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ABSTRACT

Modern wireless systems require antennas to be lightweight, flexible, safe to use close to human bodies, and capable of maintaining stable performance in bending conditions. This study suggests using a conformal microstrip patch antenna in the 2.4 GHz ISM band that is combined using an electromagnetic band gap structure. To provide for conformal functionality, the antenna is built on a polyester substrate. The EBG structure contributes to better impedance matching and radiation performance by decreasing surface wave effects. The antenna offers a gain of 8.73 dB, a return loss of −17.7 dB, and a SAR value of 0.2 W/kg. The behavior of the antenna during bending was also examined, and it was discovered that it maintains stable performance up to a bending angle of 7.5° with very minor variations. These results imply that the proposed architecture is suitable for Internet of Things, wearable technologies, WBAN, and short-range sensing.

Keywords – Conformal antenna, Electromagnetic Band gap (EBG) structure, Polyester, Microstrip patch antenna

CHAPTER 1

INTRODUCTION

In recent years, flexible electronic technology has developed and matured. These technologies are used in fields where antennas can be placed on curved or flexible surfaces while maintaining stable and effective wireless communication, such as aerospace, automotive systems, wearable devices, drone, UAV communication, wireless sensor networks, Internet of Things (IoT) systems, biomedical monitoring, and contemporary defense communication. However, the RF domain has only shown a small number of uses to date. Compact, flexible, lightweight, and conformal antennas that, depending on the application requirements, can function well when placed on curved or irregular surfaces are becoming more in demand. When integrated with different electronic platforms and systems, these antennas should continue to provide dependable radiation performance. They should also enable simple design structures, ease of fabrication, mechanical flexibility, and economical implementation, making them appropriate for a variety of contemporary wireless communication applications where surface adaptability, weight, and space are crucial factors.

1.1 Overview

18 The first designs and theoretical models of microstrip antennas (MSA) appeared in the 1950s, but the 1970s saw a significant increase in interest. The microstrip antenna was first proposed in 1952. Deshchamps and other scientists thought the microstrip was a microwave antenna. After over 20 years, microstrip antennas were used in practical applications. One could consider Howell and Munson to be the forerunners of microstrip antenna design.

4 18 Micro strip antennas are low-profile antennas. A microstrip patch antenna consists of a grounded side and a conducting patch on either side of a dielectric substrate. It is preferable to print a radiating patch rather than a microstrip line for higher radiation efficiency on a low-permeability substrate. At frequencies above 100 MHz, patch antennas are frequently employed in low-profile applications.

19 The microstrip patch is a conducting patch on a dielectric slab with the opposite side grounded. When current travels via a feed line and reaches the antenna's strip, electromagnetic waves are created. A radiation pattern is produced when waves begin to radiate from the edges of the patch.

The waves that are produced depend on the substrate's thickness; as the substrate is thin, the waves are reflected off its edges. It is important to keep in mind that radiation cannot be discharged due to the continuous nature of the strip.

After a specific discontinuity, radiation transmission starts up again from the second side of the patch. Because they only produce a little quantity of energy, patch antennas are inefficient. It is less of a transmitter and more of a hollow. Because radiation is inefficient, it cannot be used extensively.

19 The various types of microstrip patch antennas include: Rectangular, Square, Dipole, Circular, Triangular, Disc Sector, Circular Ring, and Ellipse. Microstrip or patch antennas have a wide radiation pattern. Its frequency bandwidth is limited, and its radiation power is poor. Its directivity is lower. These patch antennas can be used to create an array with higher directivity.

For any antenna to be effectively designed, design characteristics including the radiator's length, width, and thickness as well as the ground plane and substrate are generally crucial. The microstrip patch's antenna's length and breadth can be calculated using the following formulas.

$$W_p = \frac{1}{2fr\sqrt{\mu o \epsilon 0}}\sqrt{\frac{2}{\epsilon r+1}} = \frac{vo}{2fr}\sqrt{\frac{2}{\epsilon r+1}}$$

25 where, light velocity $vo = 3 \times 10^8$ ms^{-1} and f_r is resonant frequency i.e., 2.4 GHz.

ϵ_{eff} is effective refractive index is given as:

$$\epsilon_{eff} = \frac{\epsilon r+1}{2} + \frac{\epsilon r+1}{2}\left[1+12\frac{h}{Wp}\right]^{-1/2}$$

where the patch width, W_p, substrate height, $h = 1.45\ mm$, and relative dielectric strength of the substrate, $\epsilon_r = 1.44$.

The microstrip patch antenna's effective length (L_{eff}) and fringing length (Δl) can now be computed as follows.

$$L_{eff} = \frac{1}{2fr\sqrt{\mu o \epsilon 0}}\sqrt{\frac{2}{\epsilon r+1}} = \frac{vo}{2fr\sqrt{\epsilon eff}}$$

$$\Delta l = 0.412 \times h \times \frac{\epsilon r + 0.300\left(\frac{Wp}{h}\right) + 0.262}{\epsilon r + 0.258\left(\frac{Wp}{h}\right) - 0.813}$$

Patch accurate length is given by:

$$L_p = L_{eff} - 2\Delta l$$

The ground plane's size is calculated using the following equations.

$$L_g = 2L_p$$

$$W_g = 2W_p$$

The radiating patch on the grounded substrate is the primary feature of microstrip. Light weight, low profile configuration, and ease of fabrication are some of its defining characteristics. The substrate's thickness ranges from 0.03λ to 0.05λ, and for improved

radiation efficiency, we typically favor thick substrates with low dielectric coefficients.
In contrast to microstrip dipole antennas, which only display linear polarization, it displays both linear and circular polarization. It can take on any shape, including triangular, elliptical, circular, ring sector, and more. Because of its limited size, it usually has a restricted bandwidth of about 5%. Fringing, in which waves start to radiate from the patch's boundaries into space, can occasionally be caused by the coupling between the patch and the antenna, giving the impression that the patch is larger than it actually is.

1.2 Conformal Antenna

A conformal antenna is one that fits or conforms to the curvature of a curved surface rather than being positioned on a flat platform. The term "conformal" refers to the antenna's ability to conform to the shape of the item it is mounted on, such as the surface of a vehicle, helmet, aircraft, drone, or human body. Unlike traditional rigid antennas, conformal antennas are usually built using flexible substrates that enable them to bend without sacrificing their electrical performance. These antennas are frequently utilized in military communications systems, wearable electronics, drones, and aerospace because they may be smoothly incorporated into structures without compromising aerodynamics or look.
Conformal antennas fall into several kinds based on their intended function and design. One common type is a conformal microstrip antenna, with a flexible substrate and can easily bend around curved surfaces. Another type is a conformal antenna, that arranges several antenna elements onto a curved substrate to increase gain and directivity. Fabric or wearable antennas are those that are integrated into cloth for wearing electronics.
Conformal antennas that are designed to operate on curve or cylinder-shaped surfaces, such as airplane fuselages or missile bodies, also come in spherical and cylindrical varieties.
Conformal antennas have several important characteristics. Because they are lightweight, flexible, and low profile, they can easily adapt to a variety of surface geometries. Furthermore, they provide aerodynamic compatibility, meaning that when mounted to aircraft or drones, they don't obstruct airflow. Their ability to maintain consistent radiation performance despite bending situations is another feature. However, constructing conformal antennas requires careful consideration since bending can occasionally affect properties like gain, return loss and radiation pattern.
Conformal antennas are widely used in many modern communication systems. In aircraft and Drone systems, they are integrated inside aircraft, airplane wing, and fuselages used for radar and communication functions. To enable wireless connectivity and health monitoring, conformal antennas are incorporated into clothing or wearable electronics accessories. They are also used in military communication systems, satellites, and smart automobiles. Internet of Things devices, which require compact and flexible antenna solutions, benefit greatly from conformal antennas.

1.3 Electromagnetic Band Gap (EBG) Structures

EBG, also known as Photonic Band Gap structures, are intentionally constructed periodic arrangements that have the ability to prevent electromagnetic waves from moving within specific frequency ranges and in specific directions.

By managing electromagnetic wave propagation and suppressing undesired surface waves, an EBG structure can improve antenna gain, radiation efficiency, and impedance matching. By reducing the specific absorption rate (SAR), EBG structures also help wearable or conformal antennas reduce radiation directed toward the human body, improving user safety.

Another crucial aspect of EBG structures is their phase response to plane wave illumination. In this case, the reflection phase shifts from 180° to −180° as the operating frequency rises. It is also seen that EBG structures when used with microstrip patch antennas can improve their radiation patterns, increase their gain, and reduce the side lobe and back lobe levels [1, 2]. Surface waves in dielectric substrates have a negative impact on microwave and millimeter-wave circuit performance, making them undesirable. Therefore, the suppression of surface wave propagation not only improves the performance but also lead to the realization of new devices and low loss guiding structures [3]. The 1-D, 2-D and 3-D configurations of EBG structures all have been reported. A 2-dimensional pad with a type EBG configuration is the mushroom-like EBG structure. It consists of a PEC ground plane supporting a dielectric substrate, metallic patches, and vias joining patches to a ground plane. This type of structure can be modelled as a parallel LC equivalent circuit that is reported in [4]. Surface wave propagation is suppressed by the analogous LC circuit, which functions similarly to a two-dimensional electrical filter. The current passing through the vias creates the inductance (L), and the space between adjacent patches creates the capacitance (C). The surface impedance equals to the impedance of a parallel resonant circuit, consisting of the equivalent inductance L and the capacitance C and the central frequency of the band gap are calculated as reported in [5]. The inductance (L) and capacitance (C) depend on the structural parameters of the EBG configuration. The EBG surface exhibits high impedance near the resonance frequency [4]. The EBG cells that are placed close to the antenna's radiating edges function as parasitic components, adding extra stress and improving bandwidth. Some portion of the electromagnetic energy that moves over the antenna substrate can also be reflected by EBG structures. The cavity effect results from this reflected energy acting as reflective limits around the antenna. While the cavity impact tends to decrease the bandwidth, the parasitic loading effect helps to improve it. The antenna bandwidth may rise noticeably as a result. More energy traveling over substrates is reflected back as the total number of rows increases, increasing the cavity effect's dominance and decreasing of bandwidth [7]. According to [6], the structure with varying via radii created using the Blackman windowing approach has a noticeably broader band width than a uniform one.

1.4 Textile Based Materials

In order to create flexible and wearable antennas that operate in the 2.4 GHz ISM band, textile-based materials are frequently employed. The majority of these materials are polymers or textiles that can serve as conductive layers or antenna substrates. Textile antennas are attractive because they're lightweight, malleable, and simple to incorporate into clothing or curved surfaces. Wearable technology, body-centric networks, and drone antennas communication systems need to be small, pleasant, and mechanically flexible. Without sacrificing their electromagnetic performance, antennas can be integrated using textile materials into apparel, accessories, or flexible platforms.

Many textile materials are commonly used as substrates while building antennas. These include silk, cotton, denim, polyester, fleece, nylon, and felt. These materials were selected because they offer exceptional flexibility, low dielectric constant, and mechanical endurance all of which are essential for maintaining consistent antenna performance.

In addition to the substrate, conductive textile materials are used for the area of radiation and the ground level.

Body-centric wireless communications, wearable health monitoring devices, Bluetooth devices, Internet of Things gadgets, and drone communication networks are among the uses for fabric antennas operated in the 2.4 GHz ISM band. Because textile materials are used, the antenna can be integrated directly into clothing or flexible platforms, providing customers with comfort and portability. Furthermore, these antennas allow conformal incorporation on curving surfaces, which is useful for aeronautical and UAV systems where rigid antennas may not be suitable.

1.5 Wireless Communication Applications in the 2.4 GHz ISM Band

The 2.4 GHz - Industrial, Scientific, and Medical (ISM) range is one of the most widely used ranges of frequencies for wireless communication networks. This frequency band, which typically ranges from a frequency of 2.4 GHz to 2.4835 GHz, can be found everywhere and in many countries doesn't require a specific license. The broad accessibility of the 2.4 GHz frequency range has made it a popular choice for many wireless devices. Due to its reasonable transmission range, medium data rates, and reliable connectivity, the band is suitable for a variety of modern communication devices. Additionally, this band is well-liked since the 2.4 GHz frequency allows for compact antennas, which is crucial for wearable and portable electronics.

The 2.4 GHz ISM band is required because modern communication systems require wireless connectivity without complex licensing restrictions. Many consumer and industrial gadgets employ wireless communication to send information over a short or medium lengths. Several technologies may utilize the same range of frequencies thanks to the 2.4 GHz Band's outstanding coverage, power efficiency, and device interoperability. Because a band is broadly standardized, devices designed for this band of frequencies can be used in multiple regions without substantial adjustments. It makes a 2.4 GHz ISM range very advantageous for global wireless communication systems.

Another important application of the 2.4 GHz band is in drone and Aircraft communication systems. Many drones use this frequency band for video communication with the ground station, remote control, and telemetry data transfer. UAV control systems gain a lot from the band's capacity to provide consistent communication at reasonable distances. The band is frequently used in aircraft communication systems, where tiny, light antennas are required for wireless data transfer.

1.6 Problem Statement

Because of their compact, low-profile structure and capacity to conform to curved surfaces, conformal microstrip antennas are commonly employed in contemporary wireless communication systems. This makes them perfect for wearable technology, drones, and aerospace platforms.

To overcome these limitations, the microstrip antenna is used with Electromagnetic Band Gap (EBG) structures. With suppressing waves on the surface, reducing unwanted radiation, and improving impedance and radiation characteristics, the EBG structure improves the antenna's overall performance in the 2.4 GHz ISM band. Since conformal antennas are intended for flexible platforms, it is essential to analyze how bending impacts antenna performance. Therefore, either bent or mounted on curved surfaces, the antenna undergoes testing in a variety of bending scenarios to guarantee reliable functioning and constant impedance matching.

CHAPTER 2

LITERATURE REVIEW

Wearable sensors, telemedicine, wireless networks for body area networks (WBAN), these antennas have numerous uses, including short-range communication systems, Internet of Things, even biomedical monitoring. Traditional microstrip antennas tend to be chosen because to their low profile, ease of fabrication, compact size, and low production cost. However, the disadvantages of microstrip antennas include surface wave propagation, limited bandwidth, reduced radiation performance, and poor performance when placed near the human anatomy or under bending conditions. Numerous studies have examined the performance of conformal and wearable antennas operated in a 2.4 GHz ISM band. Researchers have focused on improving gain, lowering SAR, maintaining stable radiation under bending conditions, and ensuring compatibility with human tissues. The following section reviews key findings from earlier studies on flexible wearing antennas, and biomedical antenna applications, and EBG-integrated antennas.

Rezaei Abkenar and Rezaei [1] introduced a novel Electromagnetic Band Gap (EBG) structure to improve low-profile antenna performance. The study shown that incorporating an EBG structure into an antenna significantly lowers surface waves, which improves antenna efficiency and radiation characteristics. The researchers showed how EBG structures reduce unwanted electromagnetic interference and improve impedance matching. The study showed how EBG structures can improve antenna gain and lessen the decline in substrate-guided wave performance. Nevertheless, flexibility, wearable applications, and bending performance all crucial for biomedical systems were not examined in this work, which mainly concentrated on low-profile antennas.

Qu, Shafai, and Foroozesh [2] looked at employing EBG substrates to enhance microstrip patch antenna performance. According to their research, EBG integration suppresses surface waves inside the dielectric substrate, increasing radiation efficiency, lowering back-lobe radiation, and increasing antenna gain. When compared to traditional patch antennas, the results showed better radiation characteristics and impedance matching. The study mostly concentrated on rigid antenna topologies and ignored conformal or flexible antenna applications, despite the fact that the suggested strategy greatly enhanced antenna performance. Furthermore, there was no SAR study for human-body safety.

A photonic band-gap substrate was proposed by Coccioli and Itoh [3] to inhibit surface wave propagation in microstrip antennas. By increasing losses and unwanted coupling, the authors demonstrated how surface waves passing through dielectric materials seriously impair antenna performance. They were able to lessen the effects of surface waves and improved antenna efficiency through their photonic band-gap technology. This research established a essential foundation for later developments in EBG-based antennas. But wearable antenna systems and operating under distortion were not investigated; rather, the majority of study was on breakthroughs at the theoretical and substrate levels.

Zhang, Du, Wang, and Gong [4] proposed an EBG to expand antenna bandwidth structure with a mushroom-like appearance. Their research demonstrated how EBG cell layout and geometry significantly affect the performance of antennas. The writers were successful in enhanced radiation behavior and bandwidth by the development of mushroom-type EBG dimensions. Yang and Rahmat-Samii [10] developed microstrip antennas in conjunction with EBG structures to reduce mutually dependent in antenna arrays. Their study showed that while improving radiation performance, EBG configurations considerably reduce electromagnetic interference between closely spaced antenna elements. The suggested EBG-integrated architecture was very successful for array applications since it decreased coupling effects and increased gain. The study proved that EBG technology is a practical way to boost antenna performance and efficiency. Nevertheless, the suggested architecture proved inflexible and unsuitable for wearable biomedical settings.

This set of tests unequivocally shows how good EBG structures are for reducing surface waves, boosting radiation efficiency, improving impedance matching, and raising antenna gain. However, flexible, conformal, and wearable biomedical antenna applications received less attention than rigid structures and traditional wireless communication systems in the majority of prior EBG-based studies. Flexible and wearable antennas are becoming increasingly important in Wireless Body Area Networks (WBAN), telemedicine, biomedical monitoring, and short-range communication systems due to the quick development of wearable electronics and healthcare technology. Wearable antennas, in contrast to traditional rigid antennas, must ensure low electromagnetic absorption inside human tissues while maintaining steady electrical performance despite bending, deformation, and body movement. To enhance radiation performance and reduce SAR, researchers have suggested a variety of flexible substrate materials, metamaterials, artificial magnetic conductors (AMC), and textile-based structures.

Ali et al. [9] developed and analyzed the Specific Absorption Rate for portable antennas positioned on different body areas using both conventional and artificial conventional ground plane techniques.

Dalfiah, Ishwariya, and Kousalya [15] suggested a wearable textile antenna operating in the 2.4 GHz ISM band toward medical WBAN applications. The antenna was made of natural rubber textiles to provide wearable technology with flexibility and comfort. With an increase of their technology showed improved radiation characteristics suitable for biological communication at roughly 7.82 dB. However, a comprehensive evaluation of its suitability for human-body applications was constrained by the study's absence of SAR investigation and bends analysis.

Al-Adhami and Ercelebi presented an adaptable metamaterial printable antenna with wearable medical devices [16]. The antenna used wool felt material and metamaterial structures to improve electromagnetic performance. Based on their metamaterial integration reduced SAR to roughly 0.554 W/kg while improving radiation behavior and achieving a gain of roughly 5.15 dB. Bending testing was also done to ensure stable operation during distortion. Despite the antenna's safe SAR performance, the gain was only moderate for various wearable communication applications.

El Atrash et al. [17] introduced a Composite Right/Left-Handed (CRLH) antenna packed with fabric AMC for WBAN applications. The recommended design improved efficiency and decreased SAR by using cloth AMC structures. With an approximate gain of 6.56 dB having a SAR level of 0.612 W/kg, an antenna demonstrated consistent wearable performance while maintaining flexibility when bent. The study showed that AMC integration can effectively improve wearable antenna performance. However, the structural intricacy of the antenna increased the device's cost and made manufacture more difficult. Saqib Hussain et al. [18] developed a wearable patch antenna with a polyester substrate for Wireless Body Area Networks. When operating at 2.4 GHz, an antenna's efficiency of about 8.384 dB was relatively high among wearable antennas. The reported SAR value, however, was 1.53 W/kg, that's near the maximum safety limit specified by IEEE regulations. Furthermore, the absence of bending analysis raises questions about steady performance in conformal situations.

For telemedicine and mobile healthcare applications, Yadav et al. [19] suggested an Ultra-Wideband (UWB) wearable textile antenna. The antenna was made of denim fabric and has a wide frequency range of 3.1–10.6 GHz. They achieved a gain of about 3.32 dB and a SAR value of 1.601 W/kg, demonstrating wearable compatibility and versatility. Despite being appropriate for broadband communication, the antenna's efficiency for certain biomedical applications was limited by its comparatively lower gain and SAR values around safety limit.

CHAPTER 3

ANTENNA DESIGN AND GEOMETRY

3.1 Structure of Microstrip Patch Antenna

The proposed inset-fed microstrip patch antenna is numerically designed using CST Microwave Studio [8] to operate in the 2.4 GHz industrial, scientific, and medical (ISM) band. Polyester fabrics, which are easily obtained in daily life, are utilized as a substrate material in the suggested antenna design (thickness, h = 1.45 mm, dielectric constant, ϵ_r = 1.44) and loss tangent (tan δ) of 0.01. Initially, a traditional rectangular microstrip patch antenna is created. Following the selection of the substrate's thickness (h), dielectric constant (ϵ_r), and resonant frequency (f_r), the following formulas are used to calculate the patch's and ground plane's dimensions. [9], [10].

For any antenna to be effectively designed, design characteristics including the radiator's length, width, and thickness as well as the ground plane and substrate are generally crucial.

The microstrip patch antenna's length and breadth can be calculated using the following formulas.

$$W_p = \frac{1}{2fr\sqrt{\mu o \epsilon 0}}\sqrt{\frac{2}{\epsilon r+1}} = \frac{vo}{2fr}\sqrt{\frac{2}{\epsilon r+1}}$$

where, light velocity $vo = 3 \times 10^8$ ms^{-1} and f_r is resonant frequency i.e., 2.4 GHz.

ϵ_{eff} is effective refractive index is given as:

$$\epsilon_{eff} = \frac{\epsilon r+1}{2} + \frac{\epsilon r+1}{2}[1 + 12(\frac{h}{Wp})]^{-1/2}$$

where the patch width, W_p, substrate height, h = 1.45 mm, and relative dielectric strength of the substrate, ϵ_r = 1.44.

The microstrip patch antenna's effective length (L_{eff}) and fringing length (Δl) can now be computed as follows.

$$L_{eff} = \frac{1}{2fr\sqrt{\mu o \epsilon 0}}\sqrt{\frac{2}{\epsilon r+1}} = \frac{vo}{2fr\sqrt{\epsilon eff}}$$

$$\Delta l = 0.412 \times h \times \frac{\epsilon r + 0.300\left(\frac{Wp}{h}\right) + 0.262}{\epsilon r + 0.258\left(\frac{Wp}{h}\right) - 0.813}$$

Patch accurate length is given by:

$$L_p = L_{eff} - 2\Delta l$$

The ground plane's size is calculated using the following equations.

$$L_g = 2L_p$$

$$W_g = 2W_p$$

The suggested antenna arrangement and its position in relation to the human body are shown in Figure 1.The isometric view of the designed antenna is shown in Figure 2(a), which highlights the general geometry of the patch, substrate, and ground structures used in the design. Figure 2(b) depicts the antenna's top view, including a detailed configuration of the radiating patch and substrate. The position of the suggested antenna on a multiple-layer human body tissue model is shown in Figure 2(c). The various layers of the human tissue model, which are frequently taken into account in wireless antenna research, represent the skin, fat, and muscle. This arrangement aids in assessing how the human body affects antenna parameters like radiation characteristics, impedance matching, and overall performance.

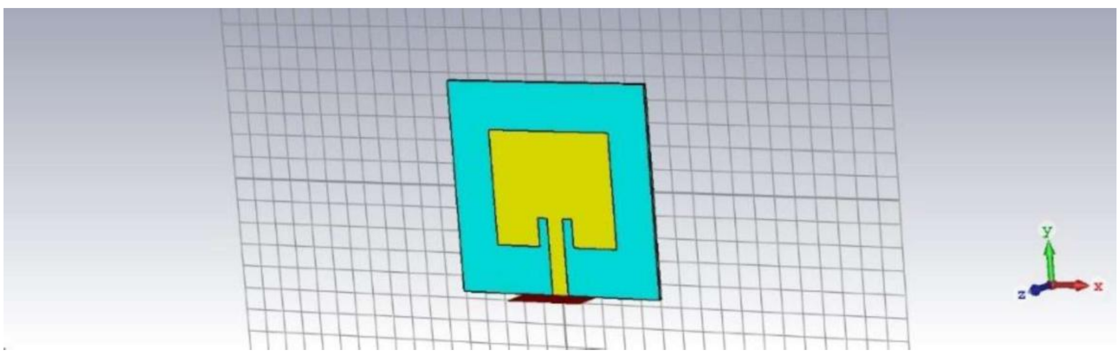


Fig. 2(a) Proposed antenna isometric view

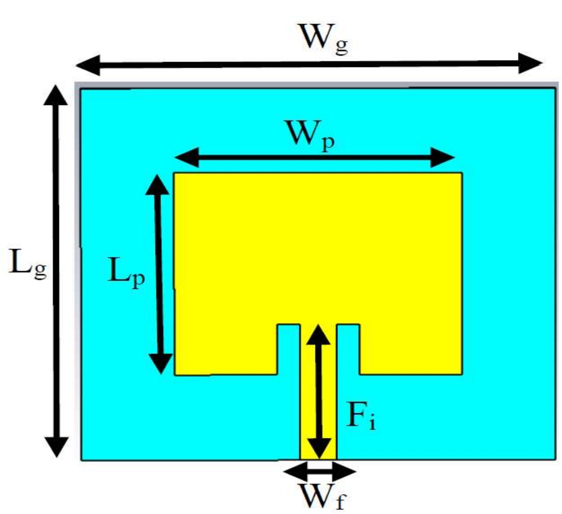


Fig.2(b) Proposed antenna top view

Both the ground plane and patch radiators use conducting copper as a component. The patch and ground plane have optimal measurements of $L_p \times W_p$ and $L_g \times W_g$, respectively. Thus, an increasing impedance bandwidth is the primary justification for employing partial ground. The suggested antenna's overall radiation performance is enhanced by using an inset gap (G_{pf}) to increase impedance matching. A 50Ω microstrip transmission line with a feed width of (W_f) is employed to feed the proposed antenna system. The CST software is used to design, optimize, and analyze the suggested antenna models. The average dielectric properties and conductivity values of the human tissue layers are as follows: skin (ε_r = 31.29, σ = 5.0138 S/m), fat (ε_r = 5.28, σ = 0.1 S/m), and muscle (ε_r = 52.79, σ =1.705 S/m) [11]. The corresponding thicknesses of the skin, muscle, and fat layers are 1 mm, 2 mm, and 30 mm, respectively.

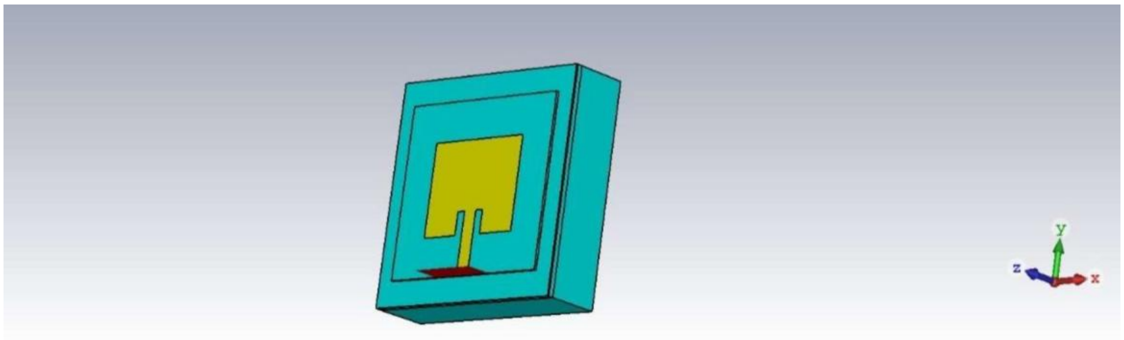


Fig. 2(c) Proposed antenna placement on human body

3.2 Feeding technique

In the proposed Conformal Electromagnetic Band Gap (EBG)-Integrated Microstrip Patch Antenna for Enhanced Performance at 2.4 GHz ISM Band, an inset-fed microstrip line feeding technique is employed to excite the radiating patch. A common feeding method for microstrip patch antennas is the inset feed, which involves inserting the feed line through a small slot or notch into the radiating patch. The inset feed allows for better control of the antenna's input impedance since it penetrates within the patch by a certain distance defined as the inset depth, in contrast to edge feeding, which connects the feed directly at the patch boundary. This feeding approach aims to match impedance to a normal 50 Ω transmission line, optimizing power transfer from source to antenna and reducing reflected power. Proper impedance matching is scritical because any mismatch between feed line and patch impedance causes signal reflection, which degrades antenna performance, reduces radiation efficiency, and increases return loss.

In this work, the inset-fed microstrip technology is chosen because to its many significant benefits, particularly for wearable and conformal biomedical antenna applications. Its capacity to offer effective impedance matching without the need for further matching networks or outside components is one of its main benefits. Antenna performance can be enhanced by optimizing the inset position to get the appropriate impedance value because the impedance fluctuates from the patch antenna's edge to its centre. This immediately helps to achieve improved radiation characteristics and a smaller return loss (S11). Because the antenna frequently functions in close proximity to the human body, where tissue loading effects may disrupt impedance characteristics, maintaining steady performance is crucial in wearable and biomedical applications.

Additionally, because the feed line is physically integrated into the antenna's planar design, the inset-fed approach reduces spurious radiation and improves radiation efficiency. As a result, the inset-fed microstrip line feeding technique was chosen for this work because it can effectively match impedance, reduce reflection loss, be easily fabricated, be compact, have a low-profile design, perform better in radiation, and be suitable for conformal wearable biomedical applications operating at 2.4 GHz.

3.3 Structure of Electromagnetic Band Gap (EBG)

A ground plane, a substrate, a metallic patch, and metallic via which joins a unit cell EBG structure is composed of the ground plane. As the stream flows through the Metallic via provides an inductive effect, and the gap between adjacent patches has a capacitance effect. The following formulas can be used to determine the values of the inductor L and capacitor C for an EBG structure with patch width W, patch gap width g, dielectric constant r, and substrate thickness h [12].

$$L = \mu h$$

$$C = W\varepsilon_o \frac{1+\varepsilon r}{\pi} cosh^{-1} \frac{2W+g}{g}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

$$\Delta f = \frac{1}{\eta} f_0 \sqrt{\frac{L}{C}}$$

The permeability of free space is represented by μ, the dielectric constant of the substrate is denoted by ε_r, and the permittivity of free space is represented by ε_0. The structure's bandgap is defined by f_0, which is the center bandgap frequency, and Δf, which is the bandgap's bandwidth. Additionally, the free space impedance is represented by η, which is equivalent to 120π

Surface waves are suppressed, and antenna performance is enhanced by the two-dimensional periodic surface known as the mushroom-like electromagnetic bandgap (EBG) structure. It is made up of metallic patches that are placed in a mushroom-like pattern on a dielectric substrate. Each patch is connected to the ground plane via a conducting via. The geometrical characteristics of the unit cell, such as the patch width (W) and the distance between adjacent patches (g), can be changed to control the band gap. The band gap in this design is tuned to meet the 2.4 GHz operating frequency. Dimensions of the mushroom EBG structure with W = 15 mm, g = 1 mm, and a via diameter of 1 mm on a polyester substrate with a thickness of 1.45 mm, relative permittivity of 1.44 and loss tangent of 0.01is shown in Fig. 2(d,e). When the EBG structure's reflection phase shifts between −180° and +180°, it functions as an artificial magnetic conductor (AMC). Additionally, when it inhibits surface wave propagation within a particular frequency range, it displays a bandgap feature.

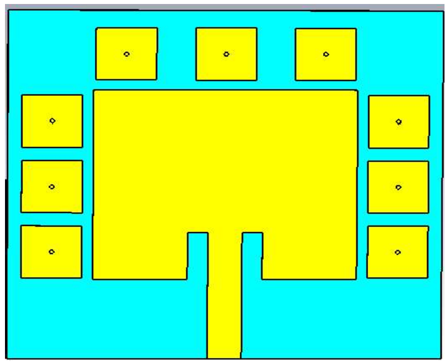


Fig. 2(d) Proposed antenna top view with EBG structure

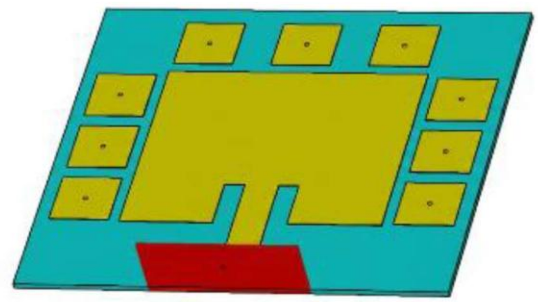


Fig. 2(e) Proposed antenna isometric view with EBG structure

The ground plane, which serves as the reference conductor, is first positioned at the bottom of the suggested antenna structure. Because of its flexibility and low dielectric constant, a polyester substrate is employed as the dielectric layer above the ground plane. The radiating patch, which serves as the antenna's primary radiating element, is positioned on the substrate's upper surface. To enhance the antenna performance, a mushroom-like Electromagnetic Band Gap (EBG) structure is introduced around the antenna. Periodic metallic patches are arranged on the substrate to form the EBG and conducting vias are used to connect each patch to the ground plane.

3.4 Calculated and Optimized Parameters of the Proposed Antenna

TABLE I. Calculated and Optimized Parameters of the Proposed Antenna

Antenna parameters	Dimensions(mm)	
Patch Width (W_p)	56.58	60.97
Patch length (L_p)	50	50.65
Substrate width (W_s)	100	100.75
Substrate length (L_s)	113.16	93.47
Ground width (W_g)	100	100.75
Ground length (W_g)	113.16	93.47
Operating frequency (f_r)	2.4 GHz	2.4 GHz
Substrate dielectric constant (ε_r)	1.44	1.44
Substrate height (h)	1.45	1.45
Feed width (W_f)	8	8
Insert gap (G_{pf})	4.7	4.7
Feed insertion (F_i)	12.7	12.7

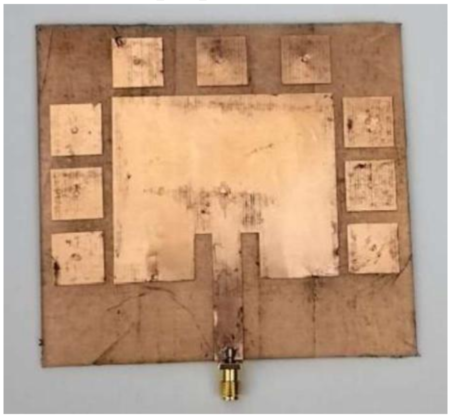
CHAPTER 4

ANTENNA FABRICATION AND MEASUREMENT SETUP

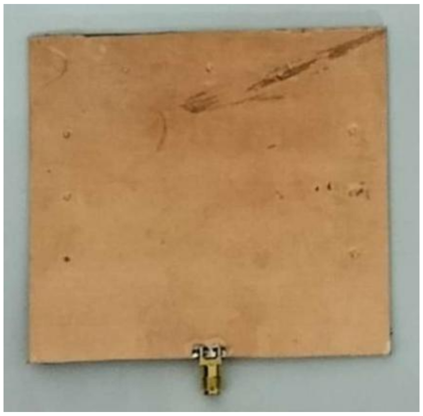
4.1 Fabrication

Because polyester is flexible and suitable for conformal wearable applications, it was used to build the proposed conformal EBG-integrated microstrip patch antenna. The dimensions of the antenna, which included the inset-fed microstrip feed line, radiating patch, the ground plane and EBG unit cells were finished using the best modeling findings for the 2.4 GHz ISM band. The antenna configuration was first created and transferred using the polyester substrate. On the top surface of the substrate, conductive metallic material was used to create the EBG structures and the rectangular radiating patch. The antenna uses an inset-fed microstrip line feeding technology, which reduces reflection loss and ensures effective power transmission by inserting the feed line through a notch into the patch to achieve perfect 50 Ω impedance matching.

The antenna is appropriate for wearable and biomedical applications because theEBG unit cells were positioned around the radiating patch to prevent undesired electromagnetic interaction with the human body, enhance radiation characteristics, and suppress surface wave propagation. To facilitate directed radiation and consistent antenna performance, continuous grounded plane was positioned on the bottom side of the substrate. For measurement and excitation, the antenna's feed line was connected to a 50 Ω SMA connector. The soldering was done appropriately to maintain signal continuity and lessen impedance mismatch. The built antenna prototype was then used for radiation characteristics, return loss, gain, SAR analysis, and performance assessment. The built prototype of the proposed antenna is shown in Figures 3(a) and 3(b).



a)



b)

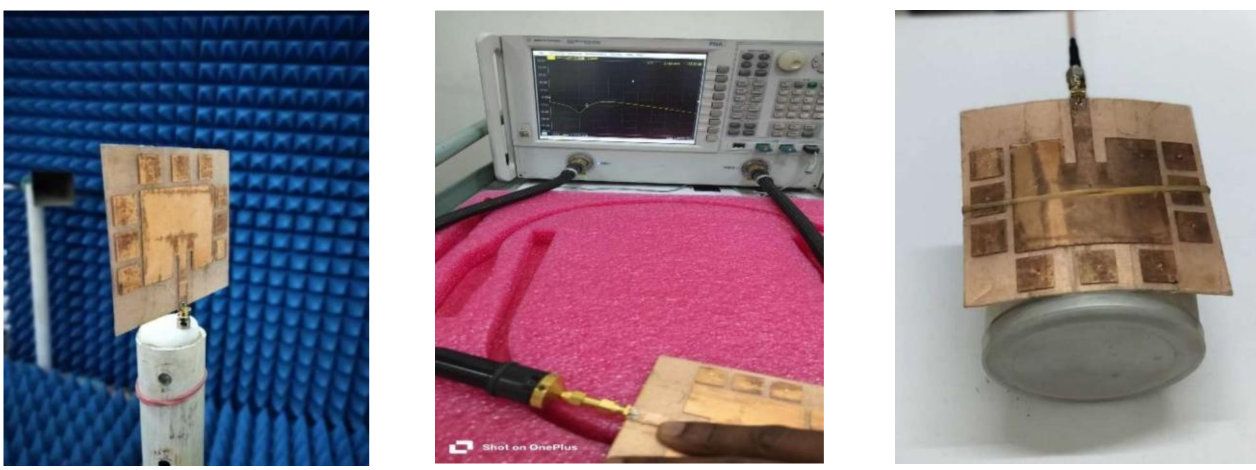
Fig. 3. The proposed prototype of an implanted antenna: (a) top view, (b) back view

4.2 Measurement and testing

Gain characterization, reflection coefficient (S11) evaluation, and bending analysis were used to experimentally test the performance of the suggested conformal EBG-integrated microstrip patch antenna in order to validate the simulation results and determine its applicability for 2.4 GHz.

Biomedical applications of ISM bands. In order to minimize outer EM interference and establish a reflection-free environment, the gain measurement was conducted inside an anechoic chamber, as shown in Fig. 4(a). This setup ensures accurate evaluation of the antenna's radiation characteristics and gain performance at the operational frequency. A Rohde & Schwarz ZNB40 Vector Network Analyzer (VNA) was used to calculate the reflection coefficient (S11), as seen in Fig. 4(b). The built antenna was connected to the inset-fed microstrip line via a soldered 50 Ω SMA connection. The S11 parameter was investigated in order to evaluate the resonant characteristics and impedance matching of the antenna. More efficiently the transfer of power among an antenna and feed is indicated by a lower S11 value line and reduced loss of reflection.

The antenna was placed on a curved cylinder surface to conduct bending research, as shown in Fig. 4(c). In order to render the antenna suitable for biomedical and wearable applications, this study looked into the effects of bending on antenna's efficiency and verify steady functioning in curved environments. Figure 4 illustrates the measurement setup for the proposed antenna, which includes (a) gain measurement in an anechoic chamber, (b) S11 measurement with a VNA, and (c) bending analysis under conformal conditions.



a) b) c)

Fig. 4. Measurement setup of the proposed conformal antenna: (a) gain measurement inside an anechoic chamber, (b) S_{11} measurement using a vector network analyzer (VNA), and (c) bending analysis

CHAPTER 5

RESULTS AND DISCUSSION

This section evaluates the performance of the proposed antenna in the 2.4 GHz ISM band using important antenna performance metrics such as return loss, VSWR, gain, and directivity. To further illustrate whether the EBG design improves performance, a comparison between the conventional microstrip patch antenna and the EBG-integrated antenna is provided.In order to determine the optimal operational bending angle, the antenna's bending performance is also analyzed to see how it responds to various conformal circumstances. Because the antenna operates in close proximity to the human body, the Specific Absorption Rate which is detailed in the next subsection is used to determine the amount of energy absorbed by the body.

5.1 Return loss

The amount of power reflected back from the antenna in relation to the power transmitted into it is described by the return loss (S_{11}) parameter. Ideally, an antenna linked to a transmission line should emit 100% of the input power. A portion of the signal, however, gets reflected back toward the source if the antenna and transmission line impedance are not correctly matched. This reflected power is measured by return loss, which also shows how well the antenna's impedance matches the feeding system. Decibels (dB) are typically used to express return loss. Better antenna performance is indicated by a greater negative return loss number, which suggests that more power is radiated, and less power is reflected. For instance, a return loss of −10 dB, which is typically regarded as acceptable for antenna operation, indicates that around 90% of the power is given to the antenna and only a little part is reflected. Even stronger impedance matching, which means the antenna transmits energy more effectively, is indicated by values like −15 dB or −20 dB.

The level of impedance matching between the source and the antenna is indicated by the return loss parameter. The return loss value should be as low as possible for effective power transfer; for wireless communication, it should ideally be less than −10 dB. Reduction reflected power and better antenna performance are indicated by a lower return loss value. The traditional microstrip patch antenna produces a return loss of −15.3 dB at the resonant frequency f_r = 2.4 GHz. As seen in Fig. 5, the inclusion of the EBG structure further lowers the return loss to −17.7 dB by reducing unwanted electromagnetic coupling and suppressing surface waves, which improves the impedance matching between the patch and the feed line.

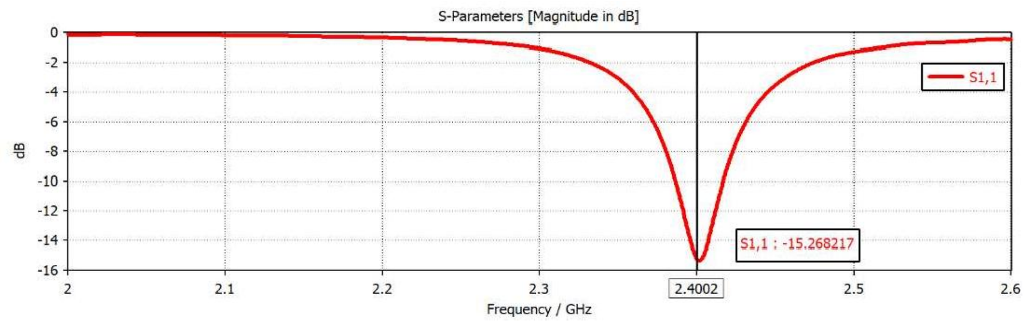


Fig. 5(a) Return loss of the simulated microstrip patch antenna

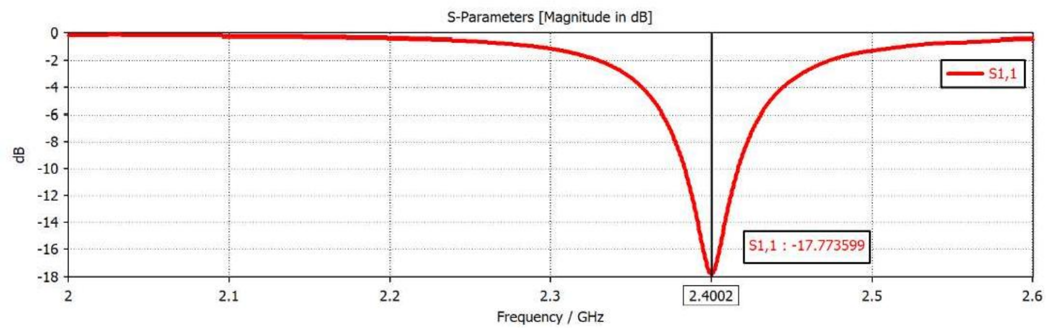


Fig. 5(b) Return loss of the simulated microstrip patch antenna with an EBG structure

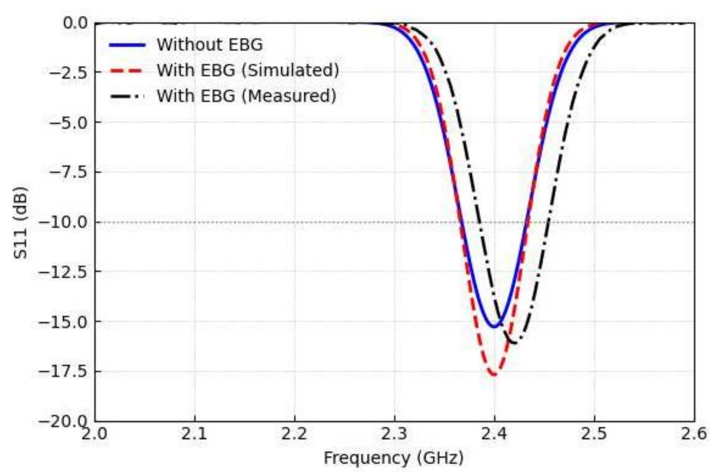


Fig. 5(c) The designed antenna's simulated and measured return loss (S11) with and without an EBG structure

5.2 Voltage Standing Wave Ratio

The voltage standing wave ratio, or VSWR, is a metric used to assess the effectiveness of power transmission from the transmission line to the antenna. It shows how well the antenna and feeding transmission line match in terms of impedance. All power is transmitted to the antenna and emitted as electromagnetic waves when the antenna's impedance precisely matches that of the transmission line. On the other hand, standing waves in the transmission line result from some of the signal being reflected back toward the source in the event of an impedance mismatch.

Figure 6 displays the simulated VSWR curve of the proposed antenna, which illustrates the amount of power reflected due to an impedance mismatch between the antenna and the feed line. A lower VSWR value indicates better power transfer to the antenna. For wireless communication to be effective, the VSWR value must be between 1 and 2 and stay below 2 (VSWR < 2) across the operational frequency band. With a VSWR value of 1.7 at the resonance frequency of 2.4 GHz, the traditional microstrip patch antenna demonstrates good impedance matching. The VSWR increases to 1.3 with the addition of the EBG structure, indicating improved impedance matching and more effective power transfer between the antenna and transmission line.

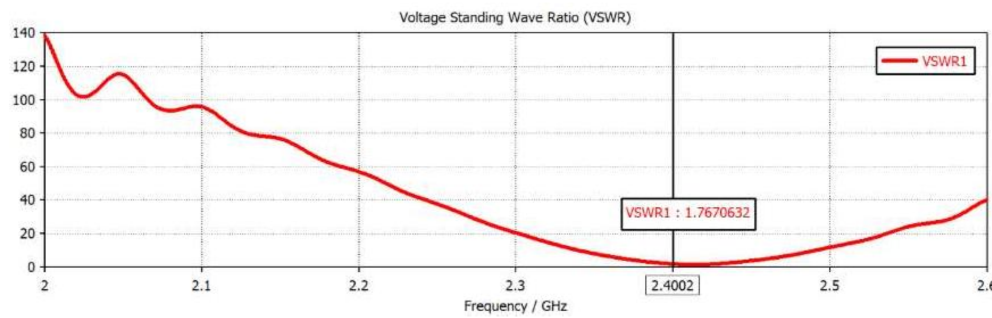
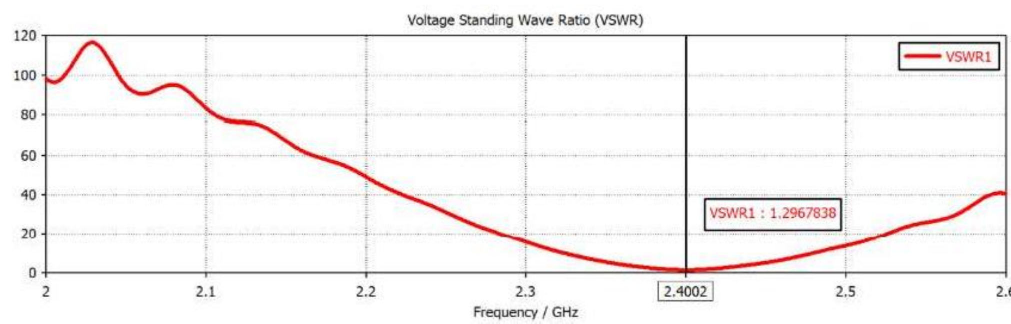


Fig. 6(a) VSWR of the simulated microstrip patch antenna



s

Fig. 6(b) VSWR of the simulated microstrip patch antenna with an EBG structure

5.3 Gain

An antenna's gain is a crucial metric that indicates how well it radiates electromagnetic energy in a certain direction in comparison to an ideal reference antenna. It shows how well the antenna can concentrate and direct radiated power in the intended direction. Typically, gain is expressed in decibels (dB) in relation to an isotropic radiator (dBi). Antenna gain, to put it simply, indicates the strength of the sent or received signal in a certain direction. Improved signal transmission and a greater communication range are the outcomes of concentrating more power in one direction with a higher gain antenna. When dependable signal propagation is needed for wireless communication systems, this is crucial.

Directivity and efficiency are the two primary determinants of antenna gain. Efficiency shows how much of the input power is really radiated rather than lost as heat or surface waves, whereas directivity shows how well the antenna concentrates energy in a particular direction. It shows how well the antenna focuses energy on a specific direction. Higher-gain antennas are preferred for longer-distance transmission because they are more directional, whereas low-gain antennas are often appropriate for short-range communication. The computed 3D far-field gain of the suggested antenna is shown in Figure 7. The traditional microstrip patch antenna reaches a maximum gain of 8.2 dB at the resonance frequency of 2.4 GHz. Because of the EBG structure's radiation efficiency and suppression of surface waves, the gain increases to 8.4 dB.

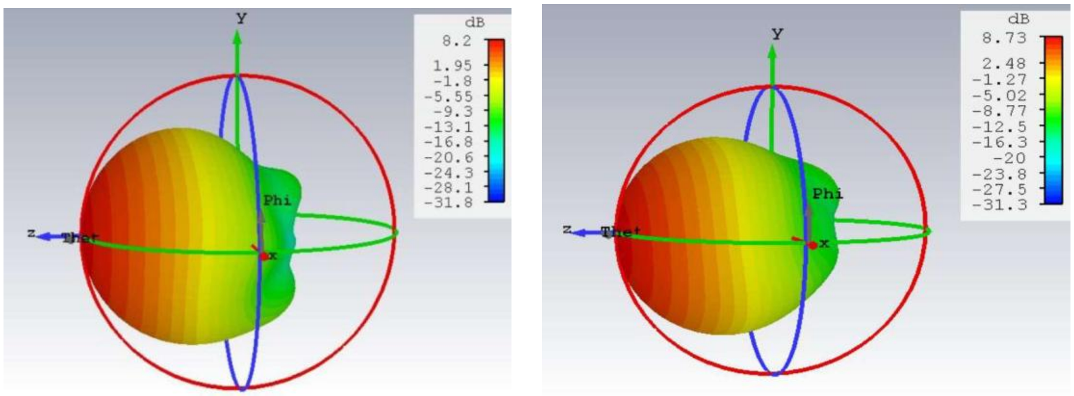


Fig. 7. The simulated 3D radiation patterns of the proposed antenna (a) without EBG (b) with EBG structure

5.4 Directivity

The degree to which antenna radiation is concentrated in one direction is known as its directivity. Instead of radiating uniformly in all directions, it shows the antenna's capacity to concentrate electromagnetic radiation in a particular direction. Directivity, to put it simply, indicates the directionality of the antenna radiation pattern. The majority of an antenna's power is radiated in a single favored direction when it has strong directivity, which increases signal intensity in that direction. Conversely, a low directivity antenna disperses the emitted power more evenly over several directions. The size and shape of the antenna construction as well as the radiation pattern it produces are the primary determinants of directivity. Directivity does not take into account power losses within the antenna, such as conductor or dielectric loss, in contrast to gain. It merely explains how well the emitted energy is concentrated in space by the antenna.

Higher directivity improves signal coverage in the intended direction and lessens interference from undesired directions in wireless communication systems. As a result, directivity is a crucial metric for evaluating an antenna's directional performance and radiation properties.

The ratio of the average power density over a sphere in the far-field region to the highest radiated power density in a certain direction is known as directivity. It shows how much energy is radiated in the desired direction by the antenna. According to Fig. 8, the standard microstrip patch antenna's simulated directivity at 2.4 GHz is 8.74 dBi. Because of improved radiation properties and better control over surface wave propagation, the directivity increases to 8.92 dBi with the addition of the EBG structure.

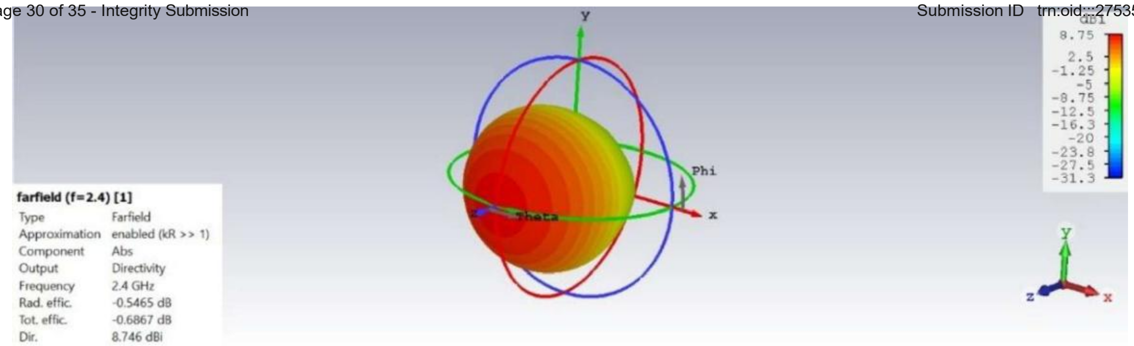


Fig. 8(a) Directivity of the simulated microstrip patch antenna

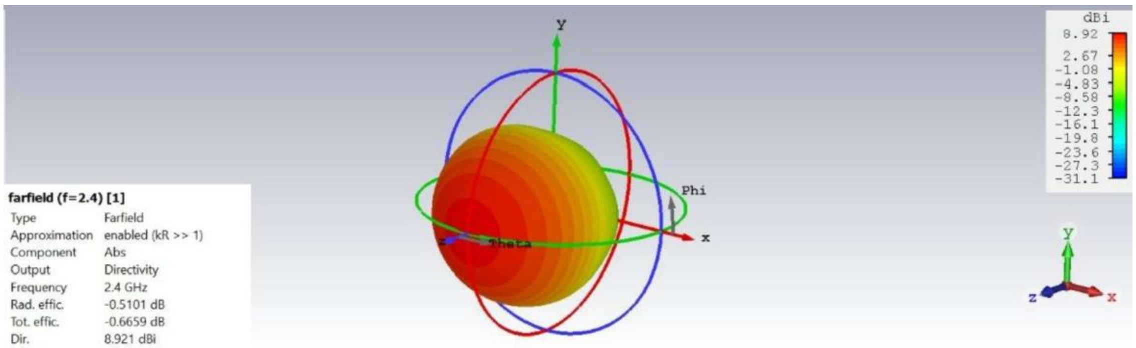
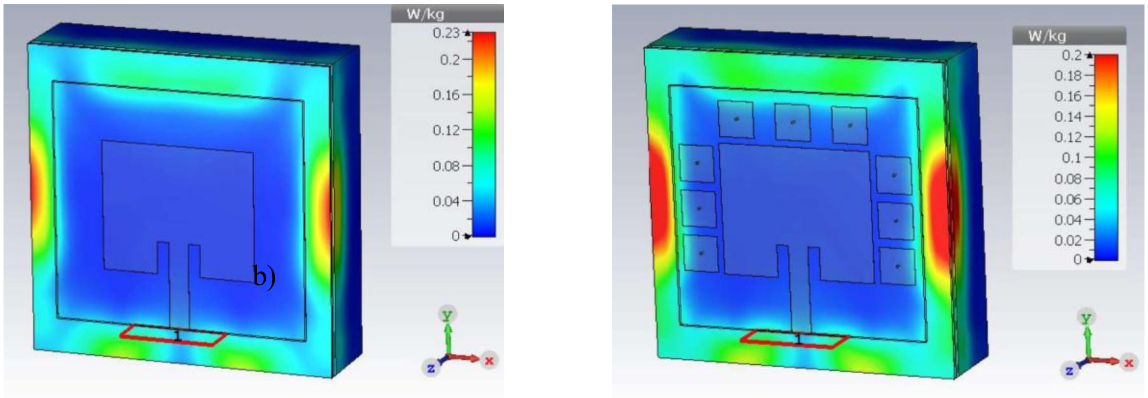


Fig. 8(b) Directivity of the simulated microstrip patch antenna with an EBG structure

5.5 Specific Absorption Rate (SAR)

When human body tissue is subjected to an electromagnetic field, it absorbs electromagnetic radiation at a rate that is measured by a metric called Specific Absorption Rate (SAR). Wearable antennas and body-centric communication devices are examples of antenna systems that are employed close to the human body. The surrounding biological tissue may absorb some of the electromagnetic energy that is radiated. This absorbed power is measured by SAR, which also shows the degree of electromagnetic exposure safety. SAR measures the amount of power absorbed per unit mass of tissue and is commonly expressed as watts per kilogram (W/kg). International safety regulations establish SAR limitations to ensure wireless devices operate safely. For example, based on the regulatory rules, the generally accepted limit for SAR in various countries is either 1.6 W/kg averaged over 1 gram of human tissue or 2 W/kg averaged over 10 grams of tissue. While the IEEE C95.1-2005 standard [13] establishes a limit of 2 W/kg averaged over 10 g of tissue to ensure human safety, the IEEE C95.1-1999 standard [14] states that the SAR value shouldn't exceed 1.6 W/kg averaged over 1 g of tissue. The SAR analysis is based on these IEEE standards. The traditional microstrip patch antenna's maximum SAR value at 2.4 GHz is 0.24 W/kg, as illustrated in Fig. 9. The SAR value is 0.30 W/kg when the EBG structure is included, which is still far below the IEEE standards' allowable safety limits.



a) b)

Fig. 9. SAR analysis of (a) patch antenna (b) patch antenna with EBG structure

5.6 Flexibility/ Bending effect

The impact of bending on the antenna performance is examined in order to look into the bending capability of the suggested antenna. The return loss characteristics are evaluated after the antenna integrated with the EBG structure is bent at various angles, including flat 0°, 2.5°, 5°, 7.5°, and 10°. Bending is used to study how mechanical deformation affects the antenna's impedance matching and resonant behavior.

The graph demonstrates that the antenna maintained its resonant behavior in the 2.4 GHz ISM band under all bending conditions. The return loss stays below −10 dB despite minor changes in resonance depth and frequency caused by structural deformation, demonstrating adequate impedance matching at all bending angles. The bending of 7.5° condition performs better than the flat conditions in terms of impedance matching close to the operational frequency and return loss (about −19 dB). Bending modifies the antenna's effective electrical lengths and current distribution, which affects the resonant characteristics and causes the return loss variance. However, flexible polyester material and the EBG structure allow the antenna to maintain stable performance even when bent. Furthermore, by stabilizing radiation and reducing surface waves characteristics, the EBG structure helps maintain consistent performance throughout conformal deformation.

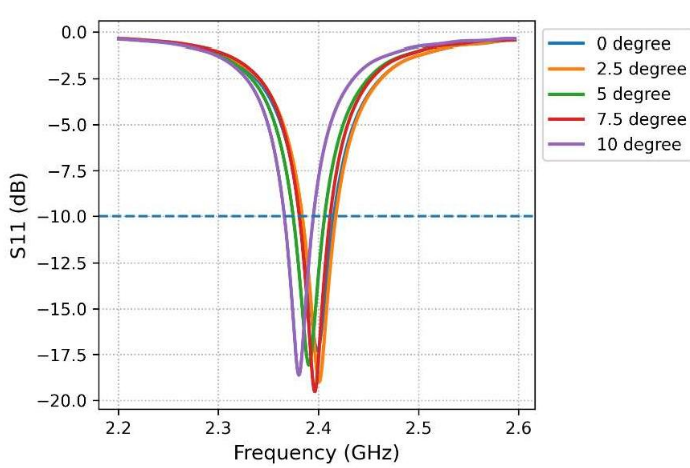


Fig. 10. The suggested antenna's simulated return loss (S_{11}) at various bending angles

As seen in Fig. 4(c), the antenna was bent over a cylinder surface to provide an estimated bending angle of 7.5° during measurement. As seen in Fig. 11, the simulated and measured $S11$ at 7.5° bending closely match, with a small frequency shift and fluctuation in return loss. The antenna maintains stable performance under bending, confirming its conformal capability.
The selected bending angle of 7.5° represents a practical wearable conformal condition corresponding to moderate curvature over cylindrical body surfaces.

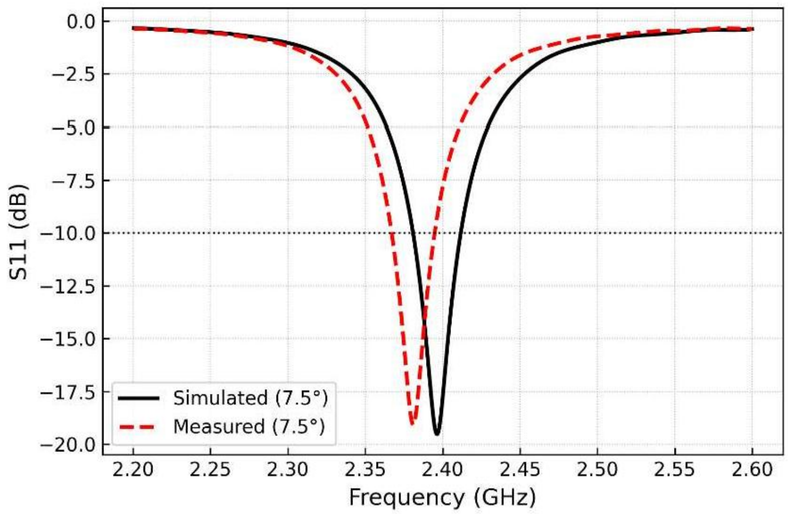


Fig. 11. Return loss (S_{11}) of the suggested antenna under 7.5° bending condition was measured and simulated

5.7 Surface Current Distribution

The surface current distribution is the distribution of current along the antenna's surface and plays an important role in studying thebehavior of the antenna's radiation. In microstrip patch antennas, the current distribution affects various factors including gain, impedance matching, and propagation of surface waves. The incorporation of an EBG layer prevents the propagation of unwanted surface waves.
Fig. 12 illustrates the distribution of surface currents of the proposed antenna at 2.4 GHz without and with the EBG integration scheme. The currents in the conventional antenna have distributed across the patch sides and the substrate's surface, which shows that the surface wave propagation is strong. However, after adding the EBG layer to the patch, the current distribution has become localized in the radiation patch and feeding area; the lateral current has been suppressed. As a result, there has been an improvement in impedance matching and gain improvement up to 8.73 dB.

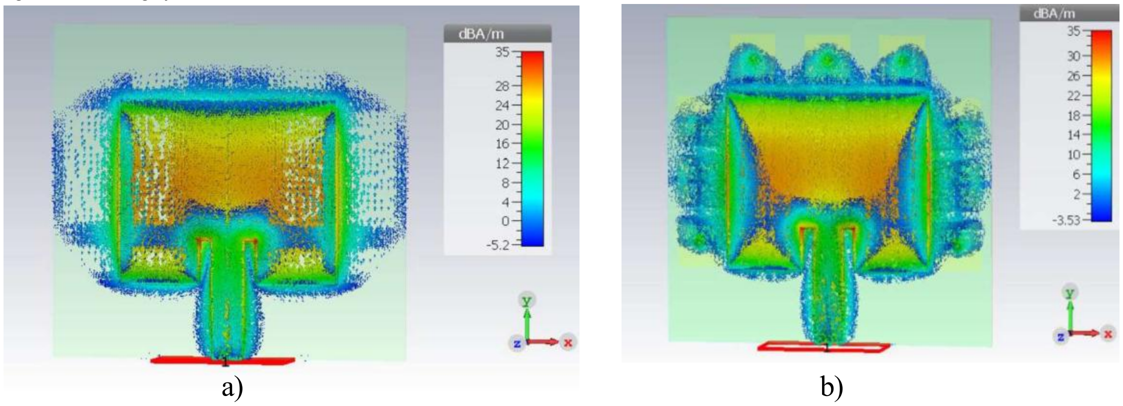


Fig. 12. Surface current distribution of the proposed antenna at 2.4 GHz: (a) without EBG structure and (b) with EBG structure.

5.8 Radiation pattern

Figure 13 shows the proposed antenna's observed radiation pattern at 4. GHz in both the E-plane and H-plane. The antenna's directional characteristics are illustrated by the E-plane radiation pattern (shown by the red dashed curve) and the H-plane radiation pattern (shown by the black solid curve). The steady and nearly symmetrical radiation profile of the antenna shows that electromagnetic waves were continuously traveling in the desired directions

Furthermore, the measured radiation behavior suggests that the antenna provides constant directional characteristics and effective radiation efficiency, both of which are essential for wearable and biomedical communication systems. Because wearable antennas are frequently subjected to changes in the environment and body motions, maintaining a constant radiation pattern is essential to guaranteeing uninterrupted signal transmission and reception. The good agreement in between E-plane and H-plane parameters shows that the suggested antenna can maintain constant radiation performance.

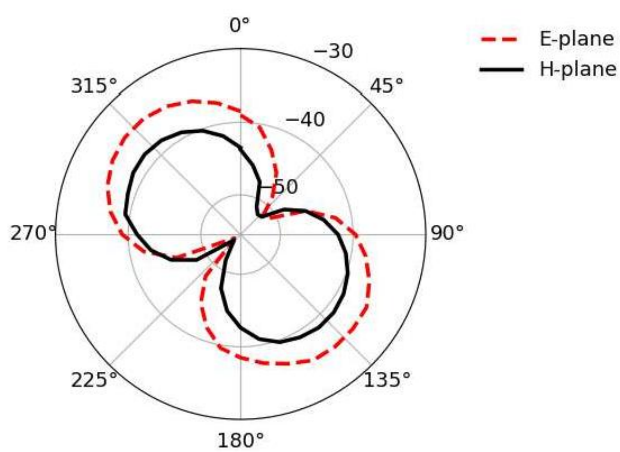


Fig. 13. The proposed antenna's measured radiation pattern in the E-plane and H-plane at 2.4 GHz

CHAPTER 6

COMPARATIVE PERFORMANCE ANALYSIS

As shown in Table II, the performance of the suggested polyester-based flexible patch antenna is compared with a number of recently published designs. While most of the studied antennas have the same 2.4 GHz resonance frequency, they vary in terms of gain, size, and SAR. The primary cause of the suggested antenna's higher gain and lower SAR is the integration of the EBG structure which suppresses the surface waves and significantly reduces backward radiation toward human tissue. Backward radiation is particularly important for body proximate antenna performance because it lowers the amount of electromagnetic energy human body may absorb. The antenna's forwards radiation is further enhanced by the EBG structure, which results in improved radiation performance all around. Because it demonstrates effective gain improvement and SAR reduction, the proposed antenna is therefore viable with the designs displayed in Table II.

TABLE II. Performance Comparison of the various conformal antennas

Ref.	Material	Technique	Freq. (GHz)	Size (mm³)	Gain (dB)	SAR (W/kg)	Bending Analysis
[13]	Fabric	Flexible patch	2.4	60×60×2.4	6.45	0.983	No
[14]	Felt	AMC-based	2.4	50×25.7×5	4.06	0.521	Yes
[15]	Natural Rubber	Textile wearable antenna	2.4	90×90×2.85	7.82	–	No
[16]	Wool felt	Metamaterial-based	2.4	40×32×2.85	5.15	0.554	Yes
[17]	PDMS	AMC loaded	2.4	60×60×8.5	6.56	0.612	Yes
[18]	Polyester	Wearable patch antenna	2.4	105×110.86×2.85	8.384	1.53	No
[19]	Denim jeans	UWB textile antenna	3.1–10.6	35×100×1	3.32	1.601	Yes
This Work	Polyester	EBG-integrated conformal patch antenna	2.4	100.75×93.47×1.45	8.73	0.20	Yes

CHAPTER 7

CONCLUSION

For wearable and biomedical applications, a conformal EBG-integrated microstrip patch antenna operating in the 2.4 GHz ISM band has been effectively built and studied. By reducing surface wave propagation and improving impedance matching and radiation characteristics, the Electromagnetic Band Gap (EBG) construction greatly enhances antenna performance. Conformal functioning is further made possible by the flexible polyester substrate, which makes the antenna appropriate for wearable and curved situations.

Table III's performance comparison of the antenna with and without EBG amply illustrates how successful EBG integration is. Table III shows a 13.04% decrease in Specific Absorption Rate (SAR) from 0.23 W/kg to 0.20 W/kg. This decrease confirms that nearby biological tissue absorbed less EM, which is important for biomedical and wearable devices where user security is the first priority.

Furthermore, the proposed antenna's conformal capabilities for wearable applications was confirmed by its consistent performance when bent. The good agreement between the measured and predicted results validated the antenna design's dependability. Considering the suggested EBG-integrated conformal microstrip patch antenna offers better return loss, gain, decreased SAR, and stable resonant operation, making it a good option for WBAN, IoT, wearable sensing, and short-range biomedical applications for communication in the 2.4 GHz ISM band, according to the results compiled in Table III.

TABLE III. Performance comparison of the proposed antenna with and without EBG structure

Parameter			**Percentage Change**
Return Loss (dB)	−15.3	−17.7	15.69% Improvement
Gain (dB)	8.2	8.73	6.46% Improvement
SAR (W/kg)	0.23	0.2	13.04% Reduction
Resonant Frequency (GHz)	2.4	2.4	No change