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ENHANCED FUNCTIONAL PERFORMANCE OF WEARABLE ANTENNA IN BODY-AREA NETWORK

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Abstract
The interaction between antenna radiation and human tissue has raised critical health questions, as prolonged exposure may contribute to serious health complications, including potentially life-threatening conditions. This study focuses on enhancing antenna performance near the human body by mitigating its biological effects. The primary objective is to minimize the Specific Absorption Rate (SAR), which measures the rate at which the human body absorbs electromagnetic energy. The Electromagnetic Band-Gap (EBG) structures enhance the overall performance and offer the most effective solution due to their low cost, ease of design, and fabrication. Further, this research presents the successful design and simulation of an antenna system that integrates EBG structures to achieve enhanced gain, efficiency, and reduced SAR.

INTRODUCTION

An antenna is a physical structure or device designed to emit and/or capture electromagnetic signals. Functioning as a type of transducer, it enables the conversion of electrical energy into electromagnetic waves and vice versa. Figure 1 depicts the most basic form of wireless communication [1].

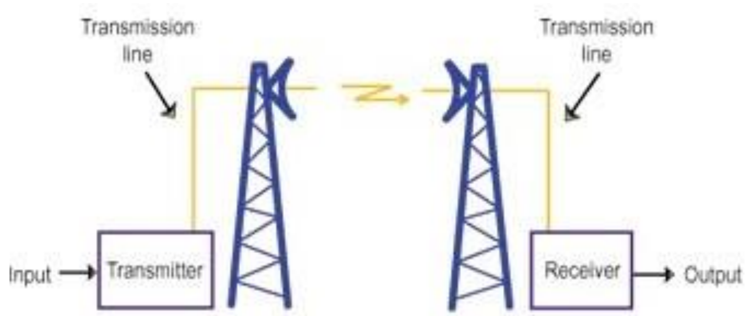

Figure 1: Basic Model of Wireless [1]

In wireless communication networks, antennas are indispensable components that directly influence system performance. A well-engineered antenna not only enhances transmission and reception capabilities but also contributes significantly to system efficiency. Beyond the mere transmission and reception of signals, modern antennas are engineered to optimize radiation patterns—amplifying emissions in targeted directions while suppressing them in others, thereby improving overall communication reliability [1]. Michael Faraday experimentally demonstrated the earliest evidence of a link between electricity and magnetism in the 1830s. Heinrich Hertz observed a disturbance resembling an electromagnetic wave. He ensured the transmission of wireless signals by developing an electrical spark in the gap of the dipole antenna. At the beginning of the 20th century, Guglielmo Marconi made further advancements in radio signal transmission technology, enabling signals to be sent across the Atlantic using an antenna. The transmitter array designed by him has many vertical wires, while the antenna, a long wire at the receiving end, is elevated about 200 meters and carried by a kite [2].

The printed antennas, generally known as Microstrip antennas, have various dimensions, configurations, and shapes, such as monopoles, short dipoles, dipoles, half-wave dipoles, and loop monopoles. These antennas are designed for various applications, such as maritime security, navigation, aeronautics, aviation, aerospace, and architectural communications. In the last few years, body-oriented communications systems have gained the status of a hot topic for research. The microstrip antenna is proposed for creating body area networks (BANs), which provide wireless connectivity by adhering to the body, such as being glued to the arm, chest, head, torso, or other body parts, for continuous connectivity. However, the antennas near the body raise serious health concerns among humans. The basic issue occurs when electromagnetic radiation interacts with human tissue. Antennas operating in the vicinity of the body uptake electromagnetic energy, creating heating effects. If these thermal effects persist for an extended period, they may cause life-threatening conditions. As shown in Figure 2, the harmful impact of radiation on human body tissue has surfaced as a crucial study area [3].

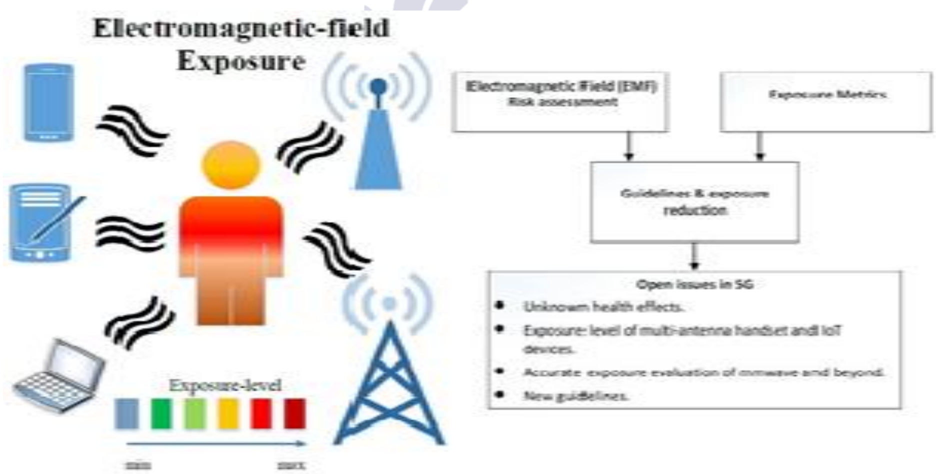

Figure 2: Health Risks Associated with Antenna Radiation Exposure [3]

The research has been conducted to design risk-free antennas that do not compromise performance. The primary focus is to minimize the adverse biological effects of antenna radiation in wearable wireless communication technologies. The existing literature study motivated the concept under consideration in our research. It paved the way for designing an optimal antenna structure that works in the presence of a human body. Specific absorption rate is the primary factor that measures and assesses the bio-impact of antenna radiation when the body absorbs electromagnetic radiation. SAR is an internationally accepted safety guideline that ensures the quantity of electromagnetic radiation absorbed by the human body's tissues. The primary goal of our research work is to mitigate the adverse health effects caused by radio frequency radiation from antennas, which can only be achieved by minimizing the value of SAR. The standard range for the absorption of radiofrequency energy by human body tissue, according to international guidelines, is specified by the Specific Absorption Rate (SAR) [4], [5]. Further, EBG structures are periodic and typically composed of repeating unit cells based on a single conductive element. At a specific frequency, all the cells of the EBG resonate and propagate their energy. The interference of electromagnetic radiation is mitigated, which improves the system's performance.

LITERATURE

Over the past decade, numerous research efforts have been dedicated to enhancing the performance of portable antennas operating in proximity to the human body. These studies aim primarily to mitigate the hazardous biological effects of EM radiation, particularly when users are exposed to RF energy. A substantial portion of this research has explored methods for lowering the Specific Absorption Rate (SAR) and employing shielding materials to limit radiation exposure.

Various strategies have been proposed for mitigating radiation exposure using handheld devices [6]. One such technique involves the combined use of electromagnetic-absorbing cards and thin metallic layers with graphene-like structures, effectively lowering SAR levels to within acceptable international safety limits [7]. Another method introduces reflective elements placed near the primary antenna to enhance radiation efficiency while minimizing SAR concurrently [8]. However, this technique is typically applicable only to antennas operating at a single, fixed frequency, limiting its versatility. A technique in which ferrite sheets are installed at the rear of the handset antenna, so the back-plane current will be subdued and will decrease the human body's exposure to electromagnetic radiation [9]. This technique is effective but costly and requires specific EM properties, such as very precise permeability and permittivity, for excellent shielding performance.

Similarly, directional antennas can also reduce SAR applications if engineered for the Ka-band [10]. High-impedance surfaces, such as EBGs and AMCs, are artificially created materials that possess significant capabilities in subduing surface waves and reducing the value of SAR [11]. EBGs are metamaterial structures designed on a dielectric substrate by ordering periodic metallic arrangements, which regulate the propagation of EM waves within specified frequency bands irrespective of the incident angle and polarisation [12], [13], [14], [15].

Recent experiments have demonstrated that when mushroom-shaped EBG structures of three rows enclose a patch antenna, the SAR is significantly decreased due to the attenuation of surface acoustic waves. Mushroom-like EBGs not only focus on reducing the SAR but also on designing compact antenna structures [16]. A mushroom-like EBG structure, when operating at frequencies near 5.4 GHz, increases bandwidth and similarly enhances performance by improving gain, directivity, and reducing backlobe radiation [17].

EBG structures, though fundamentally periodic in concept, can also be implemented in non-periodic configurations to improve the performance of low-profile antennas [18]. These structures are composed of metallic patches embedded on substrates that serve as dielectrics. This idea was first introduced in the late 1990s as part of early metamaterials research. EBGs offer an effective suppression of surface waves, resulting in improved radiation efficiency and isolation. Inhibition of unwanted electromagnetic propagation within designated frequency bands and reflection of incoming waves without phase distortion. Increased antenna gain and minimized back radiation. Further, the selective frequency characteristic of the EBG eliminates the unwanted radiation modes. Also, ensure safety by substantially reducing the SAR.

Collectively, these benefits enhance the antenna's performance when the EBG structure is implemented. EBG of mushroom type is the most desired solution to decrease the SAR in the vicinity of humans and reduce the risk of electromagnetic radiation that is absorbed by tissues [19].

The primary objective of our research is to mitigate the adverse health effects of radio frequency radiation from antennas by reducing the SAR. The standard range for the absorption of radiofrequency radiation by human tissue, as defined by international norms, is specified by the SAR. Moreover, EBG structures are periodic and generally consist of repeated unit cells derived from a singular conducting element to improve the overall performance of the system's functionality.

METHODOLOGY

CST Studio Suite is used for designing and simulation the proposed microstrip path antenna. This comprehensive electromagnetic simulation software supports a wide range of frequency domains, from low-frequency to microwave applications.

The antenna was designed to operate at a centre frequency of 2.4 GHz, which is widely used in mobile and wireless communication systems, including Wi-Fi and Bluetooth. To achieve optimal electromagnetic performance, the following materials were selected:

- Substrate: Rogers RT 5880 (lossy), known for its low dielectric loss and high-frequency stability.
- Conductive Layers (Patch and Ground Plane): Annealed copper, selected for its excellent conductivity.

DESIGNING

A. Patch Element

The copper-made patch is 0.035 mm thick. The final values are selected based on parametric analysis to achieve precise resonance at 2.4 GHz [20]. The finalized patch dimensions is shown in Figure 3.

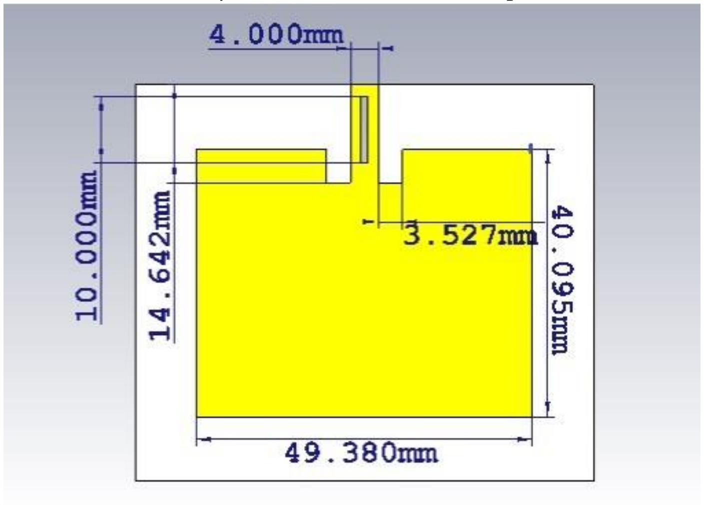

Figure 3: Optimized Patch Dimensions [20]

B. Dielectric Substrate

The dielectric substrate [20] used in the design is Rogers RT 5880 (lossy) with a thickness of 1.5 mm. This material was chosen over commonly used alternatives like FR-4 due to its superior performance in terms of return loss, radiation efficiency, and SAR minimization. The substrate's geometry is shown in Figure 4.

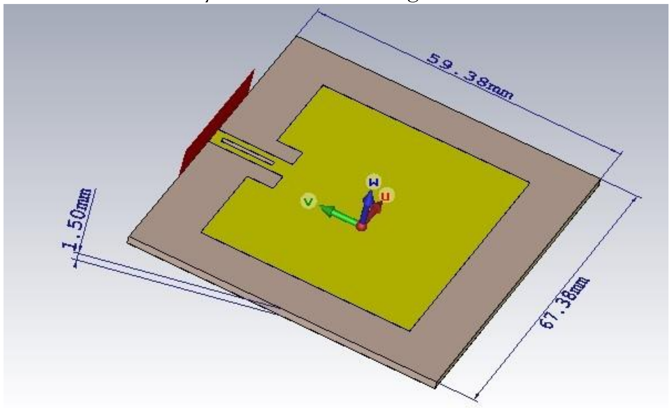

Figure 4: Substrate Geometry and Dimensions [20]

C. Ground Plane

Annealed copper having 0.035 mm thickness is used in the construction of ground plane which ensures the consistently best performance, shelfing and matches the lateral dimension of the substrate is presented in Figure 5.

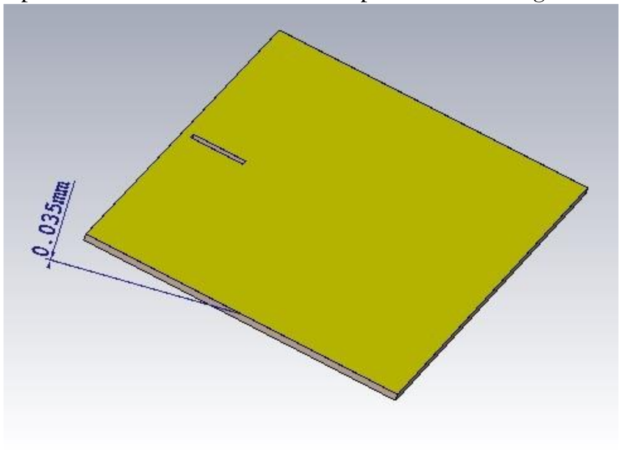

Figure 5: Ground Plane Structure [20]

D. Creation of Slot

The slot creation in feedline is the most distinguishing feature which penetrates through ground plane and substrate. such design of our antenna distinguished it from the conventional models and improved the return loss due to the creation of slot, matching impedance of antenna improved which decreased the return loss value below than threshold value of -10 dB that is necessary for signal transmission having less reflection [21]. Parameters like radiation efficiency and bandwidth is strongly influenced by the structural changes. The slot dimensions are shown in Figure 6.

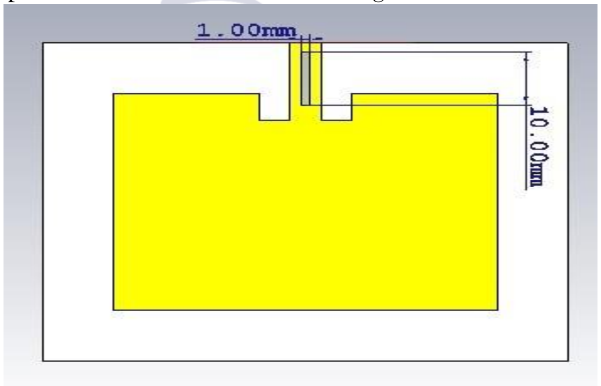

Figure 6: Slot Geometry and Measurement [21]

E. Feeding Technique

The proposed microstrip patch antenna utilizes the microstrip feedline method for signal excitation, as illustrated in Figure 7. This technique was selected due to its ability to provide effective impedance matching without the need for additional matching circuitry, thereby simplifying the overall design.

In addition to its impedance benefits, the ease of fabrication and straightforward integration with planar antenna structures further justify the adoption of this method

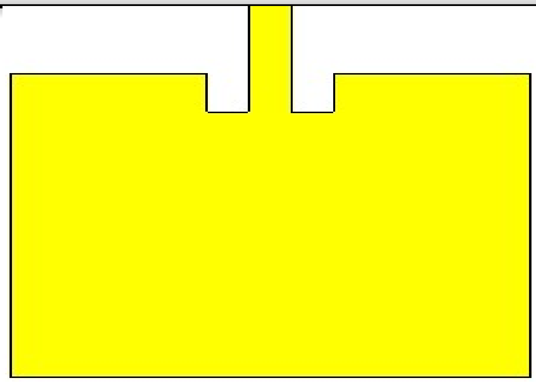

Figure 7: Microstrip Feedline Configuration

F. EBG Cell Design

The proposed Electromagnetic Band-Gap (EBG) structure is a modified two-dimensional mushroom-type configuration, incorporating vias and rectangular slots to enhance its electromagnetic performance. This hybrid structure forms a near-rectangular or square unit cell, optimized for surface wave suppression and SAR reduction. The rectangular slots integrated into the design have a width of 0.2 mm, while the via connecting the patch to the ground plane has a diameter of 0.5 mm, facilitating vertical current flow and improving high-impedance characteristics. The detailed geometry of the EBG cell is illustrated in Figure 8.

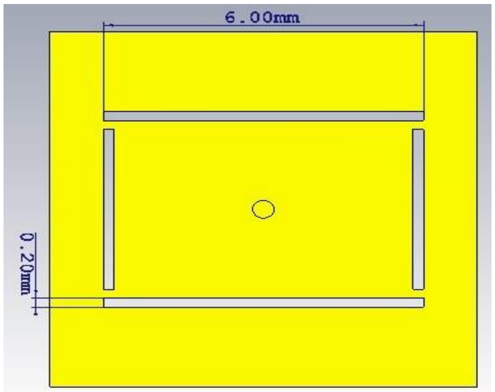

Figure 8: Geometric Dimensions of the Mushroom-Type EBG Cell

PROPOSED ANTENNA CONFIGURATION

The complete layout of the designed antenna is depicted in **Figure 9**. The structure incorporates a total of **28 mushroom-type EBG cells**, strategically positioned to maximize electromagnetic performance and minimize Specific Absorption Rate (SAR).

Specifically, the configuration includes:

- **7 EBG cells** placed along both the left and right sides of the antenna,
- **8 cells** arranged along the bottom edge,
- Moreover, **6 cells** are located on the top edge, with a deliberate gap created to accommodate the feedline.

Each EBG unit is spaced 0.3 mm apart from its adjacent cells to ensure optimal suppression of surface waves. Additionally, the feedline features an integrated slot, which is demonstrated to significantly reduce return loss compared to conventional feedlines without a slot.

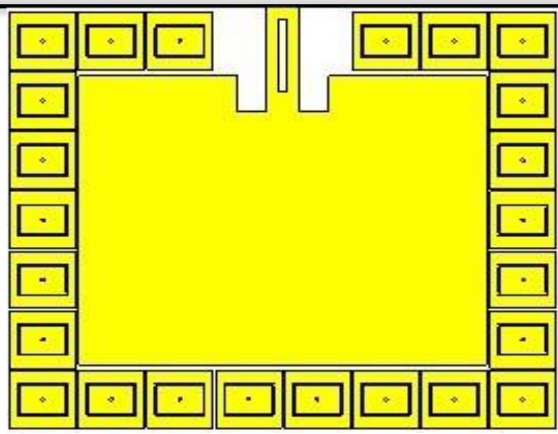

Figure 9: Complete Configuration of the Proposed Antenna

A. Specification of Biological Tissues

Since the designed antenna is intended for use in proximity to the human body, it is essential to define the electrical and physical properties of the relevant biological tissues. These parameters include **relative** permittivity, conductivity of electricity, density and tangent loss [22].

The anatomical layers and their corresponding thicknesses considered for simulation are shown in Figure 10. Incorporating realistic human tissue layers was crucial for accurately calculating the Specific Absorption Rate (SAR), enabling assessment of the electromagnetic exposure and its potential biological impact.

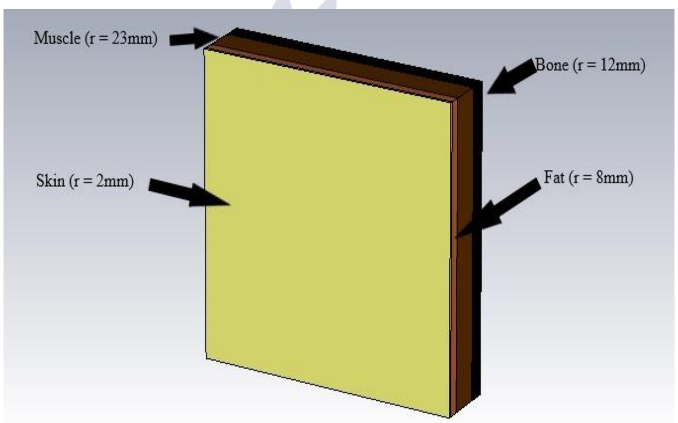

Figure 10: Cross-Sectional Thicknesses of Human Body Tissues Used in SAR Evaluation

B. Antenna's parameters

In the antenna design under discussion, the substrate measures 59.38 mm in length and 67.38 mm in width. The radiating patch features dimensions of 40.095 mm in length and 49.38 mm in width. The thickness of the ground plane is 0.035 mm, and the substrate is 1.5mm in height. The feeding structure is designed with a feedline that is 14.642 mm long and 4 mm wide. The antenna uses an inset feed with a depth of 5 mm and a notch width of 3.527 mm to ensure proper impedance matching. For electromagnetic bandgap (EBG) integration, each EBG cell is sized at 8 mm in both length and width. The total length and width of the material used for the antenna structure are both 200 mm, providing a sufficient ground area for the antenna. Additionally, the slot incorporated in the design measures 10 mm in length and 1 mm in width, contributing to the desired frequency response and performance tuning.

MATHEMATICAL MODAL

$$SAR = \frac{1}{V} \int \frac{\int \sigma(r) |E(r)|^2}{\rho(r)} dx$$

σ =Electrical conductivity(sigma)

E=Electric field density

V=volume of sample

ρ =sample density(rho)

RESULTS AND DISCUSSION

A. Return loss

Analyzing results in the presence and absence of EBG.

i) With EBG

When Electromagnetic Band-Gap structure has been placed in antenna setup & the targeted frequency of 2.4 GHz has been set so the return loss which is -13.29 dB has been achieved as shown in Figure 11.

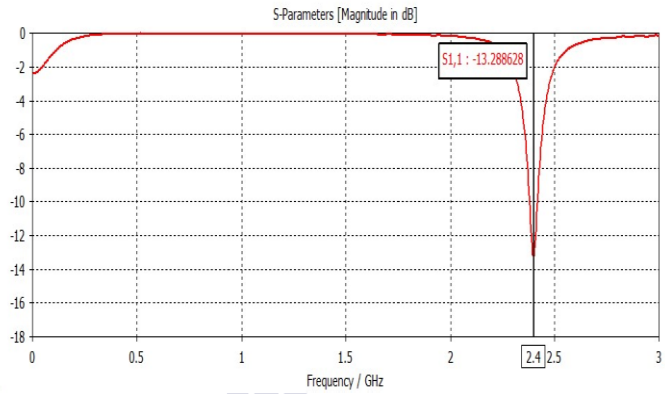

Figure 11: Measured Return Loss with EBG Structure at 2.4 GHz

ii) Without the EBG

At frequency of 2.475 GHz, return loss of -11.1 dB has been observed that deviates from 2.4 GHz which is the targeted operating frequency as illustrated in Figure 12.

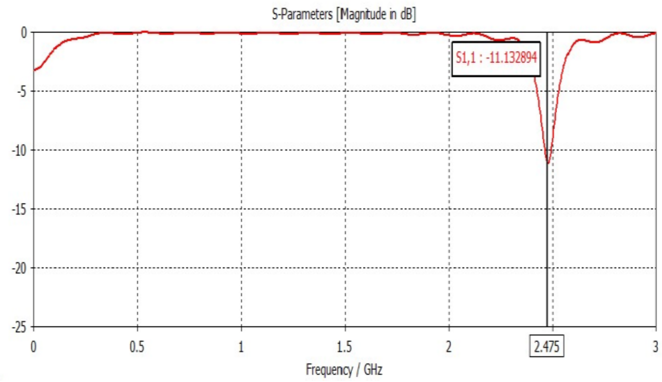

Figure 12: Measured Return Loss Without EBG Structure, Observed Near 2.475 GHz

B. Efficiency

The efficiency of antenna is evaluated under two conditions: with and without the integration of EBG structures. This comparison highlights the performance improvement when EBG elements are incorporated.

i) With EBG

As illustrated in Figure 13, the antenna achieves a total efficiency of 60.4% at the target frequency of 2.4 GHz when EBG structures are employed. This confirms a significant enhancement in overall efficiency due to the presence of EBG.

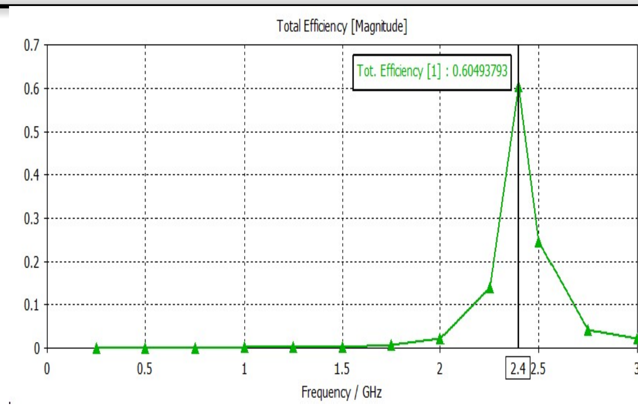

Figure 13: Antenna Efficiency with EBG at 2.4 GHz

ii) Without EBG

As depicted in Figure 14, the antenna without EBG structures exhibits a total efficiency of 46.5%, and this performance is observed at an off-target frequency of 2.475 GHz, rather than the intended 2.4 GHz. This clearly indicates a drop in efficiency and deviation from the desired operating frequency in the absence of EBG integration.

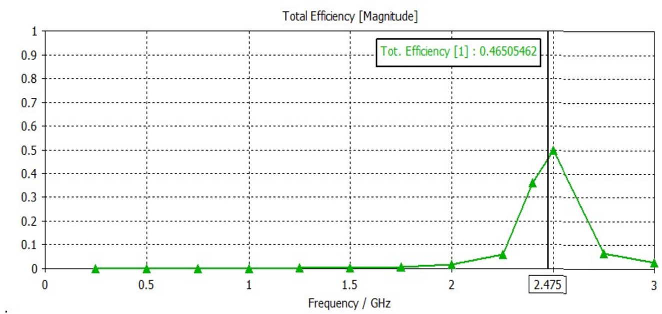

Figure 14: Antenna Efficiency without EBG at 2.4 GHz

C. Voltage Standing Wave Ratio (VSWR)

This section discusses the VSWR of the antenna, first with EBG structures included, followed by analysis without them.

i) With EBG

As illustrated in Figure 15, the Voltage Standing Wave Ratio (VSWR) in the presence of EBG structures is significantly improved. At the target frequency of 2.4 GHz, the VSWR stands at 1.55, indicating good impedance matching and efficient power transfer.

Figure 15: VSWR with EBG at 2.4 GHz

ii) Without EBG

As depicted in Figure 16, when the EBG structures are not included, the VSWR increases to **1.77**, and the resonance shifts to an undesired frequency of 2.475 GHz. This reflects a less optimal impedance match and reduces overall performance.

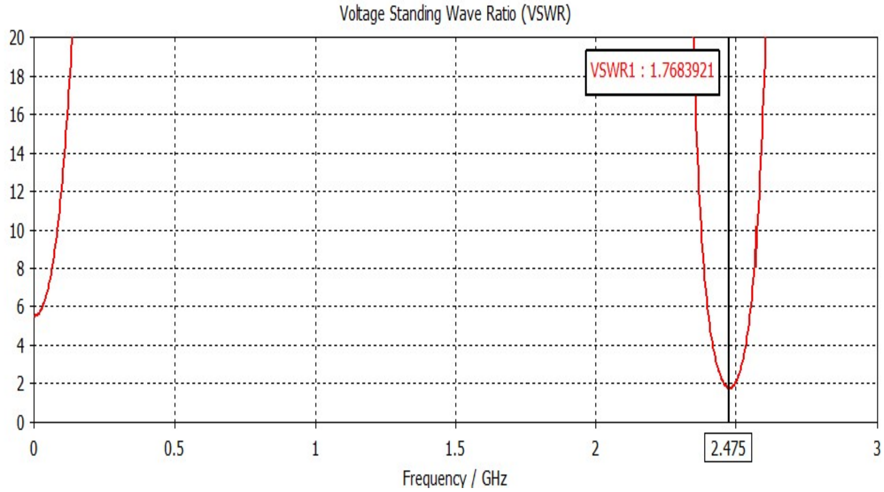

Figure 16: VSWR without EBG at 2.4 GHz

D. Directivity

This section compares the directivity performance of the antenna with and without the inclusion of EBG structures.

i) With EBG

As illustrated in Figure 17, the antenna exhibits a directivity of 7.94 dBi at the target frequency of 2.4 GHz when the EBG structures are present, indicating a focused radiation pattern and enhanced directional performance.

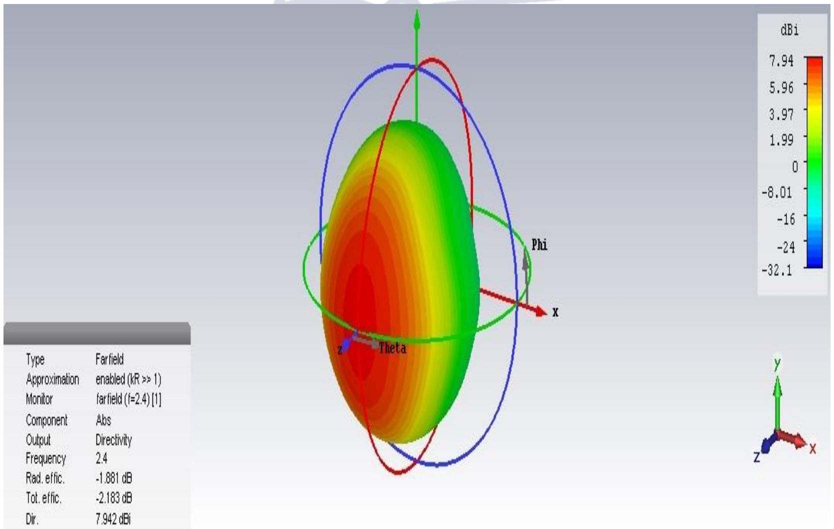

Figure 17: Directivity with EBG at 2.4 GHz

ii) Without EBG

As shown in **Figure 18**, the antenna achieves a directivity of **5.97 dBi** at **2.4 GHz** in the absence of EBG structures. This value is noticeably lower than with EBG, indicating a reduction in the antenna's ability to focus energy in a specific direction.

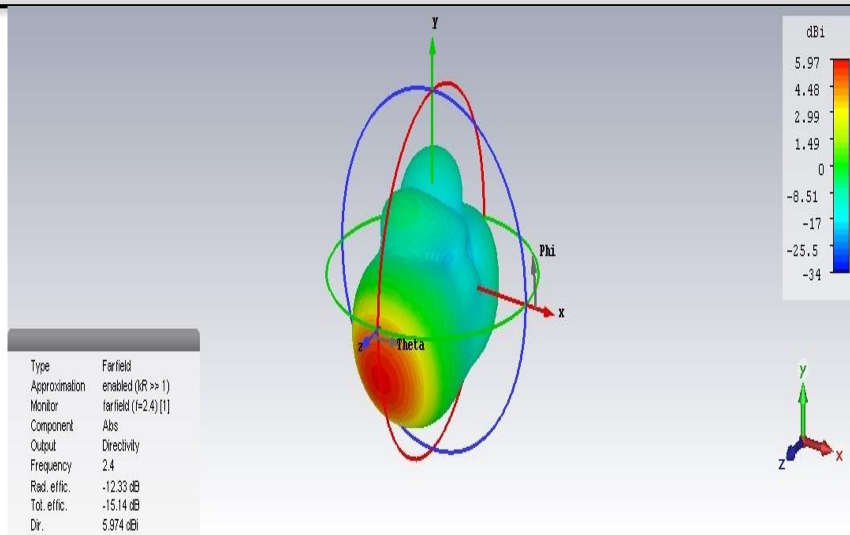

Figure 18: Directivity without EBG at 2.4 GHz

E. Gain

This section presents the gain performance of the antenna both with and without the implementation of EBG structures.

i) With EBG

Figure 19 illustrates the antenna gain when EBG structures are incorporated, measured at the operating frequency of 2.4 GHz.

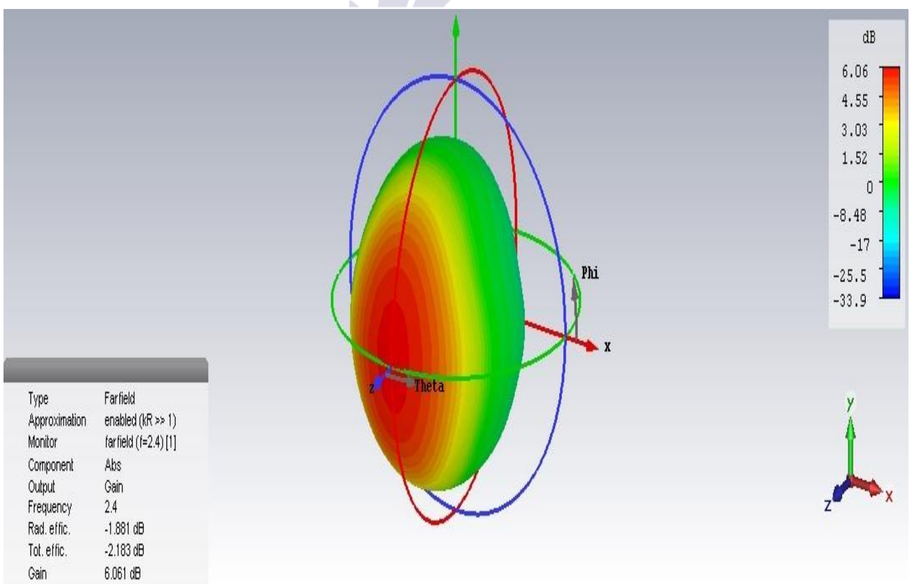

Figure 19: Gain with EBG at 2.4 GHz

ii) Without EBG

As shown in Figure 20, the antenna gain without the EBG structures is measured at 6.6 dB at the target frequency of 2.4 GHz. This value reflects a noticeable decrease compared to the gain achieved when EBG is present.

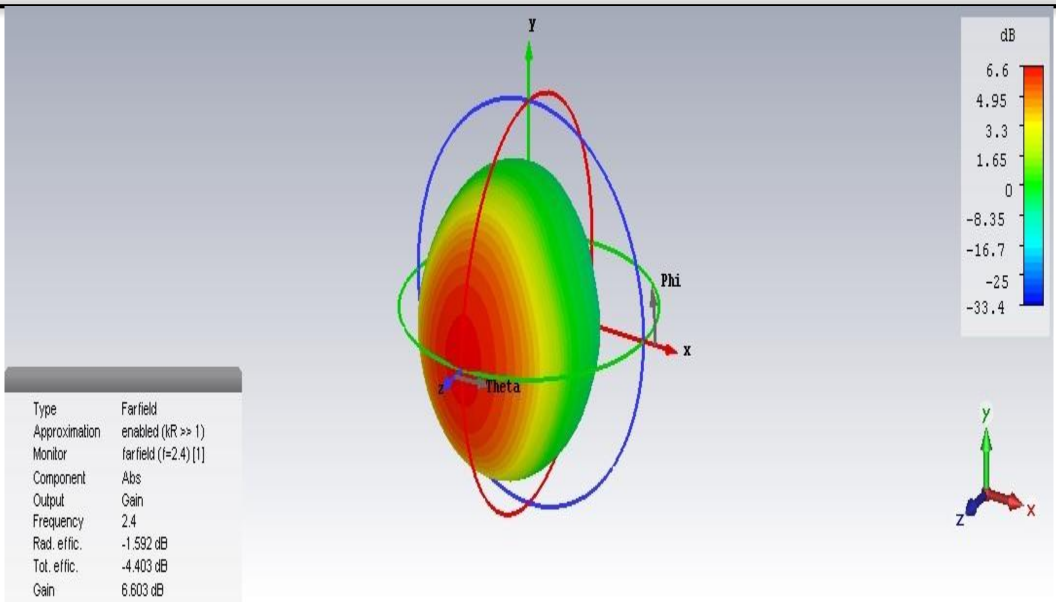

Figure 20: Gain without EBG at 2.4 GHz

F. Specific Absorption Rate (SAR)

SAR is a crucial factor in evaluating the safety of antenna radiation on the human body. According to the European IEC standard, the acceptable SAR limit is 2.0 W/kg averaged over 10 grams of tissues. Our simulation results demonstrate values well below this threshold.

i) With EBG

As illustrated in Figure 21, the value of Specific Absorption Rate is 0.262 W/kg over 10 grams of tissue in the presence of EBG is 0.262 W/kg at the operating frequency of 2.4 GHz which indicates a significant reduction in radiation exposure.

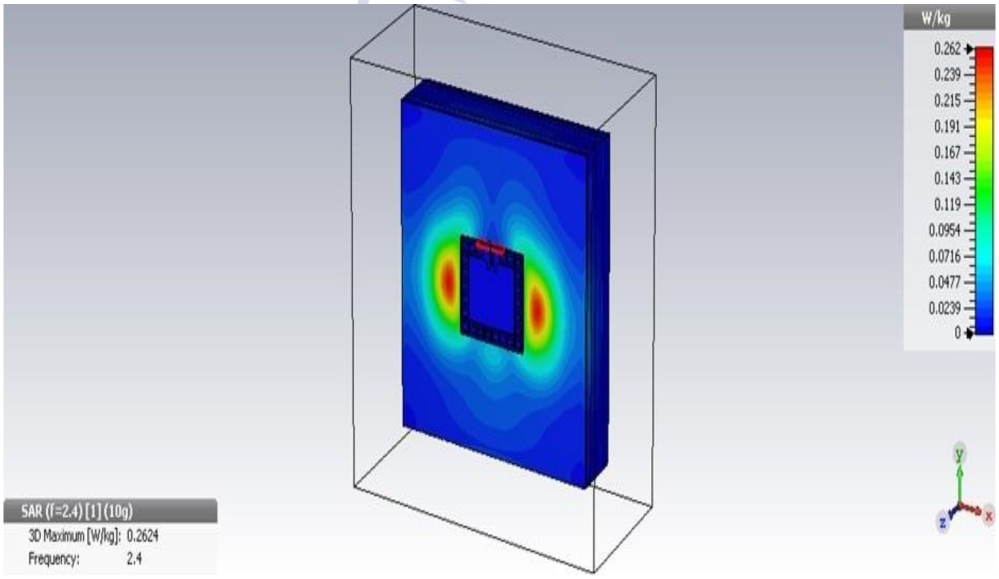

Figure 21: SAR with EBG at 2.4 GHz

ii) Without EBG

As shown in **Figure 22**, the SAR value without the incorporation of EBG structures is **0.707 W/kg** averaged over 10 grams of tissue at 2.4 GHz. This higher value compared to the EBG case indicates increased radiation absorption by the body.

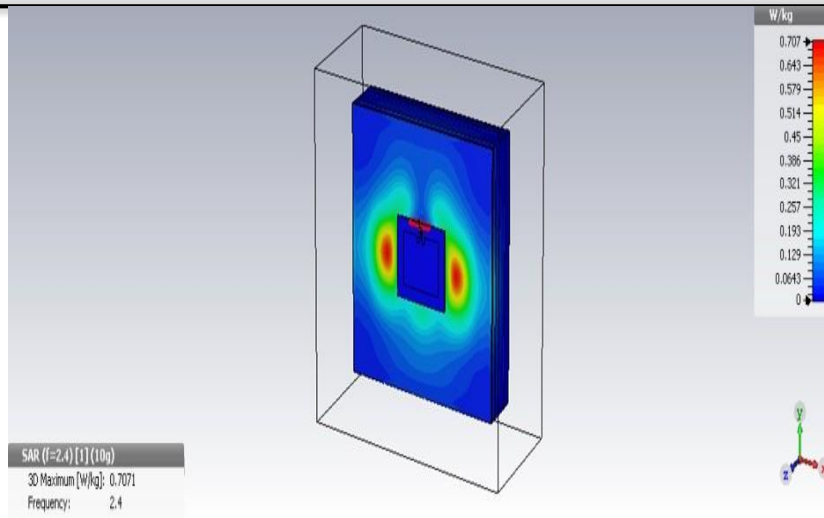

Figure 22: SAR without EBG at 2.4 GHz

CONCLUSION

Electromagnetic Band-Gap (EBG) structures improved overall performance and provide an optimal solution owing to their affordability, simplicity in design, and ease of manufacture. The results demonstrate that utilizing Rogers RT 5880 (lossy) substrate enables the design of an antenna that achieves optimal performance when combined with EBG structures. This design not only effectively reduces the Specific Absorption Rate (SAR) but also enhances other critical antenna characteristics, including gain and overall efficiency. Although the gain of the current antenna design is improved overall, the gain of the non-EBG antenna still surpasses that of the EBG-based antenna. Future research should focus on developing EBG structures that enhance gain beyond the levels achieved by conventional antennas. Additionally, there remains potential for further reducing the Specific Absorption Rate (SAR), making the design even safer for on-body applications.

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