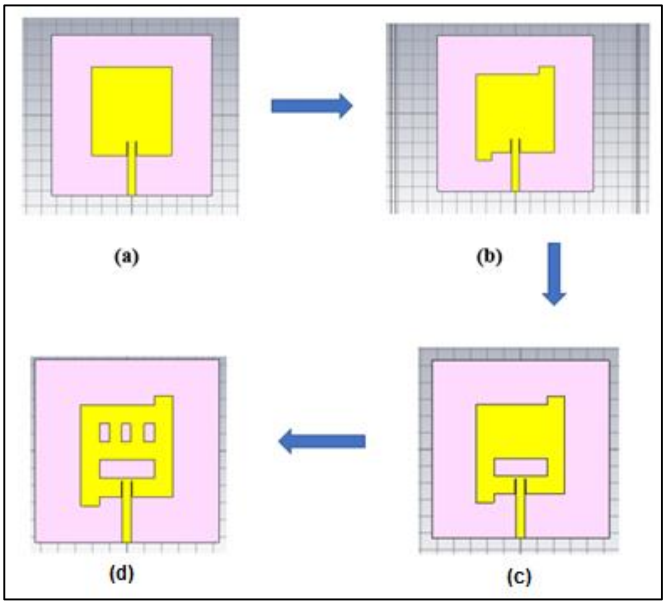

Figure 2. Step by Step Implementation of the Structure of Designed Antenna (a)Design 1 (b)Design 2 (c) Design 3 (d) Design 4

To enhance performance, the antenna is designed using three different models, distinct from the conventional rectangular patch as shown in Figure 2 (b) to (d). In design 2, some portion of the top and bottom part of the rectangular patch is removed, and the design is simulated. Then, the slot is introduced in design 2, and the performance is tabulated. Then, small holes were introduced in the upper portion of the patch.

3. Antenna Simulation

The simulation of the antenna design is carried out by using Computer Simulation Technology (CST) Studio Suite 2024 version. Using the CST studio suite, all the designs are simulated, and the results are compared as in Table 3. Out of 3 designs, Design 4 shows better results.

Table 3. Comparison of Antenna Parameters for Various Designs Simulation Results

Parameters	Design 2	Design 3	Design 4
Resonant Frequency	2.45 GHz	2.2 GHz	1.76GHz and 3.4 GHz
Return Loss, S11 (dB)	-12	-15.23	-22.67 & -25.78
VSWR	1.65	1.54	1.27 & 1.10
Directivity, dBi	1.78	4.23	7.98 & 8.25
Gain,dBi	1.2	2.29	3.01 & 5.43

In antenna design, return loss plays a important role in determining how well an antenna matches the transmission line's impedance. The software stimulated antenna's S-Parameter results are -22.67 dB and -25.78 dB at 1.76 Ghz and 3.4 Ghz respectively as shown in Figure 3.

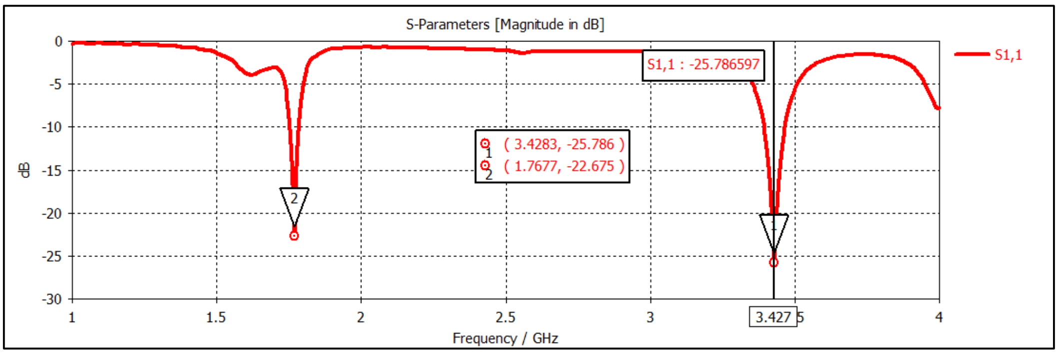

Figure 3. S-Parameter of Simulated Antenna

VSWR (Voltage Standing Wave Ratio) is a measure of the efficiency with which radio-frequency (RF) power is transmitted through a transmission line (such as a coaxial cable) and into a load. The software stimulated antenna's VSWR results are 1.27 and 1.10 at 1.76 Ghz and 3.4 Ghz respectively as shown in Figure 4.

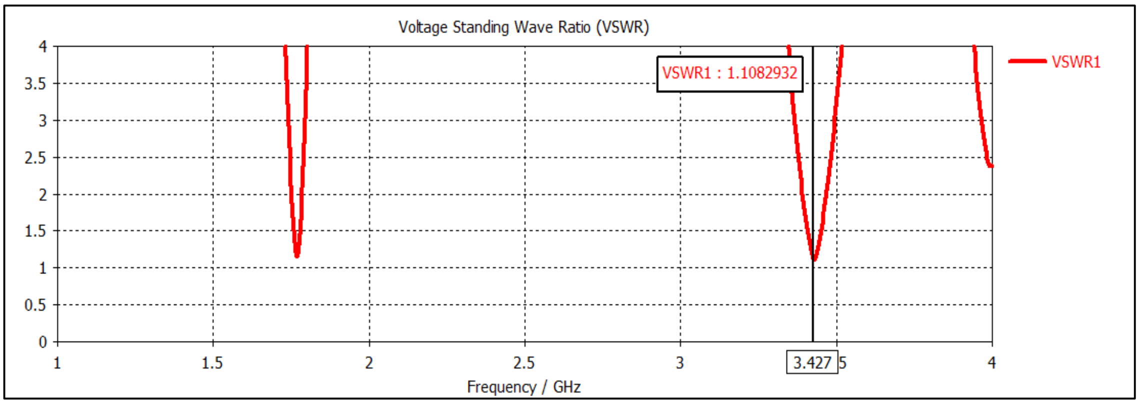

Figure 4. VSWR of Simulated Antenna

Antenna Gain is a metric that compares an antenna's ability to convert input power into radio waves in a particular direction to that of a reference antenna. The Gain of the software simulated antenna results are 3 dBi and 5.43dBi as shown in Figures 5 and 6.

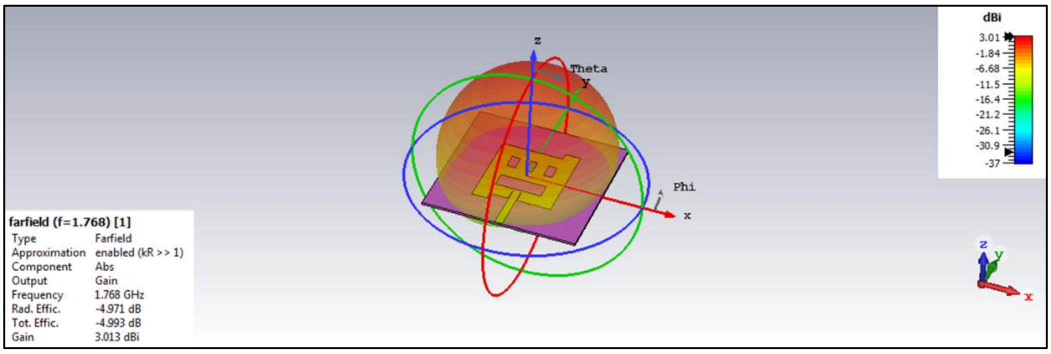

Figure 5. Gain of Simulated Antenna at 1.76Ghz

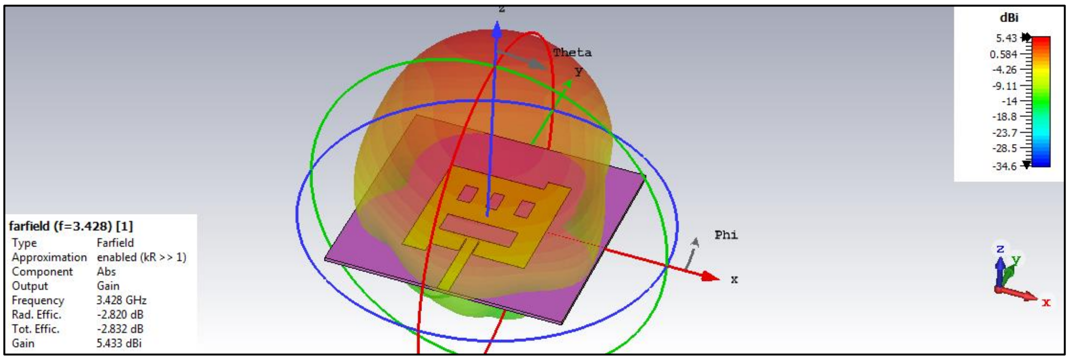

Figure 6. Gain of Simulated Antenna at 3.4Ghz

The Directivity of the software-simulated antenna results in 7.98 dBi and 8.25dBi as shown in Figures 7 and 8. Directivity measures how concentrated an antenna's radiation pattern is in a specific direction and is expressed in dB. A higher directivity indicates a more focused beam, allowing the signal to travel further.

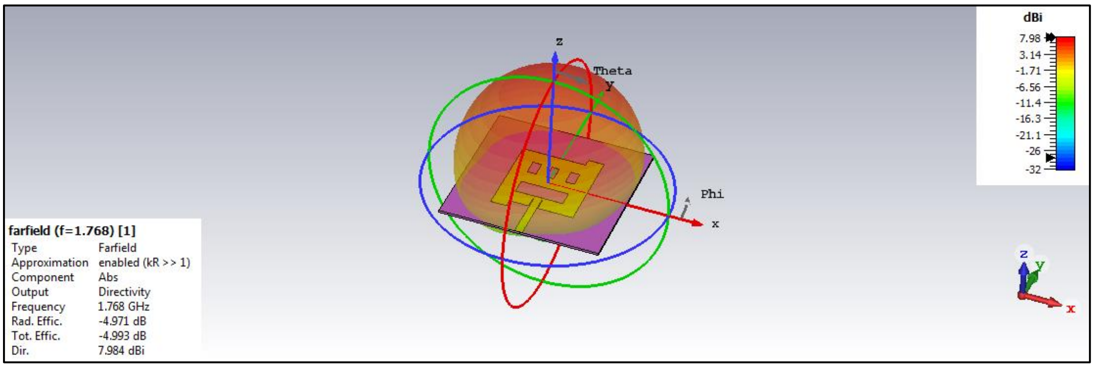

Figure 7. Directivity of Simulated Antenna at 1.76Ghz

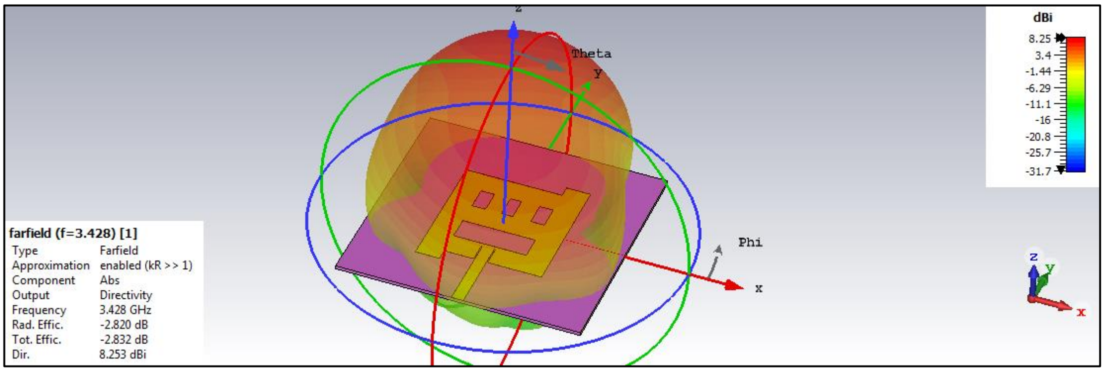

Figure 8. Directivity of Simulated Antenna at 3.42 GHz

An antenna that radiates equally in all directions is omnidirectional. While high directivity can be beneficial, it is not always ideal. For applications like mobile devices, omnidirectional antennas with low or no directivity are preferred. In contrast, high-directivity antennas are used in fixed installations, such as satellite television, where signals must be transmitted and received over long distances in a specific direction.

4. Results and Discussion

The cotton substrate is considered to be the best material with low return loss compared to other textile materials. The Voltage Standing Wave Ratio (VSWR), return loss, gain, and directivity are obtained at 1.76 GHz and 3.42 GHz. The simulated value of the proposed antenna is shown in Table 4.

Table 4. Comparison of Simulated Antenna Results

Frequency (GHz)	S11 (dB)	VSWR	Gain (dBi)	Directivity (dBi)
1.76	-22.67	1.27	3.01	7.98
3.42	-25.78	1.10	5.43	8.25

The proposed antenna is resonated at dual frequencies 1.76 GHz and 3.42 GHz respectively. The work stated in [6] employed FR-4 have gain of 1.07dB at 2.81 GHz and 2.53dB at 5.9 GHz which is less efficient than the proposed work. The parameters Return loss, VSWR, Gain and Directivity of the proposed design also have better values for both frequencies which suits the antenna for S band (1-4 GHz) applications such as Wi-Max, Wi-Fi, ISM band applications.

5. Conclusion

The proposed antenna is the primary approach for using cotton material as substrate. The new material functions as a good substrate material for flexible applications, according to the results. It can replace stiff substrate materials because of its low cost, extended durability, low environmental impact, and light weight. Using CST software, a patch antenna with a cut slot approach has been created. The antenna substrate and patch material are readily available, relatively affordable and they operate quite reliably. The results also show that using the proposed design, Gain value is improved.

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