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Photonic Crystal-Based Wi-Fi Patch Antenna Implemented on FR4 Substrate

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Abstract: Antennas are an important part of the current ecology of wireless communication, particularly as it concerns Wi-Fi data rates. The traditional antennas suffer from the issues of urban bandwidth constraints and material efficiency. These issues lead to bad performance and coverage of services. The proposed work outlines a distinctive rectangular patch antenna designed on the photonic crystal structure and partial ground plane at the frequency of 2.4 GHz Wi-Fi band (2.4–2.48 GHz). The antenna is constructed on 40 mm by 50 mm FR4 substrate with $\varepsilon_r = 4.3$, $tan\ \delta\ = 0.025$, 1.6 mm thick and excite by 50-ohm microstrip inset-feed to provide the optimal impedance matching. It is carried out using CST Microwave Studio Suite 2024 in terms of the design, simulation, and performance assessment. It is remarkable that the antenna has VSWR of 1.039064, return loss (S_{11}) of −34.26823 dB, and bandwidth of 180.043 MHz (2.314581 GHz to 2.494624 GHz). It would serve as an excellent choice in many Wi-Fi applications because of its incredible gain of 2.86 dBi, directivity of 4.61 dBi, and a radiation efficiency of 66.88 percent. The compact size, the wide bandwidth, and the effective signal transmission characteristics of the proposed antenna make it easy to incorporate into the smart home systems of consumer electronics and numerous devices of the Internet of Things. This research aims at making the performance and reliability of current wireless communication network in dynamic environment better and reliable through the provision of a scalable solution.

Keywords: bandwidth, partial ground plane, FR4 photonic crystal substrate, rectangular patch antenna, CST

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1. Introduction

The proliferation of wireless communication technologies driven by the popularity of Wi-Fi-enabled devices, smart home, and industrial IoT systems, and mobile computing has accelerated the need in miniature, broadband, and energy-efficient antenna systems. Antennas play a significant role in communication networks nowadays, especially in high-density urban areas, as they guarantee quality signal propagation, low delay, and high data rates [1, 2]. Microstrip patch antennas have grown in popularity among the available antenna types because of their low profile, lightweight, ease of fabrication, and ability to be made in planar circuitry as well as using standard printed circuit board (PCB) processes [3]. Their compatibility and affordability have seen them be incorporated in numerous wireless devices such as smartphones, laptops, Wi-Fi routers, wearables, and sense nodes [4].

Despite these advantages, traditional patch antennas have certain performance problems especially when the operating frequency is raised (e.g., Wi-Fi bands: 2.4 GHz and 5 GHz). Low radiation efficiency, high return loss, and impedance mismatches—typically less than 5 percent of the center frequency—are among their main faults that reduce their performance in high-speed communication networks [5]. In the case of FR4 substrates, the commonly used low-cost and physically stable materials but with high dielectric losses ($tan\ \delta$ approximately 0.02–0.025) and intermediate dielectric constant ($\varepsilon_r = 4.3$), these issues are still further apparent. These impacts are important for dielectric loss and surface wave propagation, both of which degrade the antenna's overall efficiency and signal integrity at microwave frequencies [6].

Recent research has investigated hybrid substrate techniques and structural changes that improve the performance of the antenna without compromising manufacturability to solve such problems. One such method holds the possibility of photonic crystal (PhC) structures embedded into the antenna substrate or surrounding medium [7, 8]. PhCs are fabricated dielectric materials which possess periodic variation in refractive index, which create photonic band gaps (PBGs): frequency ranges in which the propagation of electromagnetic waves is forbidden. Such constructions may effectively inhibit surface waves, lower mutual coupling, and improve impedance matching and radiation properties [9]. PhC components inserted or deposited on FR4 substrates have been shown to redistribute the surface currents and minimize the back lobes in addition to broaden the bandwidth over a longer frequency range [10]. The electromagnetic benefits of PhCs along with the cheapness of FR4 material suggest an escape from the conventional patch antenna limitations. Other enhancement techniques proven to increase gain and bandwidth include metamaterials, electromagnetic bandgap structures, and defected ground structures (DGS), but these often add complexity to a design, raise the manufacturing cost, or increase its physical dimensions [11–13]. Contrarily, PhCs provide a passive and

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planar solution available via conventional PCB-compatible production techniques.

This paper shows the design and simulation results of a rectangular microstrip patch antenna integrated with a PhC fabricated on FR4 substrate and optimized to operate in 2.4 GHz Wi-Fi band (2.4–2.48 GHz). This design has a periodic PhC structural element and uses a partial ground plane (PGP) to enhance impedance matching and the radiation characteristics. The antenna proposed has a small footprint measuring 40 mm × 50 mm that can be integrated into wireless systems with space constraints. The improved performance of the antenna was also confirmed by simulation results which were carried out in CST Microwave Studio Suite 2024 and showed a return loss of −34.26823 dB, a bandwidth of 180.043 MHz, and a radiation efficiency of 66.88 percent. These findings confirm that it is suitable in high-performance Wi-Fi applications.

The study produces the constantly evolving field of PhC-based antenna design, therefore offering an affordable, scalable, and high-efficiency design answer fit for the demands of modern wireless communication. It creates the groundwork of future advancements like multiband operation, gain boosting parasitic elements, and eventually experimental validation in actual world test systems by trading off the important compactness versus performance aspects. Small, multiband, and efficient antennas will become even more pertinent with the growth of Wi-Fi to Wi-Fi 6/6E and its integration with 5G and LTE technology. The suggested design provides the forward compatibility answer to these new wireless standards.

The rest of the paper is structured as follows: In Section 2, the literature pertaining to performance improvement of microstrip antennas by means of PhCs and hybrid substrates is reviewed. Section 3 explains the materials, PhC geometry, and simulation method. Section 4 gives the performance data of the antenna, that is, return loss, bandwidth, VSWR, gain, directivity, and radiation efficiency. Section 5 talks about performance analysis, trade-offs in the design, and limitations. Section 6 provisions compare the proposed design with works that exist.

2. Literature Review

The need to develop antenna technology, in particular, the high-frequency end of the frequency range used in Wi-Fi and other applications, has received much research in materials and structures that can provide enhanced functionality. Other substrate materials have been investigated with their respective merits accumulated in the form of gain, bandwidth, efficiency, and flexibility.

Investigating the use of Teflon as a substrate in Wi-Fi 6E operation, Kumar et al. [14] confirmed that the low dielectric constant and the low loss tangent result in significantly higher gain, radiation patterns, and bandwidth compared to common substrates. Due to the stability of its dielectric property, Teflon has potential in the emerging wireless technologies [14]. Investigating FR4 substrates, which have a certain flexibility in a range of frequencies, including 5G and satellite communications, Devi et al. [15] discovered that the dielectric losses are rather high. Their optimizations led to the minimalistic and low-cost design that aimed at a balance between the performance and the cost [15].

More recently, in 2024 de Sousa et al. [16] investigated graphene-enhanced antennas with photonic bandgap (PBG) substrates, and observed that the return loss and gain were greatly enhanced owing to the synergy between the electronic properties of graphene and the wave-control nature of PBG structures. Likewise, Brown et al. [17] demonstrated that the electromagnetic wave propagation in photonic crystal substrates can be better controlled, especially in the terahertz range.

Bendable polyimide antennas with a small footprint support a broad frequency range, such as satellite communications frequencies and 5G frequencies, which Abdelghany et al. [18] created. Polyimide materials are also flexible enabling original antenna designs which can conform to various geometries of surfaces without performance implications [18]. Moreover, with the nano patch antennas on graphene and PBG insertions, Bendaoudi et al. [19] have found that the return loss, the gain, and the bandwidth have been significantly enhanced. Their work also made high frequencies [19] confirmations of the accuracy of the combination of graphene with PBG constructions.

Kumar et al. [20] concentrated on graphene-based patch antennas in microstrip with specific reference to their application in 5G. Their research noted the advantages of PBG substrates in enhancing gain and bandwidth because of their capability of controlling electromagnetic waves [20]. Singh et al. [21] suggested triangular patch microstrip antennas in PhC substrates with the radical enhancement of radiation properties important in high-frequency communication.

Messatfa et al. [22] investigated printed antennas at 5 GHz with the use of PhC substrates, and it was realized that the latter significantly improve the performance, making them efficient and reliable in wireless communication systems. PhC and graphene-based microstrip antennas were applied by Temmar et al. [23] in the creation of a MIMO indoor communication system, showing that they can successfully work in the terahertz range to provide high-speed data transmission.

Lastly, Li et al. [24] explored patch antennas with PBG substrates comprising heterostructures finally with finite difference time domain methods. Their results provided informative clues on how PBG heterostructures can optimize antenna behavior through the minimization of return loss and gain thus helping in the onward quest of maximizing antenna efficiency [24]. This immense body of literature emphasizes the significance of the need to select appropriate substrates and perform optimization of design to ensure the improved performance of the antenna in a variety of applications. The innovations will ensure the development of more optimized excellent performance Wi-Fi, 5G, IoT, and other antennas that provide a new avenue of continuous improvement of the wireless technology being experienced.

3. Material and Methods

The processes and materials used in the construction and improvement of a patch antenna in microstrip are described in this study paper along with some advanced solutions used to raise its performance. To achieve these great characteristics, the antenna employs a hybrid PhC substrate, a PGP design method, and an inset-fed line arrangement.

3.1. FR4 PhC substrate material

The antenna utilizes a commercially available FR4 substrate, a common choice in PCB and microstrip antenna fabrication due to its favorable mechanical and electrical properties. FR4, composed of fiberglass cloth and epoxy resin, offers inherent flame retardancy (FR) and exhibits a dielectric constant of approximately 4.3 with a tangent loss of 0.025, suitable for radio frequency and microwave applications. Integration with a PC structure—a periodically engineered dielectric material—creates a hybrid substrate. This PC structure manipulates electromagnetic waves via PBGs, suppressing surface waves and consequently enhancing bandwidth and radiation characteristics [25, 26]. The resulting improved impedance matching, radiation efficiency, and gain make this hybrid substrate ideal for applications such as Wi-Fi [27].

3.2. PGP

A variation of the standard ground plane antenna is the antenna's PGP. The electromagnetic field distribution is changed by precisely cutting or erasing a segment of the ground plane beneath the radiating element, therefore improving bandwidth, impedance matching, and radiation efficiency. Particularly at high frequencies, the PGP approach helps to negate the effects of poor efficiency and narrow bandwidth that are thought to be a part of traditional patch antennas [27]. Exact geometric control of the ground plane is used to maximize antenna performance [28].

3.3. Inset-fed

The antenna is fed very tightly regulated inset feedline approach. In this technique, the microstrip feed line is placed at an exact inset point on the radiating patch. This position allows impedance matching between the patch and the feed line in order to maximize power transfer and eliminate reflections [27]. The resulting bandwidth and efficiency improvements are truly incredible. Fine control of the method enables optimization of its performance with respect to the specific requirements of the application [29].

3.4. Antenna structure and design

There are three parameters that are of interest to the construction of a rectangular microstrip patch antenna so as to achieve the optimal performance: the dielectric constant of the substrate (ε_r), the operating frequency (f_r), and the dielectric substrate thickness (h).

1) **Dielectric constant of the substrate ($\boldsymbol{\varepsilon_r}$):** The dielectric constant (ε_r) of the substrate material significantly influences the performance of the antenna. A smaller ε_r value results in wider fringes, reduced conductor loss, improved radiation, and increased bandwidth and efficiency. Conversely, a higher ε_r value leads to a decrease in the patch size of the antenna. The chosen substrate material, FR4 lossy, has a dielectric constant ε_r of 4.3, which falls within the typical range of 2.2 to 12 for microstrip patch antennas [30].
2) **Operational frequency ($\boldsymbol{f_r}$):** The resonant frequency (f_r) is imperative to antennas as it affects both their efficiency and effectiveness [31]. Within Wi-Fi-band of 2.4–2.5 GHz, there are a few advantages of the chosen resonance frequency of 2.4 GHz, including enhanced antenna performance, extended functionality of systems, and preservation of signals.
3) **Dielectric substrate thickness ($\boldsymbol{h}$):** The thickness of the dielectric substrate significantly affects various antenna parameters, including bandwidth, surface wave propagation, radiation efficiency, spurious feed radiation, and overall physical dimensions [32]. The substrate thickness of the planned antenna (1.6 mm) is better in terms of bandwidth and can provide more stability in broadband activity. However, increasing the substrate thickness also has disadvantages such as increasing the surface wave energy, spurious feed radiation, and reduction in the radiation efficiency. These elements ought to be balanced to form a small, effective, and very effective antenna.

3.4.1. Design equations

Following here are the design equations for the suggested antenna:

1) **Step 1: the patch's width ($\boldsymbol{W}$) [33]:**

The microstrip patch antenna's width (W) is found using the next formula:

$$\mathrm{W} = \frac{\mathrm{c}}{2\mathrm{f_r}\sqrt{\frac{(\varepsilon_\mathrm{r}-1)}{2}}} \tag{1}$$

Where:

c = light speed in vacuum (approximately 3 × 10^8 m/s)
f_r = resonant frequency
ε_r = relative permittivity of the substrate

Patch width from Equation (1) is determined by the dielectric constant of the substrate material and the resonance frequency. Because it controls the resonant frequency, antenna bandwidth, and radiation pattern, the width is rather crucial. Since it is necessary for their intended wireless communication application and it resonates at the intended operating frequency, designers also choose the appropriate antenna width.

2) **Step 2: substrate thickness ($\boldsymbol{h}$) [33]:**

The efficient radiations and good operations of a microstrip patch antenna require that the width of the patch (W) ought to be large compared to the substrate thickness (h). The relationship can be commonly written as:

$$W/_{h} > 1 \tag{2}$$

This requirement makes the patch width to be much greater than the substrate thickness which is important in efficient radiation.

3) **Step 3: $\boldsymbol{\varepsilon_{reff}}$ (effective dielectric constant) [33]:**

A parameter that is vital in the design of patch antennas in microstrip is the effective dielectric constant (ε_{reff}). It considers the fringing fields which extends beyond the dielectric substrate causing the antenna to look larger physically than its actual size. It is particularly important when the substrate is of low dielectric constant or is thick compared with the wavelength.

The expression to compute effective dielectric constant is:

$$\varepsilon_\mathrm{reff} = \frac{\varepsilon_\mathrm{r}+1}{2} + \frac{\varepsilon_\mathrm{r}-1}{2}\left[1+12\frac{\mathrm{h}}{\mathrm{w}}\right]^{-\frac{1}{2}} \tag{3}$$

Where:

h = thickness of the substrate

This constant is very crucial in determining the size of the patch antenna in terms of length and width since it affects resonant frequency and impedance. The fringing effects always cause the effective dielectric constant to be lower than the actual dielectric constant (ε_{reff}). $\left[1+12\frac{h}{w}\right]^{-\frac{1}{2}}$ is the ratio of the electric field in the air above the substrate to that in the dielectric material. The modification is beneficial towards the proper simulation of the electromagnetic performance of the patch antenna resulting in improved performance prediction and design optimization.

4) **Step 4: patch length ($\boldsymbol{L}$) [33]:**

Among the most important physical factors of a microstrip patch antenna that specifies the resonant frequency and so its performance is patch length (L). The computation takes into account the fringing effect (ΔL) in increasing length as well as the effective length (L_{eff}).

$$L = L_{eff} - 2\Delta L \tag{4}$$

Where:

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} \tag{5}$$

The length extension brought on by fringing fields is known as ΔL and is specified by:

$$\Delta L = 0.412\mathrm{h}\frac{\left(\varepsilon_{reff} + 0.3\right)\left(\frac{\mathrm{w}}{\mathrm{h}} + 0.264\right)}{\left(\varepsilon_{reff} - 0.258\right)\left(\frac{\mathrm{w}}{\mathrm{h}} + 0.8\right)} \tag{6}$$

Taking into account the geometry of the patch and the dielectric constant, the effective length, L_{eff}, is determined. The term $2\Delta L$ helps to explain the extra length brought by the fringing fields at the edges of the patch. Calculating the resonant frequency of the antenna depends on this correction, typically derived from empirical formulae or simulation programs, which considers the substrate material and patch size, L_{eff} and ΔL.

5) **Step 5: length of substrate (L_s) and width (W_s) equals length of ground plane (L_g) and width (W_g):**

The sizes of the substrate and ground plane are especially important in antenna design—specifically microstrip patch antennas—for best performance. The substrate affects the electromagnetic characteristics of the antenna as well as gives it mechanical support.

The length and width of the ground plane help to define the equations for the substrate length (L_s) and width (W_s). Ahmed et al. [33] list these dimensions:

$$L_s = L_g = \mathrm{L} + 6\mathrm{h} \tag{7}$$

$$W_s = W_g = \mathrm{W} + 6\mathrm{h} \tag{8}$$

These calculations guarantee that the antenna's performance parameters—including bandwidth, gain, and radiation efficiency—are best by providing a steady foundation and appropriate grounding for the substrate and ground plane.

6) **Step 6: length and width of inset feedline of rectangular patch antenna:**

Following formulas will be taken by utility to find the lengths and widths of an inset feedline on a rectangular patch antenna.

a. Inset feedline width (W_f) [30]:

The width of the inset feedline is calculated by the following formula:

$$W_f = \frac{W}{2\sqrt{2}} \tag{9}$$

Where:

W = width of the patch antenna

b. Inset feedline length (L_f) [30]:

The inset feedline's length is calculated as follows:

$$L_f = \frac{L}{\pi}\arcsin\left(\frac{W_f}{W}\right) \tag{10}$$

Where:

L = length of the patch antenna
W_f = inset feedline width

c. Inset distance (y_0) [34]:

The distance from the edge of the patch to the point where the inset feedline connects (y_0) is:

$$y_0 = \frac{W - W_f}{2} \tag{11}$$

Where:

W is width of the patch antenna
W_f is inset feedline width

This equation set locates and determines the dimensions of the inset feedline. Its correctness is imperative because this is the basis on which impedance matching between the feedline and radiating patch occurs. Proper impedance matching is vital since it helps to minimize signal reflections and maximize power transmission, therefore ensuring the antenna functions at the intended resonant frequency.

3.4.2. *Proposed antenna structure*

All four major antenna design elements shown in Figure 1 are conscientiously selected for their performance. These include the FR4 PhC substrate, rectangular patch, PGP, and 50-ohm inset feedline.

The PhC substrate, built upon the FR4 substrate thereby being the most common type of material found in PCB fabrication, is said to have some periodic structure governing electromagnetic wave propagation in it. The substrate has a dielectric constant of $\varepsilon_r = 4.3$ and $tan\ \delta = 0.025$. The substrate size is set to 40 mm × 50 mm ($L_s \times W_s$), having a thickness (h) of 1.6 mm from the lower surface, right on the ground plane.

The rectangular patch ($L \times W$) 29.75 mm × 38.75 mm, which is the radiating element, lies on a PGP ($L_g \times W_g$) of 40 mm × 34 mm, limiting the antenna size and also facilitating improved radiation patterns. Both the patch and ground plane are made of annealed copper with a uniform thickness (t) of 0.035 mm. The copper has excellent electrical conductivity that facilitates a smooth flow of current along with minimum signal losses.

A 50 Ohm inset feedline is used by the antenna to connect the patch to external circuitry. Measuring 16.1 mm × 3.137 mm ($L_f \times W_f$), the inset feedline guarantees best impedance matching and lowest reflections for maximum power transfer with an inset distance (y_0) of 1.3 mm and an inset gap (g) of 1 mm. The parameters of the antenna in Table 1 were tuned to ensure proper operation in the 2.4 GHz Wi-Fi band. Thus, the design and all of its parameters are modeled into the CST MW studio software, which guarantees the final design will fit all requirements for Wi-Fi applications.

4. Simulated Results

This segment discusses in detail the performance metrics of the designed antenna being analyzed with respect to the CST Microwave Studio software simulation at a resonant frequency of 2.4 GHz. Following the simulation results are the realized features of the antenna regarding return loss, bandwidth, VSWR, gain, directivity, radiation pattern, and efficiency. These parameters are the metrics for identifying the performance of the antenna as regards its possible applications.

4.1. Return loss (S_{11})

Return loss (S_{11}) measures how much power is fed back to the source as a result of impedance mismatch between the antenna and the feedline. It is usually expressed in decibels (dB). The degree of

Figure 1
Geometry of the proposed with partial ground plane: (a) front view, (b) back view, and (c) structure of photonic crystal in substrate

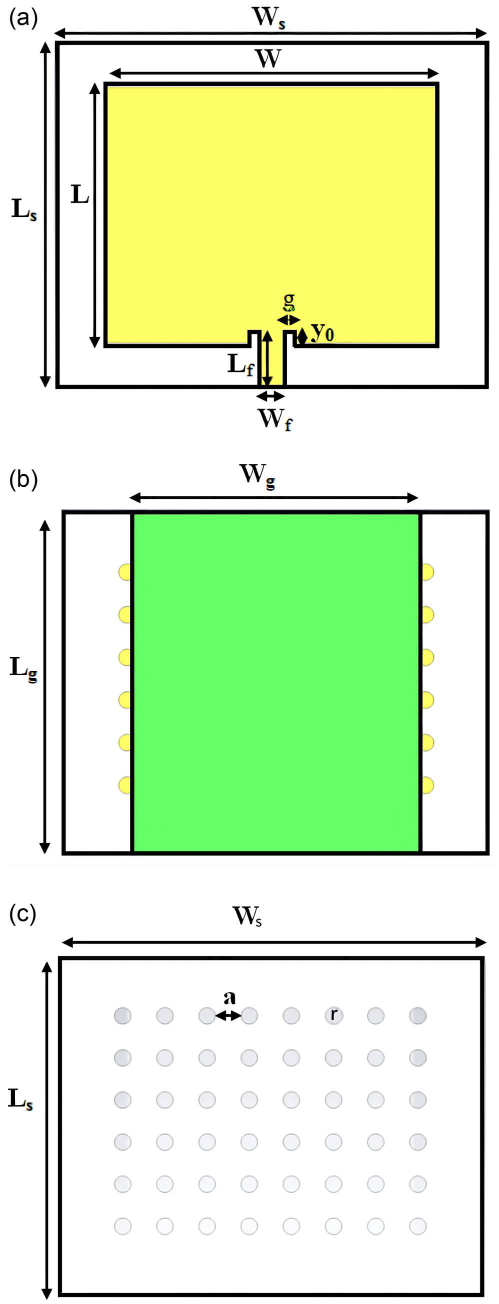
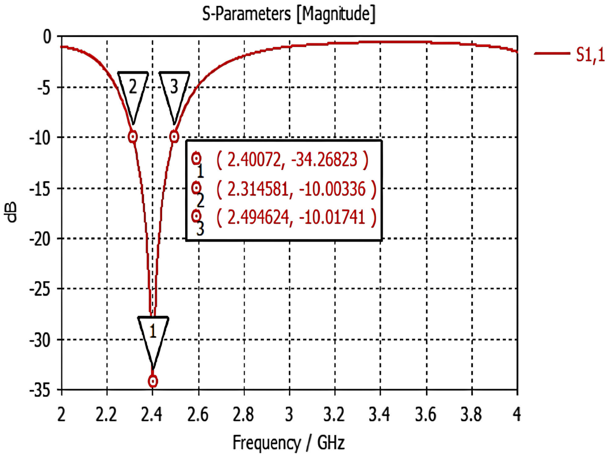


Table 1
Geometric characteristics of the proposed antenna under consideration

Parameters	Value
Frequency band used	Wi-Fi
Operating frequency, f_r (GHz)	2.4
Substrate dielectric constant, ε_r	4.3
Substrate thickness, h (mm)	1.6
Substrate length, L_s (mm)	40
Substrate width, W_s (mm)	50
Substrate hole radius, r (mm)	1
Substrate hole gap, a (mm)	5
Partial ground width, W_g (mm)	34
Ground length, L_g (mm)	40
Patch length, L (mm)	29.75
Patch width, W (mm)	38.75
Copper thickness, t (mm)	0.035
Width of the feed, W_f (mm)	3.137
Length of the feed, L_f (mm)	16.1
Inset distance, y_0 (mm)	1.3
Inset gap, g (mm)	1
Characteristics impedance of feedline (Z_0)	50 Ω

Figure 2
Return loss (S_{11}) characteristics of the proposed antenna



S_{11} indicates the performance of the antenna when it comes to matching the impedance since a low S_{11} guarantees efficient power transfer and little signal reflection. Generally, for practical antennas, less than –10 dB of return loss is acceptable since more than 90% of the input power is so radiated rather than reflected. High S_{11} values, on the contrary, signify that matching is poor, and increased reflection will result in a decrease in efficiency.

Figure 2 depicts the return loss (S_{11}) characteristics of the proposed antenna simulated using CST Microwave Studio Suite 2024. At the resonant frequency of 2.4 GHz, the antenna achieves an S_{11} of –34.26823 dB, which falls within the Wi-Fi band (2.4–2.48 GHz). This value, based on $|\Gamma| = 10^{\frac{-S_{11}}{20}} \approx 0.0199$, indicates that only ~1.99% of the input power is reflected with ~98.01% effectively transmitted or absorbed. This is already significantly above the -10 dB threshold, which certainly suggests a superior impedance match because of PhC-enhanced FR4 substrate and the 50 Ω inset-feed design.

This is a notable enhancement compared with the traditional antennas that tend to have high return losses [33–40]. Its low S_{11} enables the antenna to operate effectively across various 2.4 GHz applications, including WLAN, Bluetooth, ISM, 4G LTE, microwave ovens, S-Band, and RFID. The minimized reflection improves efficiency and provides stable communication. These measurements confirm the suitability of the antenna in small, low-cost wireless applications that need high efficiency operation. The efficiency of design suggested by the low return loss makes it a possible solution in the contemporary wireless platforms, and eventually, the design will be experimentally verified to ascertain its practical operation.

4.2. Bandwidth

The range of frequencies within which an antenna has acceptable impedance matching and therefore low reflection of signal and efficient transfer of power is the bandwidth. It is usually characterized by the range of frequencies over which the return loss is less than −10 dB, or in other words, less than 10 percent of the applied power is reflected. It has been seen from Figure 2 that the bandwidth of the proposed antenna was determined from the return loss curve. The antenna is said to have return loss of less than 10 dB from 2.314581–2.494624, which correlates to 0.180043 (180.043 MHz) measured bandwidth. Such a large operational bandwidth area confirms that the antenna can perform satisfactorily in the 2.4 GHz frequency band.

The higher the bandwidth, the more diverse the communications systems and standards the antenna can support, including Wi-Fi, WLAN, Bluetooth, ISM Band, 4G LTE, RFID, S-Band, Wireless Communication Services (WCS), WiMAX, and even microwave ovens. Further, broad bandwidth guarantees flexibility to variations in frequency with alterations in temperature, aging of materials, or production tolerances to guarantee similar performance under realistic conditions. The antenna has better bandwidth performance than the previously published structures in literature [33–40]. Such enhancement shows the efficiency of the suggested PhC-based design in supporting a wider frequency range. It guarantees robust, effective communication especially to systems functioning near the 2.4 GHz frequency. This capability of having good impedance matching over a broader frequency range not only enhances the versatility of the antenna but also renders it into a viable solution to multiband and high-speed wireless communication systems. This makes it applicable to contemporary, small, and budget-conscious wireless applications.

4.3. VSWR

The VSWR measures how effectively an antenna is attached to its transmission line. It indicates whether the antenna impedance matches the transmission line impedance, thus allowing the maximum amount of power to be transferred. VSWR is derived by the ratio of maximum voltage to minimum voltage on the transmission line. This change is due to the interference of the transmitted and the reflected signals.

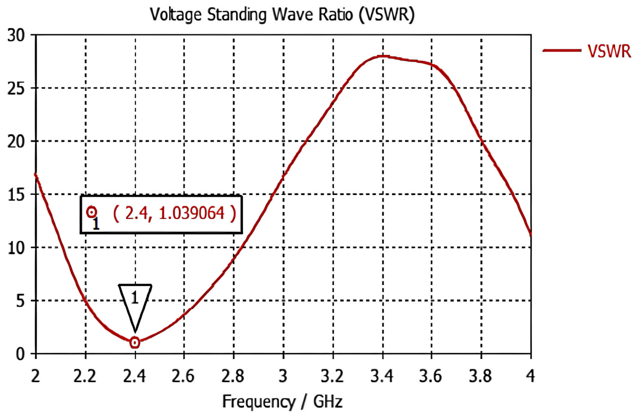
A VSWR of 1 denotes the condition of perfect impedance matching; in this case, all power is fed into the antenna without any reflections. However, as the VSWR increases, reflections of the power increase due to the mismatch in antenna impedance, which in turn causes signal degradation and thereby raises issues with efficiency. The poor match would, therefore, hamper antenna performance so that non-distorted signals are wasted.

As represented in Figure 3, the proposed antenna shows a VSWR of 1.039064 at 2.4 GHz. Such a value is correspondingly near perfection, confirming our statement of good impedance matching-probably even better than previous studies [37–40]. Lower reflections and higher transfer of power ensure a clean signal, and hence the antenna is suited for durable wireless communication.

4.4. Gain

Antenna gain—a significant parameter—represents the antenna's ability to direct radio frequency energy in a particular direction compared to an isotropic radiator. Gain measured in decibels referred to isotropic (dBi). Higher the value of dBi, the more energy can be directed in only one direction; thereby creating more stronger signals and increased distance of communication in that direction. The performance of the proposed antenna indicates a gain of 2.86 dBi at 2.4 GHz and therefore outshines many earlier reported designs [35, 36, 38]. This means that the antenna could radiate or receive signals with 2.86 times efficiency in its most favorable direction as compared to an isotropic antenna.

Figure 3
VSWR characteristics of the proposed antenna



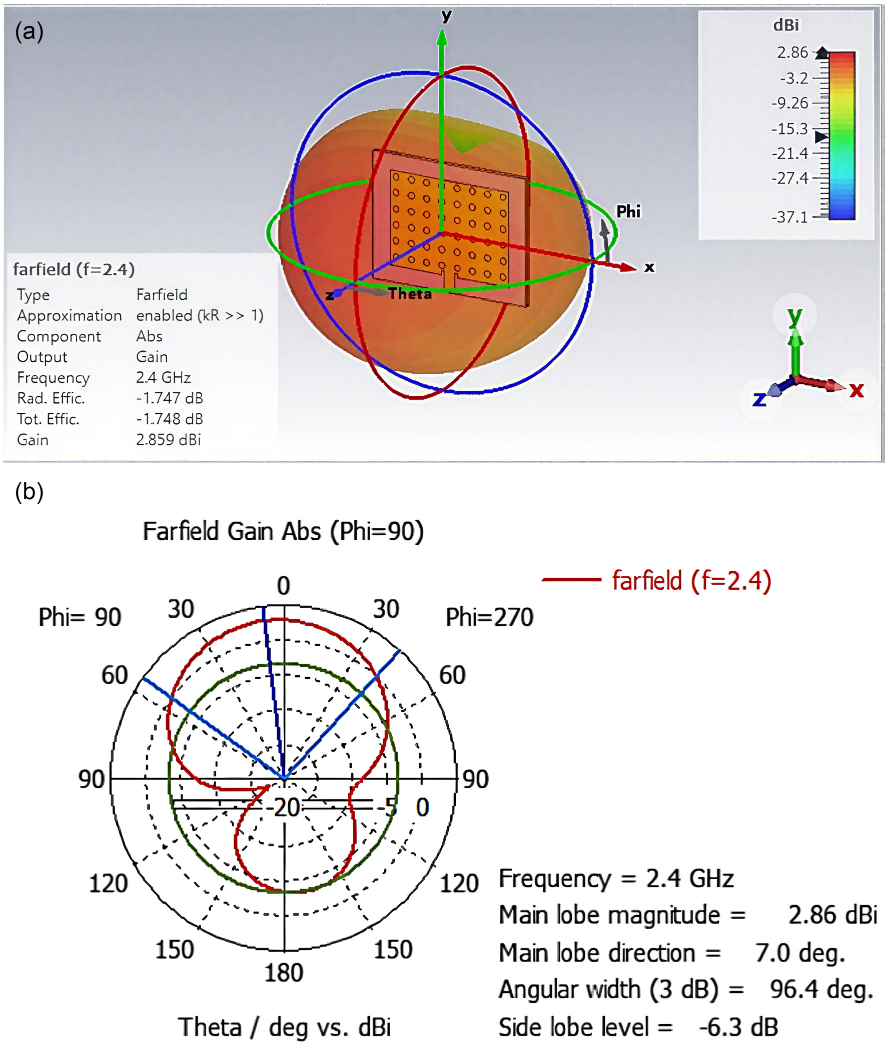
This directional behavior is represented in Figure 4(a) and (b), wherein the antenna is seen to effectively concentrate energy. This directed energy is particularly well suited to applications where directed communication is required (as in point-to-point links, or equipment which must serve a defined area). Gain of 2.86 dBi is useful in increasing the communication distance and in reception of smaller signals. This antenna is therefore very applicable in 2.4 GHz applications such as Wi-Fi, Bluetooth, and ISM band systems. The quality and the strength of its signal transmission guarantees its consistency in keeping the connection especially in a modern wireless network where the coverage and the quality of the signal are both important aspects.

4.5. Directivity

The ability of an antenna to concentrate energy in a specific direction relative to an isotropic antenna, which emits signals in all directions equally, is known as antenna directivity. It is expressed in decibels above isotropic (dBi), and the higher its value, the more the energy it can concentrate. A half-power antenna is isotropic (directivity of 0 dBi) and thus radiates equally in all directions. A higher directivity antenna, by contrast, concentrates its signal in a narrower beam, useful when communicating over long distances, or controlling the signal in a specific direction. Conversely, low-directivity antennas dissipate their energy across a larger space and are therefore useful in such applications as Wi-Fi, where a number of devices must be served within a wide coverage area.

Figure 5(a) and (b) demonstrate that the proposed antenna has a directivity of 4.61 dBi at 2.4 GHz. This value implies a moderate directionality, and it concentrates energy better than an isotropic radiator but has still a large area coverage. This is useful to enhance the signal strength and reliability in the primary direction of transmission without compromising the capability to serve multiple devices in the close proximity. This combination of directional gain and omnidirectional coverage area leads to an antenna particularly well adapted to Wi-Fi uses, where long range and large connective area are both desired. The antenna has a directivity of 4.61 dBi, which guarantees constant and stable wireless communication both at home, in public places, and in business spaces.

Figure 4
Far-field gain of the proposed antenna unit: (a) 3D plot and (b) 2D polar plot



farfield (f=2.4)

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Gain
Frequency	2.4 GHz
Rad. Effic.	-1.747 dB
Tot. Effic.	-1.748 dB
Gain	2.859 dBi

Frequency = 2.4 GHz
Main lobe magnitude = 2.86 dBi
Main lobe direction = 7.0 deg.
Angular width (3 dB) = 96.4 deg.
Side lobe level = -6.3 dB

4.6. Efficiency

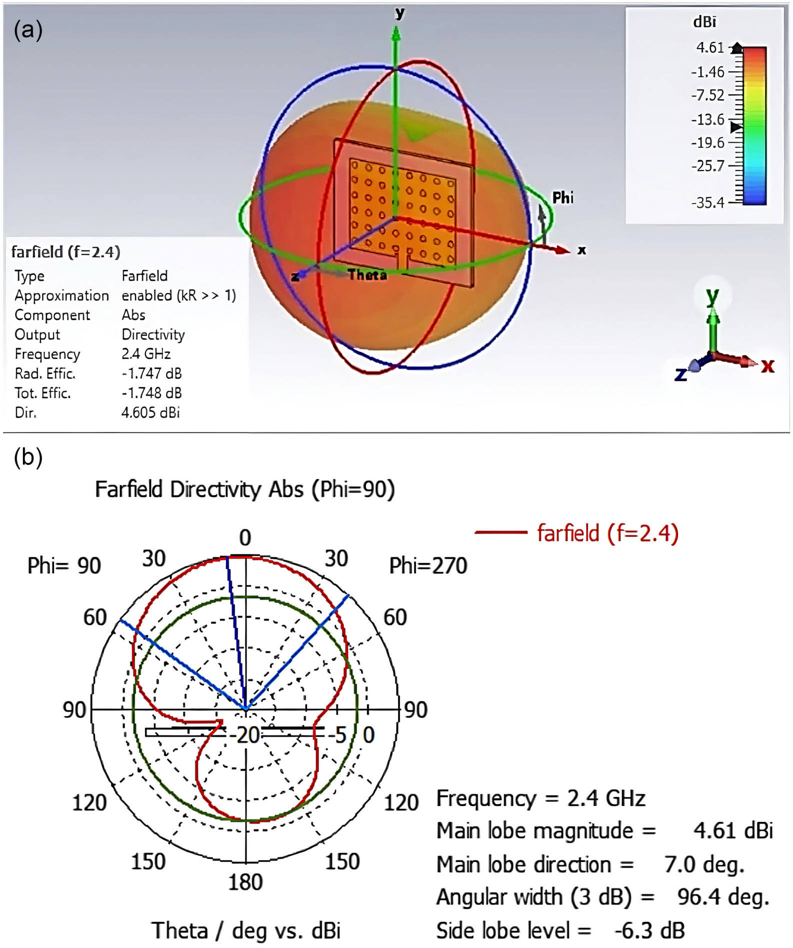
The rate at which an antenna transforms the power provided to it into emitted electromagnetic energy is known as antenna efficiency. Typically given as a percentage, it is the ratio of emitted power to the whole input power. Dielectric losses (from the substrate material) and conductor losses (from metal traces and connections) cause some power loss in practice.

Theoretically, 100% efficiency would mean that all input power is being radiated and that rarely comes close to usefulness because of limitations in materials and flaws in fabrication. However, highly efficient antennas are in most cases advantageous. They prolong communication distance, enhance signal strength and quality, lower electric power needs, reduce heat generation, and increase reliability and performance of the system. For the proposed antenna, efficiency has been measured at –1.747 dB or 66.881% as shown in Figures 4(a) and 5(a), implying that 66.881% of the input power is actually being radiated, while 33.119% is lost within the antenna structure. Even though not commendable enough, this is reasonable for almost all practical wireless applications including Wi-Fi, WLAN, and Bluetooth, taking into consideration the use of FR4 substrate which is the cost option but has a lot of dielectric losses compared to high-grade materials. Therefore, enhancing efficiency is a significant consideration in antenna design, as it affects signal coverage, cuts back on energy waste, and allows for stable performance in different working environments.

4.7. Overview of the simulated findings

Table 2 shows the simulated results which confirm that the proposed antenna is highly suitable to be used in Wi-Fi application since it works well in the frequency range of 2.4 GHz. and it has good impedance matching, with low return loss and VSWR, efficient signal transmission with low reflection losses. The antenna also possesses a good gain and directivity that ensure stable reception of signal and reliable communication. It has a wide bandwidth that allows it to be used in a number of frequencies; thus, it can be used in a number of wireless technologies. This is because the efficiency of the antenna is high, and as a result, most of the input power is effectively converted to radiated signals and not lost as energy. A combination of these features emphasizes the antenna reliability and performance and the suitability to be used in the contemporary communication systems demand high connection and effective performance.

Figure 5
Far-field directivity of the proposed antenna unit: (a) 3D plot and (b) 2D polar plot



farfield (f=2.4)

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Directivity
Frequency	2.4 GHz
Rad. Effic.	-1.747 dB
Tot. Effic.	-1.748 dB
Dir.	4.605 dBi

Frequency = 2.4 GHz
Main lobe magnitude = 4.61 dBi
Main lobe direction = 7.0 deg.
Angular width (3 dB) = 96.4 deg.
Side lobe level = -6.3 dB

Table 2
Overview of the simulated outcomes obtained from the suggested antenna design

Performance parameters	Proposed antenna
Resonant frequency (GHz)	2.4
Return loss (dB)	–34.26823
VSWR	1.039064
Bandwidth (MHz)	180.043
Gain (dBi)	2.86
Directivity (dBi)	4.61
efficiency	–1.747 dB (66.881%)

5. Discussion

The antenna proposed has been shown to have good performance and there are few limitations that should be handled to make it have a broader application. It has a moderate gain of 2.86 dBi which might not be suitable in long-range applications or high-power applications, and hence, it cannot be used effectively in applications that need long-range signals. It also has an efficiency of 66.88 percent implying that 33.12 percent of the input power is wasted as dielectric and conductor losses, which may be important in power-sensitive applications. The bandwidth of 180.043 MHz is sufficient as per the present Wi-Fi standards but might not be suitable with the future technologies such as Wi-Fi 6E, which demands a wider bandwidth to achieve faster data transmission speeds and better connectivity. The present performance is simulation-driven, implying that actual performance may vary in the real world since it is subject to manufacturing variances and environment.

In order to surmount these difficulties, the subsequent studies ought to be directed toward the fabrication of prototypes and experimental verification. The gain improvement can be done by incorporating parasitic elements, reflectors, or metamaterials, and the efficiency maximization can be done with low loss substrates and improved fabrication processes. Also, slot loading and DGS may be used to increase compatibility with newer Wi-Fi standards such as Wi-Fi 6E. It is a good antenna shape to be used in IoT and wearable because of its compact size and efficient design. Future work must look at how it can be optimized to perform better on these uses and look at multiband capability, enabling it to operate outside Wi-Fi—possibly to serve LTE and 5G cellular networks. Although the antenna can satisfy the existing demands in the wireless communication, its weaknesses can be overcome by future research and experimental works in the real-world scenario, and this will open the door to wide usage of the antenna.

5.1. Implications for wearable technology

The suggested antenna is small (40 mm × 50 mm × 1.6 mm), efficient (66.88 percent), and has a broad bandwidth (180.043 MHz)

Table 3
Comparisons of the past and current works

Ref. No's.	Antenna size (mm^3)	Substrate	Return loss (dB)	VSWR	Operating bandwidth (GHz)	Bandwidth (MHz)	Gain (dBi)	Efficiency (%)	Methods
[33]	60 × 60 × 1.6	FR4	–25.90	——	2.426–2.382	44	4.66	48.518	Multislot
[34]	60 × 60 × 1.6	FR4	–22.28	. . . .	2.4375–2.3722	60	. . . .	. . . .	Inset-fed
[35]	45 × 42 × 1.6	Rogers 5880	−30	. . . .	2.48–2.33	150	2.73	94.93	Multislot
[36]	113.92 × 100.5 × 1.6	FR4	−28	0.9366	2.438–2.358	80	1.48 dB	. . . . . .	Inset-fed
[37]	80 × 80 × 1.6	FR4	−25.72	1.1092	2.385–2.335	50	2.97	19.011	Inset-fed and Computer Numerical Control (CNC)
[38]	100 × 100 × 1.5	FR4 and Rogers RT/Duroid	−20.40 (FR4)	1.211 (FR4)	2.488–2.4142 (FR4)	74.6 (FR4)	2.592 (FR4)	34.69 (FR4)	Inset-fed
[39]	50 × 47.8 × 1.6	FR4	−28.150305	1.08	2.4575–2.3393	118.16	3.023	. . . .	Inset-fed, slotted, and partial ground
[41]	46.86 × 60.86 × 1.6	FR4	−34.6069	1.0379	2.9932–2.0912	90.2	4.95	. . . .	Photonic crystal structure with through-holes drilled
[40]	60 × 65 × 1.6	Rogers RT/Duroid 5880	−13.89	1.50	2.4219–2.3572	64.7	6.66	41.773	. . . .
Proposed Antenna	40 × 50 × 1.6	FR4	–34.26823	1.039064	2.494624–2.314581	180.043	2.86	66.881%)	Inset-fed, Partial ground and Photonic crystal structure

that can be employed in wearable devices. A smart fabric, health monitors, and AR/VR devices with this technology would permit low-power reliable wireless connectivity for enhancing user experience. In the future, researchers will be able to find ways of using flexible materials to conform even better to wearable designs.

6. Comparisons of the Past and Current Works

The performance of the proposed antenna has been compared with several existing designs, as shown in Table 3. With compact dimensions of 40 × 50 × 1.6 mm^3, this antenna is noticeably smaller than most previous models referenced in studies [33–40]. Its small size makes it ideal for integration into modern portable devices where space is limited. Made from cost-effective FR4 substrate, the antenna maintains affordability, in contrast to earlier designs that used high-end materials like Rogers 5880 or RT/Duroid 5880 to improve electrical performance [35, 38, 40]. One of the standout features of this design is its excellent return loss of –34.26823 dB, which means minimal signal reflection and nearly perfect impedance matching. This result outperforms most previous designs, with only one study [41] reporting a slightly better value (–34.61 dB). The antenna also achieves a VSWR of 1.039, which is very close to the ideal value of 1. This performance matches top results in Verma et al. [36] and Ding et al. [41], where VSWR values were 0.9366 and 1.0379, respectively. The bandwidth of the antenna spans 180.043 MHz, covering frequencies from 2.314581 GHz to 2.494624 GHz, making it much wider than the bandwidths reported in other related works. This wide bandwidth ensures strong performance across the 2.4 GHz Wi-Fi spectrum.

The antenna has a gain of 2.86 dBi and efficiency of 66.88 percent that compete with the previous models. The specialty of this design is that it has employed Inset-fed technique, PGP and PhC structure. These techniques comply with one another to enhance significant antenna parameters such as bandwidth, gain, and efficiency. Past studies usually resorted to standard methods such as multislot designs or CNC machining.

The overall performance of the proposed antenna is impressive and balanced. It has high return loss, low impedance matching (VSWR), and broad bandwidth which makes it a contender in the present-day wireless applications. These are Wi-Fi, Bluetooth, ISM Band, 4G LTE, microwave ovens, S-Band, RFID, WCS, and WiMAX at 2.4 GHz frequency range. Conclusively, the antenna will provide an effective, low cost, and high performing solution to the present wireless communication systems.

7. Conclusion

In this paper, the design and simulation of a FR4 rectangular patch antenna using PhC are accomplished properly and according to the Wi-Fi standard of 2.4 GHz operation frequency. The antenna performance is also high, having a return loss (S_{11}) of –34.26823 dB, an impedance bandwidth of 180.043 MHz (2.494624 GHz to 2.314581 GHz), and voltage standing wave ratio (VSWR) of 1.039064. It has a gain of 2.86 dBi, directivity of 4.61 dBi, and efficiency of 66.88 percent. Such performance figures render the antenna applicable to modern Wi-Fi application. Its miniature size, PGP, and inset-feed line impedance of 50 Ω prevent it from being useful in integration into consumer electronics, smart home devices, and Internet of Things. The broadband operation and acceptable efficiency responds to the present needs in wireless communication systems with reliability in performance. The gain and efficiency of the antenna will be improved in future. Also, it will be experimentally verified and implemented in reality to examine its performance and consider the possibilities of its utilization in general wireless communication cases. The work has a sensible contribution to the development of antenna technologies with the contemporary communication networks.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

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

Author Contribution Statement

A. N. M. Shihab Uddin: Software, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Visualization. **Samiul Bashir:** Software, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Visualization. **Pronab Kumar Paul:** Software, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Visualization. **Md. Firoz Ahmed:** Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Md. Bipul Islam:** Software, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Visualization. **M. Ismail Hossain:** Writing – review & editing. **M. HasnatKabir:** Writing – review & editing.

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