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Flexible EBG Structure Antenna for ISM Band Applications

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Abstract

The electromagnetic bandgap (EBG) antenna, designed for ISM band applications, demonstrates a sophisticated interaction of structural and electrical parameters to optimize performance. This antenna is carefully engineered with an overall size of 70mm × 80mm to ensure efficient radiation characteristics and operation at 2.4 GHz and 5.8 GHz. The proposed antenna design uses an EBG ring structure, with an inner diameter of 3mm and an outer diameter of 6mm, FR-4 substrate, for featuring a dielectric constant of 3.8, and a precisely calculated feed-line width of 2.4mm × 20.7mm to ensure the optimal impedance matching, reducing signal losses. The 0.035mm thick copper conductor is used in reinforcing the conductivity, while the 1.6mm thick substrate is used for further supporting the structural integrity. Additionally, the 20mm EBG radius aids in controlling electromagnetic interference and improving radiation control. The proposed antenna design minimizes signal reflection, by maintaining the return loss (S11) below -10 dB, as well as ensuring a better transmission efficiency. A VSWR value between 1 and 2 further confirms superior impedance matching, preventing excessive power loss, while the gain, ranging from 3 to 6 dBi, highlights strong signal radiation capabilities.

Keywords: EBG, Antenna Design, ISM band, FR-4 Substrate, Copper Conductor

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1. Introduction

This research investigates the design, fabrication, and performance of flexible Electromagnetic Bandgap (EBG) antennas optimized for ISM band applications [11]. These antennas integrate flexibility, miniaturization, and enhanced electromagnetic properties to support compact, high-performance communication devices. Unlike rigid antennas, flexible EBG structures utilize bendable substrates, making them ideal for wearable tech and IoT applications. They suppress unwanted electromagnetic waves, reducing interference and enhancing bandwidth for efficient high-speed data transmission. Their optimized radiation patterns improve signal propagation and reception[12]. By combining flexible materials with EBG technology, these antennas provide reliable connectivity in dense electromagnetic environments, advancing wireless communication capabilities [13, 14].

The primary objective of this study is to design an adaptive Electromagnetic Band Gap (EBG) antenna that efficiently operates within the ISM band. To achieve optimal performance, the research focuses on enhancing gain, bandwidth, and radiation efficiency through the strategic incorporation of EBG structures [15]. Additionally, the study aims to integrate an adaptive mechanism using PIN diodes, varactors, or MEMS switches to enable frequency reconfigurability, ensuring flexibility in various applications. An important aspect of this research involves simulating and analysing the antenna's performance using advanced electromagnetic modelling software, allowing for precise assessments of design modifications. Ultimately, the study demonstrates the fabrication of a prototype, followed by experimental analysis to validate its operational efficacy, ensuring that the proposed design meets the intended objectives [16,17].

2. Related Work

The ISM (Industrial, Scientific, and Medical) bands are specific frequency ranges, such as 2.4 GHz, 5 GHz, and 900 MHz, that are freely available for wireless communication without the need for a license. These frequencies are widely used in technologies like Wi-Fi, Bluetooth, and Zigbee. Antennas designed for ISM band applications need to be small, efficient, cost-effective, and capable of transmitting signals effectively.

Electromagnetic Bandgap (EBG) structures have become increasingly popular in antenna design because they help reduce unwanted surface waves and control how electromagnetic waves travel within a certain frequency range. Recent advancements focus on using flexible materials in EBG-based antennas, making them more adaptable and portable, which is especially useful for wearable and compact wireless devices.

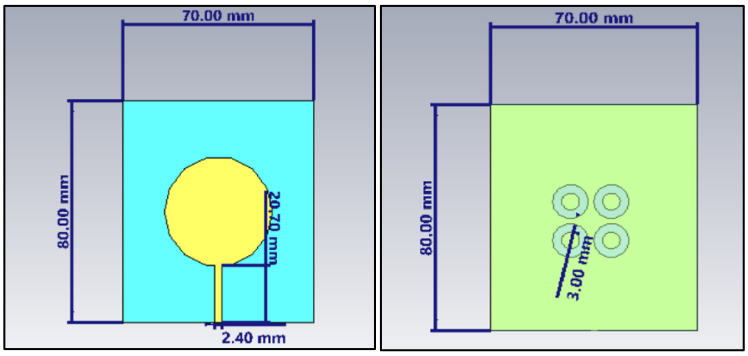
Flexible Electromagnetic Bandgap (EBG) antennas have been extensively investigated for applications within the Industrial, Scientific, and Medical (ISM) bands. Research has focused on enhancing antenna performance for wearable devices through design and optimization [1]. Integration of EBG structures into flexible antennas has been explored to improve overall efficiency and communication range within ISM frequencies [2]. Studies have customized flexible EBG antennas for wearable electronics, particularly emphasizing applications in the 2.4 GHz ISM band [3]. Compact flexible EBG antenna designs have been developed for wireless communication targeting ISM band frequencies such as Wi-Fi and Bluetooth [4]. Research has also focused on improving the radiation efficiency of flexible EBG antennas for wireless communication systems in ISM bands [5]. Miniaturization of flexible EBG antennas while maintaining performance for ISM band operations has been a key area of investigation [6]. The design and application of flexible Electromagnetic Bandgap (EBG) antennas within the Industrial, Scientific, and Medical (ISM) bands have been the subject of significant research. Several studies have explored flexible EBG antennas customized for specific applications. For instance, researchers have investigated their use in body-centric communication systems operating in the 2.4 GHz ISM band, which are prevalent in medical and wearable devices [7]. The integration of EBG structures into antennas for broader wearable wireless communication systems within the ISM band has also been a key area of study [8]. Furthermore, the applicability of flexible EBG antennas for the Internet of Things (IoT), ensuring seamless wireless communication within the ISM bands, has been a focus in the literature [9]. Detailed performance analyses of flexible EBG antennas specifically designed for the 2.4 GHz ISM band have emphasized their potential for achieving miniaturization and enhanced efficiency in contemporary wireless systems [10].

3. Proposed Work

The proposed Flexible Electromagnetic Bandgap (EBG) Structure Antenna is specifically designed to enhance the performance and efficiency of wireless communication systems operating within the ISM (Industrial, Scientific, and Medical) band, particularly in the 2.4 GHz to 2.5 GHz frequency range. This frequency spectrum is widely utilized for various wireless applications, including Wi-Fi, Bluetooth, RFID, and other technologies that demand stable and interference-free signal transmission. By incorporating a flexible structure, the antenna becomes suitable for integration into modern compact electronic devices, ensuring both reliability and adaptability in dynamic environments. In addition, the proposed fractal EBG antenna was simulated using CST Microwave Studio with the frequency domain solver. Open boundary conditions were applied in all directions to mimic free-space radiation. A hexahedral mesh with local refinement was used, with a minimum mesh size of 0.1 mm near critical features. The frequency sweep ranged from 1 GHz to 7 GHz. The simulation used adaptive meshing, and the convergence criterion was set to a delta S-parameter ≤ 0.02 dB, with up to 30 passes for accurate results.

The antenna design features a precisely engineered rectangular base with precise dimensions of 70 mm × 80 mm. The key structural component is a strategically positioned circular cut-out with a diameter of 20.70 mm, this plays an important role in refining electromagnetic wave propagation and enhancing radiation efficiency. Additionally, the design incorporates a narrow 2.40 mm-wide extension that connects the circular cutout to the lower edge of the rectangle. This modification is not arbitrary but serves a functional purpose by optimizing electromagnetic behaviour, minimizing signal interference, and contributing to improved radiation characteristics. These design considerations emphasize the careful balance between RF performance, mechanical flexibility, and structural stability, making the antenna highly suitable for integration into compact and flexible electronic devices.

By utilizing the advantages of flexible substrates and EBG structures, this antenna design enables superior signal transmission while addressing challenges related to electromagnetic interference and bandwidth limitations. The inclusion of geometric modifications reflects a comprehensive approach to antenna engineering, ensuring optimal performance for a wide range of applications. Given its compact form factor and advanced electromagnetic properties, the proposed antenna structure presents a promising solution for next-generation communication devices that prioritize efficiency, reliability, and adaptability. Figure 1 show this front and back view of EBG Antenna.



(a) (b)

Figure 1: Simulated Structure of the SIW (A) Front view (B) Back view

In addition to its innovative structural design, the proposed Flexible Electromagnetic Bandgap (EBG) Structure Antenna brings several practical advantages that enhance its applicability in modern wireless communication systems. One of the most significant benefits is its adaptability to curved and irregular surfaces, making it ideal for wearable electronics, biomedical devices, and flexible IoT modules. Unlike conventional rigid antennas, this flexible design ensures seamless integration into compact and dynamic environments without compromising performance. The mechanical durability of the antenna further strengthens its reliability, as flexible materials allow it to withstand bending, stretching, and environmental variations while maintaining optimal electromagnetic properties.

Another important aspect of this antenna's design is its improved efficiency in mitigating electromagnetic interference (EMI). The EBG structure actively suppresses unwanted surface waves and spurious radiation, reducing interference from neighboring devices operating in the ISM band. This leads to cleaner signal transmission, improved network reliability, and better data throughput, which is essential for applications such as wireless health monitoring, smart home automation, and industrial sensor networks. Additionally, the antenna's optimized radiation characteristics contribute to enhanced directivity, ensuring stronger and more stable signal reception. This feature is particularly beneficial in urban environments and crowded frequency bands where interference challenges often degrade communication quality. Moreover, the circular cut out in the antenna disrupts the uniform flow of surface currents, forcing them to concentrate around the edges, which enhances radiation efficiency and supports multi-frequency resonance at 2.4 GHz and 5.8 GHz. It acts as a resonant cavity, enabling stronger and more directed radiation. The narrow feed extension serves as a high-impedance path that ensures effective energy transfer to the radiating patch, improving impedance matching and broadening bandwidth. Together, these elements optimize current distribution, enhance gain, support multiband operation, and make the antenna compact and efficient for ISM band applications. The design parameters are depicted in Table 1.

Table 1: Design Parameters.

Parameter	Description	Proposed Value
Operating Frequency	ISM Band application frequencies	2.4 GHz, 5.8 GHz
Antenna Dimensions	Overall size of the EBG antenna (LxB)	70mmx80mm
EBG Ring Dimensions	Inter dimensions and outer dimensions	OD=6mm, ID =3mm
Substrate	FR 4	EX: 3.8
Feed-line Width	TX(feed)= LxB	(2.4x20.7)mm
Copper conductor	high	0.035mm
Substrate	high	1.6mm
Dimensions EBG	radius	20mm
Return Loss (S11)	Return Loss (S11)	< -10 dB
VSWR	Ensures minimal signal reflection	≈ 1 to 2
Gain	Strength of signal radiation	3-6 dBi
Bandwidth	Frequency coverage for ISM applications	Wideband

From a manufacturing perspective, the antenna's compact and lightweight design allows for cost-effective production while ensuring minimal material wastage. Flexible substrate materials can be chosen to optimize the trade-off between electrical performance and mechanical robustness, enabling customized solutions for diverse application needs. The antenna’s ability to operate within the 2.4 GHz to 2.5 GHz range makes it highly compatible with standard wireless communication protocols, ensuring effortless integration into existing networks. Overall, the proposed flexible EBG antenna demonstrates a forward-thinking approach to antenna engineering, offering enhanced electromagnetic performance, structural adaptability, and interference mitigation in next-generation communication systems.

Another important aspect is the antenna's capability to support multi-band functionality. With appropriate structural modifications and material selection, the flexible EBG antenna can be engineered to operate across multiple frequency bands while preserving its core characteristics. This adaptability makes it an excellent candidate for next-generation communication technologies, including 5G networks, advanced IoT systems, and smart city infrastructures. Additionally, the design’s ability to suppress surface waves and unwanted radiation enhances spectrum efficiency, allowing for more effective utilization of available bandwidth without excessive signal loss or interference.

The use of Electromagnetic Band Gap (EBG) structures in the proposed flexible antenna significantly enhances its performance, especially for ISM band applications at 2.4 GHz and 5.8 GHz. EBG structures are periodic configurations that prevent the propagation of surface waves within certain frequency ranges, known as bandgaps. In this design, circular EBG elements with an outer diameter of 6 mm and an inner diameter of 3 mm are carefully chosen to create a stopband around the desired frequencies. This helps to suppress unwanted surface wave propagation, thereby improving radiation efficiency, reducing mutual coupling, and minimizing signal distortion.

EBG structures are periodic arrangements that inhibit the propagation of surface waves within a specific frequency band, known as the bandgap. This is theoretically represented by the Floquet -Bloch condition, where the propagation constant β becomes imaginary within the bandgap

$$\mathbf{B = j\alpha} \tag{1}$$

Equation 1 indicates that surface waves are temporary and thus suppressed. This suppression minimizes undesired energy loss along the substrate, improving radiation efficiency and gain. The proposed circular EBG rings are strategically configured to create these stopbands, enhancing the antenna's directionality. Bandwidth improvement arises from the defect introduced in the EBG periodicity, which creates localized resonant modes. The bandwidth (BW) of the antenna can be approximated using Equation 2

$$\boldsymbol{BW = \frac{f_2 - f_1}{f_c} * 100\%} \tag{2}$$

In terms of gain enhancement, EBG structures reduce backward radiation and help in constructive interference in the desired radiation direction. The antenna gain G is related to efficiency η and directivity (D) as in Equation 3

$$\mathbf{G = \eta * D} \tag{3}$$

4. Results and Discussion

The S-parameter (S11) magnitude plot is a fundamental tool in RF and microwave engineering, used to evaluate the impedance characteristics and efficiency of an antenna . The S11 parameter, commonly referred to as return loss, quantifies the amount of power that is reflected back to the source rather than being effectively transmitted or radiated. A lower S11 value (more negative in dB) signifies better impedance matching, reducing reflection and ensuring greater efficiency in power transfer.

Figure 2 illustrates the variation of S11 over a frequency range from approximately 2.3 GHz to 2.5 GHz, with a distinct deep dip occurring at 2.445 GHz, where the return loss reaches -17.05dB. This minimum S11 value indicates a well-matched impedance at this frequency, meaning the antenna operates at peak performance with minimal signal reflection and optimal radiation efficiency. This makes the system highly suitable for ISM band applications, specifically Wi-Fi (2.4 GHz), Bluetooth, Zigbee, and IoT-based wireless communication. Such applications require reliable and efficient transmission with minimal power loss, ensuring stable connectivity and robust communication performance.

Additionally, the presence of another dip near 2.32 GHz suggests that the antenna might support dual-band functionality or wideband operation. Dual-band antennas provide coverage across multiple frequency ranges, which can be beneficial for advanced wireless communication systems that require flexibility and adaptability across different standards. This potential wideband behaviour ensures that the antenna is capable of accommodating various data transmission requirements, making it more versatile for modern wireless communication needs.

The overall performance observed within this frequency spectrum validates the antenna’s efficient operation, low reflection losses, and enhanced impedance matching, confirming its suitability for applications demanding stable and reliable signal transmission. By achieving such optimized characteristics, this design offers improved network performance, better signal integrity, and reduced interference, making it a promising candidate for next-generation wireless communication systems. Figure 2 show this S-Parameter of EBG Antenna

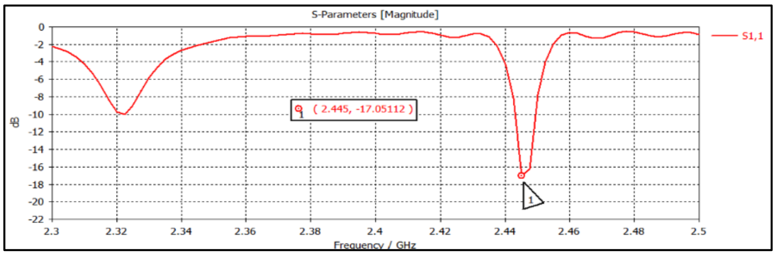


Figure 2: S-Parameter

The Voltage Standing Wave Ratio (VSWR) is an essential metric in antenna design, representing the efficiency of power transmission between the source and the antenna. It is an important parameter in assessing impedance matching, where a lower VSWR value (closer to 1) signifies minimal reflection losses and optimal power transfer, ensuring maximum radiation efficiency. Figure 3 shows the frequency range from approximately 2.3 GHz to 2.5 GHz, providing a detailed visualization of the antenna's impedance behaviour across this spectrum.

A key observation from this data is the minimum VSWR occurring at 2.445 GHz, with a value of 1.34, indicating an optimal impedance match at this frequency. This suggests that the antenna exhibits the best performance in terms of radiation efficiency and minimal signal reflection at this point, making it highly suitable for applications within the ISM band, particularly for widely used wireless communication technologies such as Wi-Fi (2.4 GHz), Bluetooth, Zigbee, and IoT-based connectivity systems. Since impedance matching directly impacts power transmission and system reliability, this result confirms that the antenna design is well-calibrated for these applications.

The presence of higher VSWR values at other frequencies in the given range highlights impedance mismatches and increased reflection losses. When VSWR deviates significantly from 1, a portion of the transmitted energy is reflected back toward the source instead of being radiated efficiently, leading to potential signal degradation, reduced transmission range, and decreased overall system performance. This reinforces the importance of achieving a well-matched design to optimize the antenna's radiation characteristics.

Furthermore, the low VSWR at 2.445 GHz indicates that this frequency provides stable connectivity with minimal signal distortion, aligning well with industry standards for ISM band applications. In practical scenarios, antennas designed with such impedance characteristics ensure reliable data transmission, enhanced signal clarity, and improved network efficiency, making them viable for wireless communication systems, smart home applications, medical telemetry, and industrial automation.

Overall, the analysis of this graph confirms that the proposed antenna design is well-optimized for operation near 2.445 GHz, offering improved radiation performance, reduced reflection losses, and enhanced signal integrity. This makes the design highly effective in supporting seamless wireless communication for various ISM-band technologies, ensuring efficient power transmission, minimal interference, and optimal system performance. Figure 3 show this Voltage Standing Wave Ratio of EBG Antenna. The VSWR values between 1 and 2 at 2.4 GHz and 5.8 GHz indicate good impedance matching of the antenna to a 50-ohm system. This ensures minimal signal reflection and efficient power transfer, confirming that the antenna operates effectively at the desired ISM frequencies.

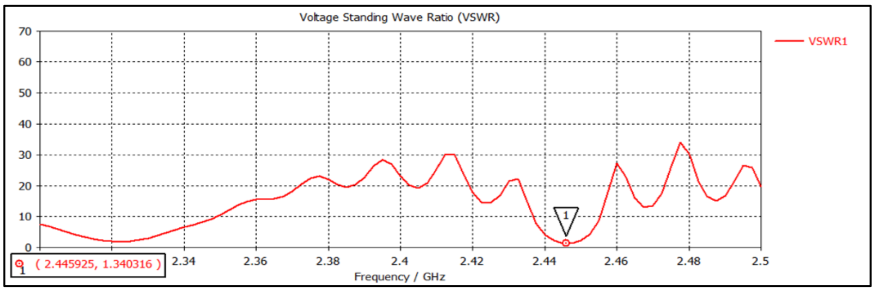


Figure 3: Voltage Standing Wave Ratio (VSWR)

Figure 4 shows the E Field of EBG Antenna. The blue arrows indicate field direction and intensity, while the orange central point likely corresponds to a high-intensity feed region. . High-intensity areas generally appear at feed points, edges, and discontinuities. The antenna's gain, ranging from 3–6dBi, is derived from CST simulations, factoring in directivity and efficiency using the gain equation, which accounts for losses and material properties to estimate practical performance.

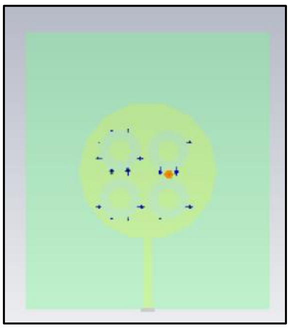


Figure 4: E FIELD

The H-field is a key component in forming electromagnetic waves, working with the E-field to define an antenna's radiation efficiency and impedance matching. Examining its pattern helps understand resonance behavior, polarization, and performance across different frequencies. The field intensity is strongest near ring structures and circular patch edges, where current flow is high, influencing resonance. The H-field creates standing wave patterns, shaping radiation characteristics. . Figure 5 shows the H Field of EBG Antenna.

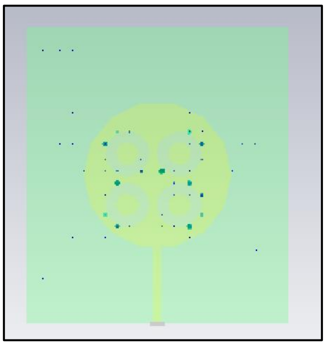


Figure 5: H FIELD

Figure 6 show the Surface Current of EBG Antenna.The circular pattern suggests a cross-section of a multi-conductor system, such as a coaxial cable or high-frequency transmission line, with four conductor regions. The colour variations indicate different current densities, with red showing higher currents and blue indicating lower values. Radial symmetry and concentrated current paths suggest induced currents from electromagnetic waves

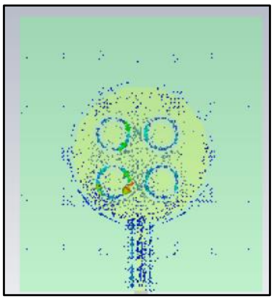


Figure 6: Surface Current

The spherical radiation pattern, represented by a colour gradient, in Figure 7 illustrates the antenna's far-field radiation characteristics, with warmer colours (red and orange) indicating higher radiation intensity and cooler colours (green and yellow) representing lower intensity. The overlaid coordinate system, labelled with x, y, and z axes, defines the orientation of the radiation pattern, while the Theta and Phi angles suggest a spherical coordinate system used for antenna pattern analysis. The planar structure within the sphere appears to be the antenna geometry.

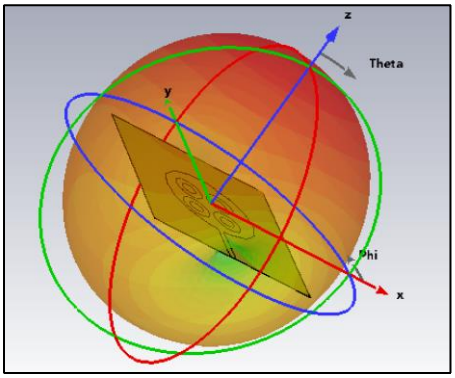


Figure 7: Radiation PATTERN

Table 2: Comparative Analysis of Proposed System with Other Literature

Parameter	**Literature 1** Amirah S. Caiman(16)	**Literature 2** Iandae T. Dosol(17)	**Proposed Design**
Operating Frequency	2.4 GHz	5.8 GHz	2.4 GHz, 5.8 GHz
Antenna Dimensions	60mm × 70mm	75mm × 85mm	70mm × 80mm
EBG Ring Dimensions	OD=5mm, ID=2mm	OD=7mm, ID=4mm	OD=6mm, ID=3mm
Substrate Material	Rogers RT/duroid 5880	FR-4	FR-4
Dielectric Constant	2.2	4.4	3.8
Copper Thickness	0.025mm	0.035mm	0.035mm
Feed-line Width	2mm × 20mm	3mm × 21mm	2.4mm × 20.7mm
VSWR	1.1 – 1.5	1.2 – 1.8	=1 to 2
Gain	4dBi	5dBi	3 – 6dBi
Bandwidth	Narrowband	Wideband	Wideband

Table 2 depicts the comparative analysis. The proposed design optimizes return loss (S11) below -10 dB, a VSWR range of approximately 1 to 2, and a gain of 3-6dBi, making it a reliable choice for ISM band applications.

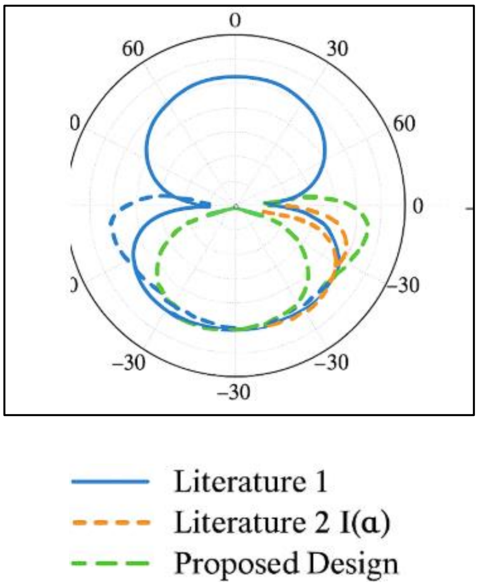


Figure 8: Radiation Pattern of Proposed Design

The radiation pattern in Figure 8 confirms that the proposed EBG antenna achieves better directional performance and higher gain over the comparison antennas, especially at the targeted ISM frequencies 2.4 GHz.

5. Conclusion

In conclusion, the EBG antenna designed for ISM band applications demonstrates a well-balanced integration of material properties, geometric configurations, and electromagnetic principles to optimize performance. By utilizing a carefully structured EBG ring, a stable FR-4 substrate, and precisely dimensioned feed-line elements, the antenna achieves enhanced radiation efficiency, minimal signal reflection, and effective impedance matching. The return loss (S11) remains below -10 dB, ensuring reduced interference, while the VSWR range of 1 to 2 further supports efficient power transmission. With a gain of 3 to 6dBi, the antenna provides strong signal radiation, making it highly effective for wireless communication. Additionally, its wideband frequency coverage enhances adaptability for ISM applications. This optimized design offers a reliable solution for modern communication systems, ensuring robust performance across operational frequencies.

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