Design and Characterizations Analysis of a Linear Polarized Star-Shaped Multiband Patch Antenna for Wireless Applications

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ABSTRACT

This paper discusses the design and performance analysis of a fractal antenna intended for multiband wireless communication applications. The proposed antenna supports various wireless standards including Wi-Max, C-band, WLAN and X-band satellite communication. Utilizing a star-shaped fractal patch configuration on an FR-4 substrate, the antenna exhibits enhanced bandwidth, improved gain, and excellent return loss performance. As part of our experimental process, we incorporated an Electromagnetic Band Gap (EBG) in the ground structure to compare its performance with the actual output of our proposed antenna. The dimensions of the proposed antenna are 30 mm × 30 mm × 0.96 mm. Simulation results reveal that the fractal antenna significantly improves efficiency, with a maximum gain of 4.76 dB and polarization characteristics, making it an excellent possibility for next-generation wireless and satellite communication systems.

Keywords- Fractal Antenna, Star Shaped, Multiband, Wireless Communication, EBG, Microstrip Patch, Satellite Communication.

INTRODUCTION

The rapid evolution of wireless communication technologies necessitates the development of high-performance antennas capable of operating over multiple frequency bands. The antenna is an essential component in wireless systems. It is a metallic structure that captures electromagnetic waves [1]. While compact and easy to fabricate, conventional microstrip antennas often suffer from limited bandwidth and efficiency [2]. Researchers have explored advanced antenna designs such as fractal geometries, Electromagnetic Band Gap (EBG) structures, and optimized substrate materials to overcome these limitations [3].

Multiband antennas are quite attractive in wireless communication systems. They are particularly desirable for applications spanning various frequency bands, including Wi-Max (2.4–2.7 GHz), C-band (14.3–14.9 GHz and 21.5–22.3 GHz), WLAN (10.9–12.8 GHz and 28–29.8 GHz), and X-band Satellite communication (32.9–34.9 GHz, 38.4–41.3 GHz, 42.7-45.1 GHz, and 47.2–50 GHz) [4],[5]. A key challenge in designing such antennas is achieving wideband operation while maintaining compact size and high gain. The fractal geometry approach is an effective solution, as it enhances resonance characteristics and increases bandwidth without significantly increasing the antenna size.

This paper introduces a unique fractal antenna with a star-shaped patch configuration, designed on an FR-4 substrate and by maintaining a compact size [6]. The antenna is optimized for various wireless standards, including Wi-Max, C-band, WLAN, and X-band satellite communication [7],[8],[9]. The effects of incorporating an EBG-based ground plane to further enhance performance are also examined in the study. With EBG, a stop band is created to block electromagnetic waves in particular frequency ranges.

The proposed design is evaluated through CST simulation software, and its performance is compared with a stereotyped microstrip patch antenna. After the EBG is inserted at the ground plane, the properties of the ensuing EBG-equipped and EBG-deficient antennas are assessed. The findings show that the fractal antenna is a good choice for modern wireless applications as it provides better multiband operation, increased gain, and improved return loss performance.

Design & Analysis

Antenna Structure

The proposed fractal antenna is designed to operate across a broad frequency spectrum, covering key wireless communication bands. The antenna consists of three primary layers:

Patch layer: A star-shaped fractal patch structure, designed to support multiband operation.

Substrate layer: FR-4 material with a dielectric constant of 4.3, chosen for its cost-effectiveness and performance stability [10].

Ground plane: Two variations are considered, one with a conventional copper ground plane (Ant-1) and another incorporating an EBG-based ground plane (Ant-2) [11].

Antenna Design

The antenna design process involves multiple optimization steps to enhance its multiband and polarization characteristics. The patch design has developed using a methodical process:

Initial patch design: On the base structure, two identical square patches measuring 12 mm × 12 mm overlap at a 45° angle, as shown in Fig. 1.

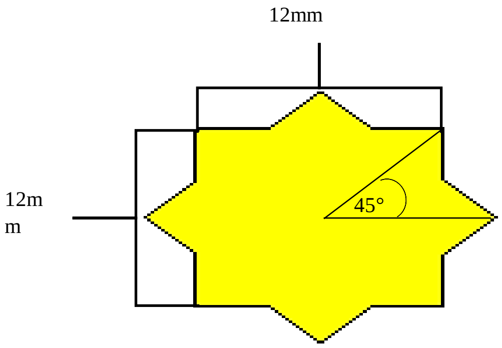

Fig. 1: Two initial patch (with dimension) overlapped by 45° angle

Fractal geometry application: In order to improve the multiband response, four (4mm × 0.4 mm) and four (5mm × 0.4 mm) insets are induced into the patch, each of which is positioned at a 45° angle to the other, as shown in Fig. 2, in order to increase the multiband' s reflection coefficient.

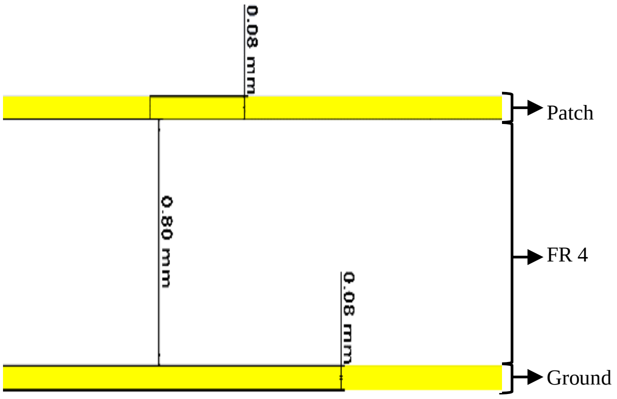

Fig. 2: The patch now has eight fractal rectangular elements in total

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Final optimization: To improve it even more, seven triangular fractal pieces are placed outside the patch, aligning with each patch top. Two equilateral triangles that has a specific angular dimension of 60°, overlapping each other to form a hexagon with 120° displacement. As seen in Fig. 3, the triangle's sides are 6.93 mm long.

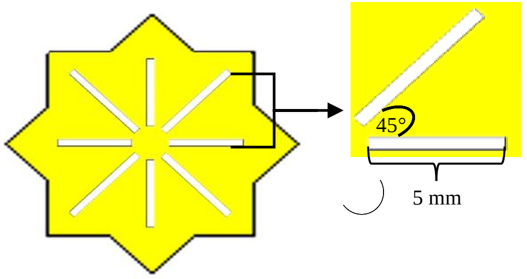

Fig. 3: Triangular fractal piece with dimension

This leads to a fractal pattern in the shape of a star, which improves radiation properties and raises resonance frequencies. The antennas have transmission lines of 50Ω resistance with dimensions of 8 mm x 2.98 mm as shown in Fig. 4. The overall measurements of the antenna are 30 mm × 30 mm.

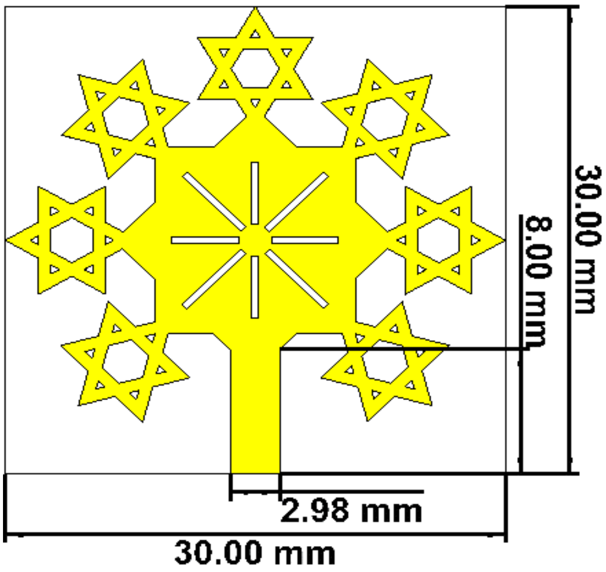

Fig. 4: Front view of the antenna with dimension

The FR-4 substrate is used as the dielectric material that have a dielectric constant of 4.3 (Ɛr = 4.3). FR-4 substrate provides a balance between performance and cost. The substrate thickness is optimized for stable impedance characteristics. This substrate is sandwiched between the patch and ground of the antennae which are shown in Fig. 5. The height of the substrate is 0.80 mm so the total height of the antenna is 0.96 mm.

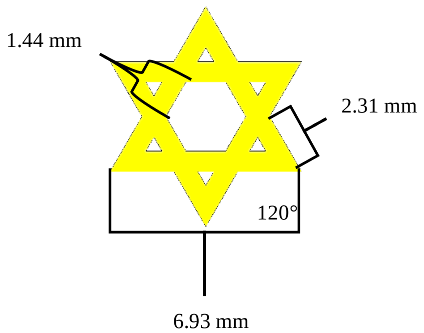

Fig. 5: Lateral view of the antenna with dimension

Additionally, we constructed an EBG based antenna for comparison of the output result. The evaluation process of patch design are same for both antennas. Fig. 6 shows the antenna's detail dimensions in front view.

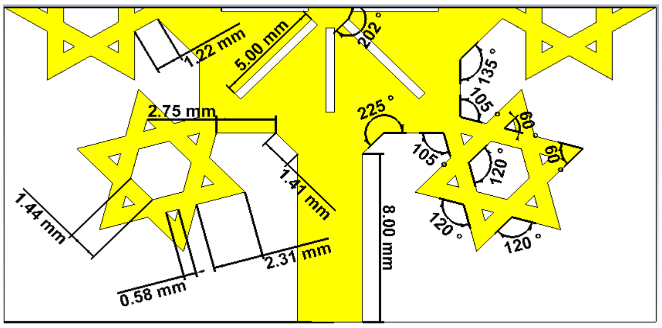

Fig. 6: A measurement-based image of half of the antenna from the front side

Ground plane variation: As previously mentioned, we also constructed an EBG based antenna to compare our suggested antenna; the key distinction between them is their ground configuration.

Ant-1: Conventional copper ground for baseline comparison shown in Fig. 7.

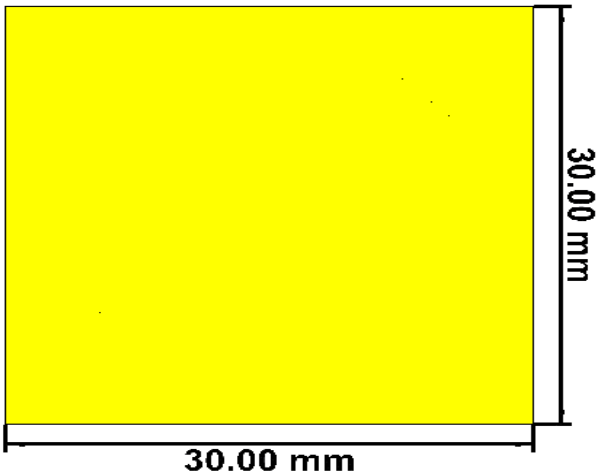

Fig. 7: Back view of Traditional antenna

Ant-2: Generally, EBG-based ground with periodic dodecagonal structures (diameter: 1.00 mm) to suppress surface waves and enhance radiation efficiency [11]. The entire ground plane is inserted by 105 number of dodecagon. Fig. 8 displays the EBG-based antenna ground.

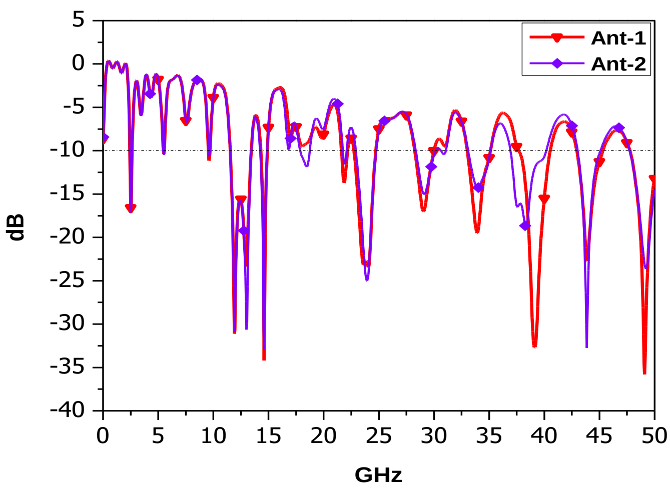

Fig. 8: Back view of our proposed antenna with EBG

Ant-1 is a conventional antenna with a clear ground, as shown in Fig. 7, and is made of copper. The bottom of Ant-2 is set up with EBG defected characteristics, and 105 dodecagon numbers are positioned there.

Performance Analysis

The both antennas are analyzed using CST electromagnetic simulation tools to evaluate S-parameters, gain, and efficiency. The benefits of the fractal technique are confirmed by comparing the outcomes.

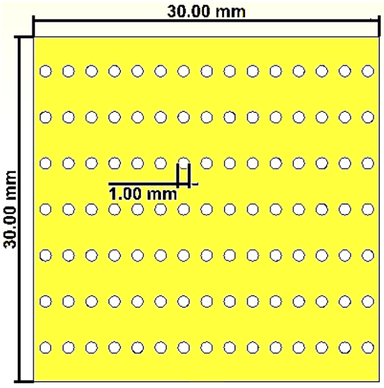

Fig. 9: S_{11} Comparison

After simulating, the Ant-1 has obtained a total number of ten resonant frequencies at 2.5 GHz, 11.9 GHz, 14.6 GHz, 21.85 GHz, 24.06 GHz, 29.05 GHz, 33.9 GHz, 39.1 GHz, 43.9 GHz, and 49.1 GHz whereas the Ant-2 has seven resonant frequencies at 2.5 GHz, 14.6 GHz, 24 GHz, 29.1 GHz, 34 GHz, 38.3 GHz, and 43.8 GHz which is shown in Fig. 9. The above frequencies achieved from -10 dB to -40 dB for Ant-1 and from -10 dB to -35 dB for Ant-2 [12].

Moreover, the reference impedance remains the same as Ant-1 even after changing the antenna design. The obtained reference impedance for both antennas is 50Ω [13]. The performance of those antennae also depends on some important parameters like VSWR, Efficiency, Axial Ratio, and Farfield [14],[15]. After simulating Ant-1 and Ant-2, those parameters are compared.

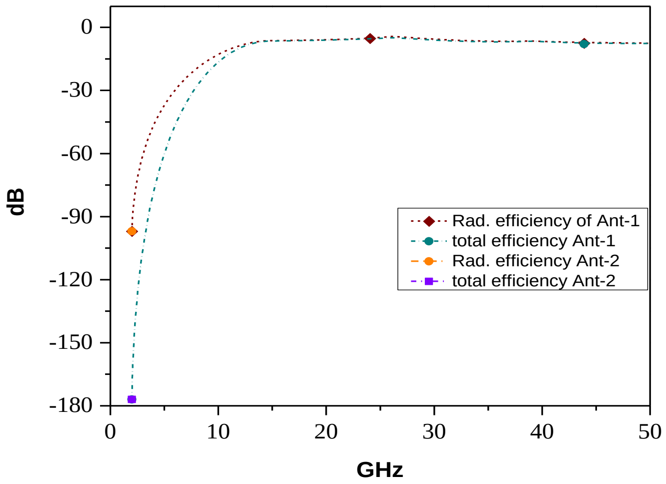

Fig. 10: Efficiency comparison for Ant-1 and Ant-2

The antenna efficiency is the ratio of the radiated power and the input power of the antenna. Though there is Radiation efficiency and Total efficiency, antenna efficiency typically refers to Total efficiency. The efficiency data for Ant-1 and Ant-2 are shown in Fig. 10, those are efficient and fairly similar to one another. Also, the axial ratio is the ratio of the orthogonal component of an E-field [7]. For pure linear polarization, the axial ratio is infinite because the orthogonal components of the E-field are zero. The axial ratio is 40 dB. So, it can be regarded as a linear polarized antenna.

RESULT AND DISCUSSION

By incorporating a fractal geometry, the proposed antenna achieves significant improvements in bandwidth, gain, and return loss, making it an excellent choice for modern wireless applications. For Ant-1 and Ant-2, the resulting number of frequencies, maximum bandwidth, and maximum gain are compared above. When the ground of the Ant-2 antenna is defective, the overall resonance frequency decreases. The maximum bandwidth for this antenna also shrunk. However, the highest gain exceeds Ant-1.

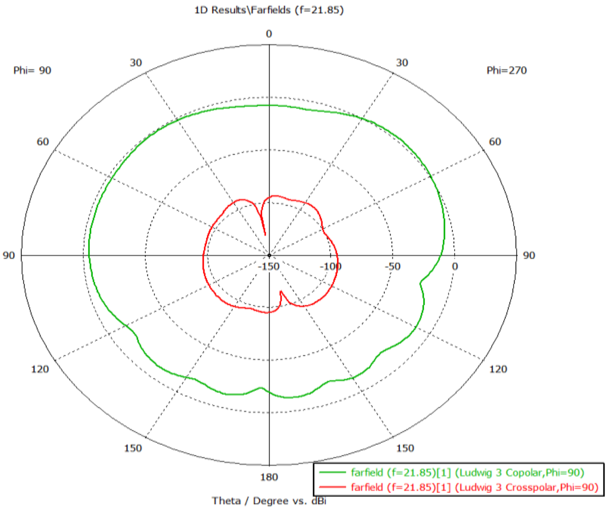

Fig. 11: S_{11} of Ant-1

Considering all of the simulated results, the Ant-1 antenna has been proposed in this paper. The following Fig. 11 shows the total number of ten different bandwidths of Ant-1 which has been achieved from -10 dB to -40 dB. The achieved bandwidths are 240 MHz, 1920 MHz, 600 MHz, 700 MHz, 2000 MHz, 1800 MHz, 2100 MHz, 2900 MHz, 2400 MHz, and 2800 MHz respectively for the resonant frequencies of 2.5 GHz, 11.9 GHz, 14.6 GHz, 21.85 GHz, 24.06 GHz, 29.05 GHz, 33.9 GHz, 39.1 GHz, 43.9 GHz, and 49.1 GHz.

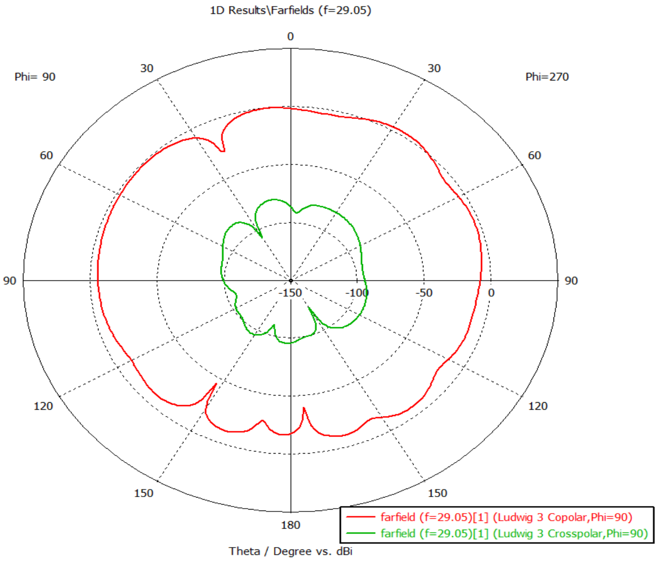

Fig. 12: Farfield of Ant-1 at 21.85 GHz

In either linear or circular mode, an antenna is never fully polarized. Thus, the cross-pol and co-pol radiation patterns are given. Co-polar and cross-polar are depicted at resonance frequencies of 21.85GHz, 29.05GHz, and 39.1GHz in the following Figures respectively. In those diagrams, the cross-polar at phi 900 is shown by the green line, while the co-polar is shown by the red line. The Fig. 12, Fig. 13, and Fig. 14 diagrams illustrate the strong resonance pattern of the Ant-1 antenna at various resonant frequencies.

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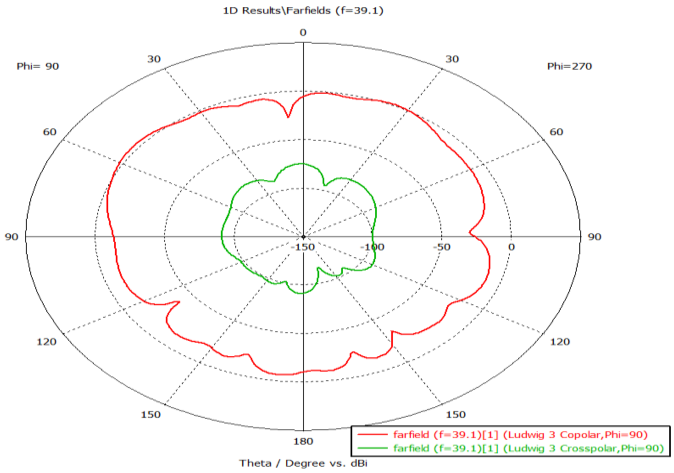

Fig. 13: Farfield of Ant-1 at 29.05 GHz

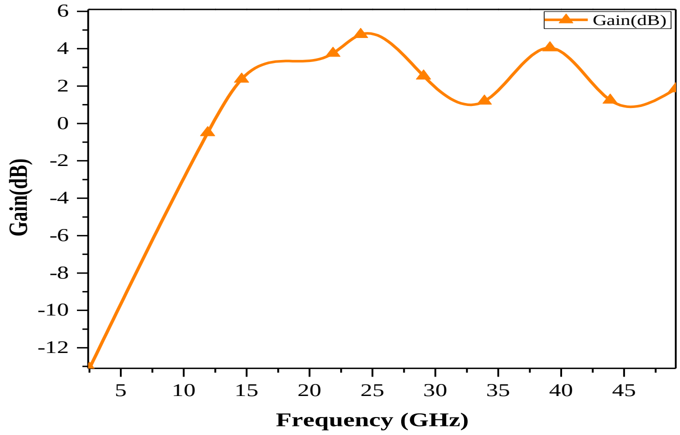

Fig. 14: Farfield of Ant-1 at 39.1 GHz

Multiple gains are present in Ant-1 at different resonant frequencies. The Gain vs. Frequency curve of Ant-1 is displayed in Fig. 15. The maximum gain of this antenna was 4.76 at the resonance frequency of 24.06 GHz. As seen in Fig. 11, the reflection coefficient is modest even though the gain is best at 24.06 GHz. Therefore, the other bands have been taken into consideration for a better performance. Consequently, this antenna is linearly polarized and multiband.

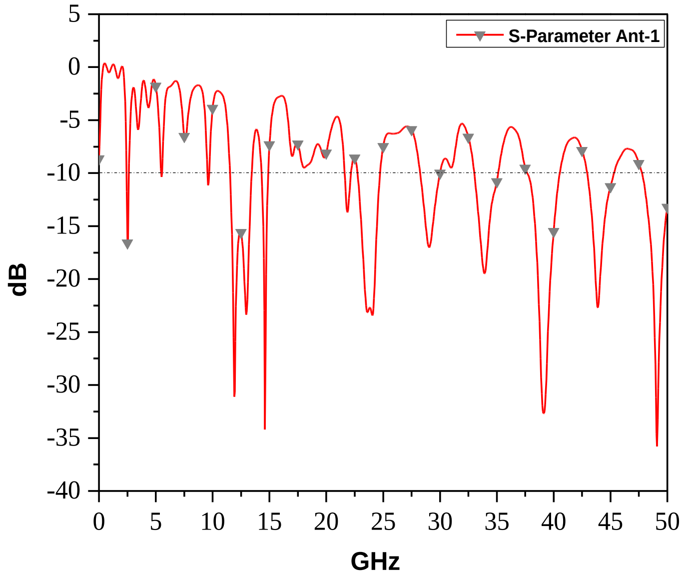

Fig. 15: Gain vs Frequency of Ant-1

The following TABLE I compares various works with the proposed antenna (Ant-1) in terms of their maximum gain and bandwidth. These designs are all made using a FR-4 substrate.

Table I Comparison with other works based on fr-4 substrate.

Ref.	Type of Polarization	Dimension (Length × Width)(mm)	Max. BW (GHz)	Max. Gain (dB)
[16]	Linear	36 × 29.8	0.25	3.3
[17]	Linear	29.2 × 29.2	0.02	4.6
[18]	Circular	40 × 40	0.7	2.73
Proposed Antenna	Linear	30 × 30	2.9	4.7

CONCLUSION

In this work, a star-shaped microstrip linearly polarized multiband patch antenna has been developed, demonstrating effective multiband operation with a total of ten resonant frequencies. The use of FR-4 material contributes to a wide bandwidth of 2.9 GHz and a maximum gain of 4.7dB. Additionally, the proposed antenna is more compact and cost-effective compared to other designs, which typically exhibit a peak return loss of -35dB.

Furthermore, a comparative analysis of defective ground structures and normal ground structures has been conducted. While EBG offers improved band-gap characteristics, its overall performance is found to be inferior to that of a normal ground structure. In particular, the reflection coefficient of EBG is not as favorable. Therefore, despite its advantages in band-gap enhancement, the normal ground structure remains the preferred choice due to its superior overall performance.

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