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Design and Realization of Metamaterial Antenna for Enhancement of Antenna Parameters in 5G Frequency

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Abstract

Technological advancements, particularly in telecommunications, are rapidly accelerating. The ever-increasing need for high-speed data transmission and reception has become a crucial requirement in the expanding telecommunications industry. Fifth generation (5G) technology necessitates the use of an antenna that can effectively send and receive data. This study examines the design and realization of a microstrip antenna that operates at 3.5 GHz utilizing an Electromagnetic Band Gap (EBG). The usage of an EBG can optimize antenna quality and dimensions. Based on the simulation results, the original antenna without EBG obtained S11 of -30.76 dB with a Gain of 2.653 dBi at 3.5 GHz. By adding the EBG structure with a 4 x 4 configuration, the simulation results show a better S11 of -40.021dB and a higher Gain of 4.229 dBi, at 5 mm distance between the antenna and the EBG structure. For the measurement results, this antenna obtained S11 of -33.088 dB with a Gain of 4.3 dBi. In addition, there is a change in the radiation pattern between the Regular Antenna and the Antenna with EBG. In the antenna radiation pattern with EBG, the current direction is reflected in phase and results in constructive reflection. Based on the parameters obtained from measurements and simulations, the antenna has achieved the target specification and can be used at a frequency of 3.5 GHz.

Keywords: *fifth generation*, antenna, *microstrip*, EBG

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1. Introduction

Currently, antenna technology is undergoing rapid advancements, primarily driven by the growing demand for high-speed wireless internet access. Wireless technology with fast internet access has reached the fifth generation (5G) with data speeds reaching 20 Gbps [1]. It is widely recognized that 5G technology holds significant potential for emerging technologies such as Artificial Intelligence, Massive Device to Device Communication, Machine Learning, Cloud Computing, and more. To effectively support this rapid development, the implementation of an antenna with exceptional radiation performance becomes imperative.

Metamaterials offer great potential for enhancing antenna performance and have emerged as a promising candidate. These artificial structures exhibit unique electromagnetic characteristics, including negative permittivity and permeability, exceptionally high impedance, and perfect magnetic properties [2, 3, 4]. Among the various types of metamaterials, Electromagnetic Band Gap (EBG) has gained significant attention in recent studies due to its remarkable ability to control the electromagnetic wave characteristics at specific frequencies [5, 6, 7].

The natural ability of EBG to suppress surface waves is utilized widely to reduce mutual coupling in multiple antenna configurations [8, 9, 10]. In such studies, the proposed EBG structures are printed in between the two-radiating patch to help reduce the mutual coupling and element separation. EBG structures are also implemented in wearable antenna to reduce Specific Absorption Ratio (SAR) to safety level [11, 12]. In these methods, the EBG structures are usually placed between the antenna and the human body phantom. Its band gap capability prevents electromagnetic waves travel and causes harmful effects on the human body. Another research also reported the use of EBG to increase the bandwidth of the antenna [13]. The EBG is placed beside the feedline structure to improve the matching impedance capabilities.

In this research, EBG was used as a reflector to increase antenna gain. The proposed structure was placed behind the antenna at a distance below λ/4. The reflection diagram method was used to validate the phenomena that occur. Utilizing the previously mentioned approach, constructive interference was attained between the incident wave and the reflected wave by adjusting the phase value within the unit cell to 0° at the specified frequency. After obtaining the unit cell phase value, the EBG structure was placed behind the antenna. The result showed that by using the EBG structure, the gain value was increased from 2.376 dBi to 4.229 dBi. The disappearance of the back lobe could also be observed in the radiation pattern due to the perfect reflection caused by the EBG structure.

2. Methods

2.1 Circular Patch Antenna Design

The proposed antenna is designed using a circular patch type and works at a frequency of 3.5 GHz as the base structure. The antenna and EBG structure use FR-4 epoxy as the substrate and thin copper as the radiating patch and the ground plane respectively. The material characteristics of the antenna can be seen in Table 1.

Component	Material	Relative Permittivity (ε_r)	Thickness (mm)
Groundplane, Patch	Copper	-	0.035
Substrate	FR-4 Epoxy	4.3	1.6

Table 1. Antenna Material

After determining the material used, the next step is calculating the dimensions of the antenna. The effective radius of the circular patch a_e is calculated using (1):

$$a_e = a\left\{\sqrt{\left\{1 + \frac{2h}{\pi\varepsilon_r a}\left[\ln\left(\frac{\pi F}{2h}\right) + 1{,}7726\right]\right\}}\right\} \tag{1}$$

With h as the thickness of the substrate, ε_r is relative permittivity, F and a (radius of the patch) is obtained by (2) (3):

$$F = \frac{8{,}791 \times 10^9}{f_c\sqrt{\varepsilon_r}} \tag{2}$$

$$a = \frac{F}{\sqrt{\left\{1+\frac{2h}{\pi\varepsilon_r a}\left[\ln\left(\frac{\pi F}{2h}\right)+1{,}7726\right]\right\}}} \tag{3}$$

With f_c is the frequency resonant of the antenna. After that, the width (W_f) and length (L_f) of the feed line can be calculated using (4)-(8):

$$W_f = \frac{2h}{\pi}\left[B - 1 - ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left\{ln(B-1) + 0{,}39 - \frac{0.61}{\varepsilon_r}\right\}\right] \tag{4}$$

$$B = \frac{60\pi^2}{Z_0\sqrt{\varepsilon_r}} \tag{5}$$

$$\lambda_0 = \frac{c}{f_r} \tag{6}$$

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \tag{7}$$

$$L_f = \frac{\lambda_g}{4} \tag{8}$$

With λ_0 is the wavelength of the related resonant frequency in the free space medium, and λ_g is the wavelength affected by the antenna substrate. ε_{eff} can be found using (9)

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\,\frac{h}{w}\right]^{-\frac{1}{2}} \tag{9}$$

The width and length of the ground plane can be found using (10) & (11)

$$W_g = 6h + W_f + D_{patch} \tag{10}$$

$$L_g = 6h + L_f + D_{patch} \tag{11}$$

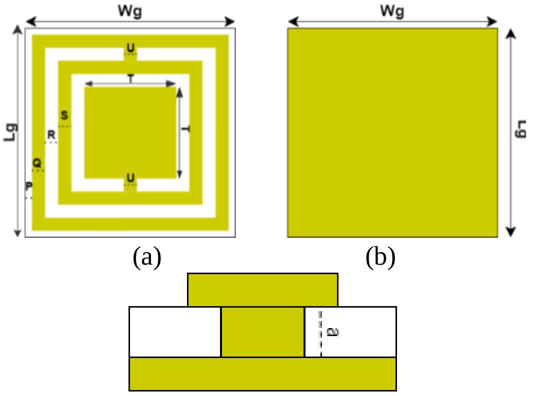
2.2 Electromagnetic Band Gap (EBG) Structure

EBG has the natural characteristic of preventing the propagation of electromagnetic waves, thus creating a stopband at certain frequencies[14]. The initial mushroom shaped EBG was created by Sievenpiper under the name of High Impedance Surface (HIS) due to its high impedance value on the surface of the structure [15]. The flow of current along the vias contributes to the antenna's inductance, while the gap between adjacent unit cells generates the capacitance. Additionally, wave suppression on the surface yields several beneficial effects, including enhanced gain, reduced back radiation, and minimized mutual coupling between antennas. [16].

Changes in radiation characteristics caused by EBG can be observed through the reflection phase coefficient of the unit cell [14]. If the EBG is placed behind the antenna with an omnidirectional radiation pattern, the back radiation intensity emitted can be reflected towards the front. If the reflected wave's phase is nearly equal to the original wave, constructive interference occurs, thus increasing the intensity radiated by the antenna and increasing the boresight gain on the antenna. When EBG is not present, moving a radiation element closer to the conductive ground plane results in a decrease in radiation power due to the phase difference between the reflected and original waves. Such a problem can be avoided by placing the antenna and ground plane at λ/4 distance. However, a microstrip antenna does not have this luxury due to its thin substrate characteristics. Without such distance, the incoming reflected wave phase is different from the original wave which creates destructive interference and poor radiation efficiency.

By embedding EBG into the original structure, the back radiation is reflected in phase towards the front thus producing constructive interference and more efficient radiation [17, 18]. In this study, a unit cell with the finite structure model is utilized. The reflection coefficient diagram is obtained by using a 3D modeler simulation. The boundary of the unit cell is set as perfect electric conductor ($E_t = 0$) for the $X \pm$ axis and $Z -$ direction, and perfect magnetic conductor ($H_t = 0$) for $Y \pm$ axis direction. For the $Z +$, the open space boundary condition is configured.

The shape, dimensions, and geometric parameters of the EBG structure used in this research could be seen both in Fig.1 and Table 2.



(a) (b)

(c)

Fig 1. Parameter Design of EBG (a)Front- (b)Back- (c)Side-Parts

Symbol	Wg	Lg	P	Q	R
Value (mm)	13	13	0.5	1	0.9
Symbol	S	T	U	a	
Value (mm)	1	8.6	1	4	

Table 2. Parameter Data of EBG

In order to get a good reflection, a unit cell must have 0° of phase at the desired frequency. In this paper, the antenna works at a frequency of 3.5 GHz which must get a phase of 0 ° at that frequency. The value of 0° at a frequency of 3.5 GHz can be seen in Fig 2.

2.1 Antenna Design

An antenna designed using canamaterial is expected to exhibit a significant gain improvement compared to conventional antennas. The antenna specification can be seen in Table 3.

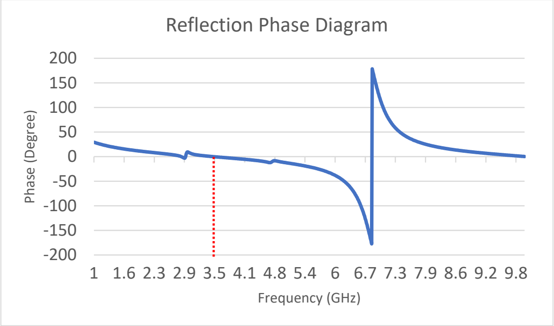
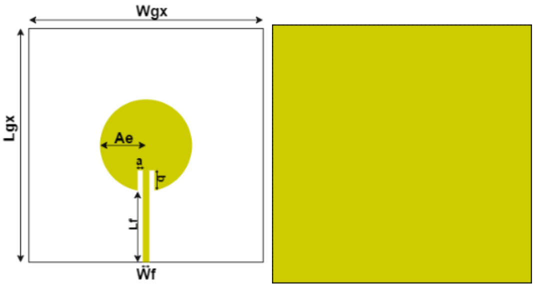


Fig 2. The reflection Phase Diagram shows 0° at a frequency of 3.5 GHz.

Specifications	**Value**
Frequency	3.5 GHZ
Return Loss	<10 dB
VSWR	<2
Gain	4dB

Table 3. Antenna Specification

The first step of the proposed antenna design is by creating a regular antenna without EBG. The dimension parameter obtained using Equation (1) - (11) could be seen in Table 4 and Fig. 3.



(a) (b)

Fig. 3. Initial Design of the Regular Antenna (a) Front View (b) Back View

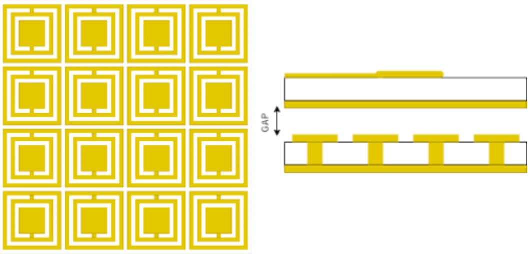
Symbol	Wgx	Lgx	Ae	Wf	Lf
Value (mm)	60	60	12.23	2.33	11.85
Symbol	b	a	h	T	
Value (mm)	2.6	9	1.6	0.035	

Table 4. Parameter of the Regular Antenna

After obtaining the antenna's dimensions, the subsequent step involves integrating the EBG structure depicted in Fig. 1. The EBG structure is arranged 4x4 at the back of the antenna as seen in Fig 4.

3. Result and Discussion

3.1 Result Analysis



(a) (b)

Fig 4. (a) EBG 4 x 4 Structure (b) Position of EBG on the back of the antenna

Fig. 5 shows the S11 simulation results for the antenna with and without EBG in the background. The return loss value on the antenna with the EBG demonstrates a better S11 result compared to the regular antenna without EBG. A regular antenna has an S11 value of -30.76218 dB, while by adding EBG structures, the S11 is improved to -40.021031 dB at a frequency of 3.5 GHz. This means that the use of the EBG structure behind the antenna increases the value of the return loss.

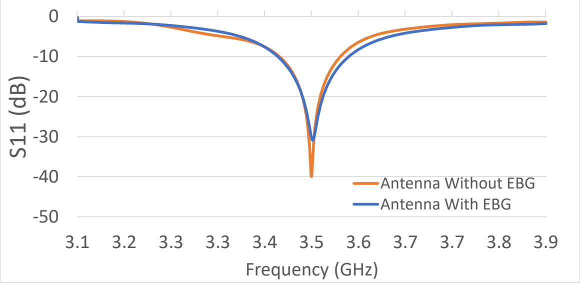


Fig 5. Return Loss Antenna Simulation

An improvement in the gain parameter can also be observed when the EBG structures are integrated behind the regular antenna. As could be seen in Table 5, the antenna with EBG and without EBG has a gain of 4.229 dBi and 2.64 dBi respectively. This improvement could be attributed to the reflection phase achieving a value of 0° at a frequency of 3.5 GHz, as illustrated in Fig.2 from the previous chapter. In addition to the S11 and gain value, the shape of the normalized azimuth radiation pattern also changes, as seen in Fig 6. The existence of the EBG structure behind the antenna helps to minimize back lobe radiation, which is often observed in regular antennas.

No	Name	Gain (dBi)
1	Antenna Without EBG	2.64
2	Antenna With EBG	4.229

Table 5. Comparison of Gain of Regular Antenna Without and with EBG

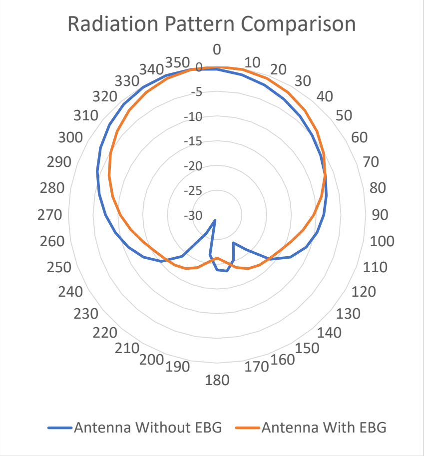
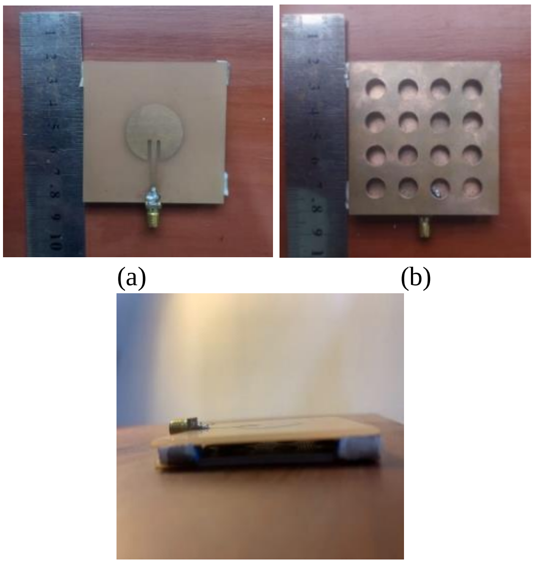


Fig 6. Azimuth Radiation Pattern Comparison Between Antenna with and Without EBG

3.2 Realization of Antenna with EBG

To validate the simulation results, antenna realization and measurement were conducted. The antenna is realized using the Epoxy FR-4 substrate with specifications according to Table 1. The realization of the antenna from the front, back, and side can be seen in Figure 7.



(a) (b)

(c)

Fig 7. Antenna Realization a) Front-, b) Back-, c) and Side-Parts

An analysis is conducted by comparing the simulation results with measurements. The S11 value can be observed in the measurement results diagram using the Vector Network Analyzer (VNA) in Fig 8. The results indicate that the S11 from the measurement conforms to the result from the simulation with the value of -33.088 dB and -40.021 dB respectively at a frequency of 3.5 GHz. The shape of the normalized radiation pattern obtained after taking measurements can be seen in Fig 9. The radiation pattern, shaped by the simulation, also exhibits a directional radiation pattern in accordance with the expected outcome.

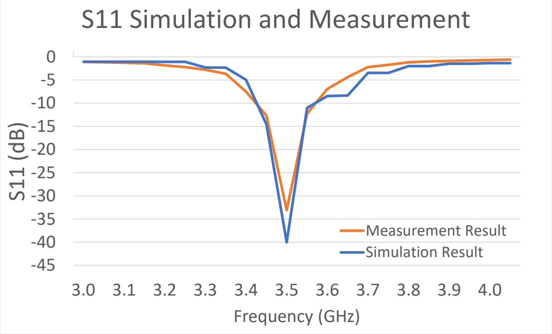


Fig 8. S11 of Simulation and Measured Antenna With 4x4 EBG

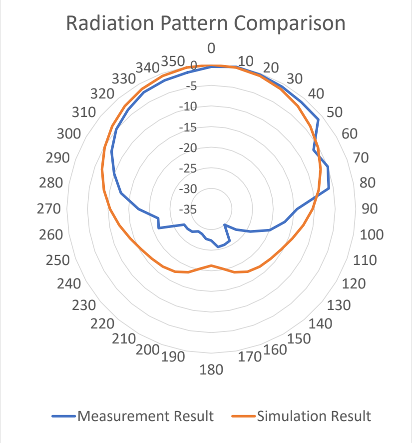


Fig 9. Radiation Pattern of Antenna Realization

To see the value of the gain, calculations are needed using (12) and (13):

$$S_{21} = -L_{Tx} + G_{Tx} - FSL + G_{Rx} - L_{Rx} \tag{12}$$

$$FSL = 92{,}45 + 20\ Log f_{GHZ} + 20\ Log\ r_{km} \tag{13}$$

where S_{21} is the transmission loss measured from VNA, L_{Tx} and L_{Rx} is both losses of the transmitter, and receiver cable respectively, G_{Tx} and G_{Rx} are also gain of the transmitter and receiver respectively, f_{GHZ} is the frequency of the antenna measured and r_{km} is the distance between transmitter and receiver. The Gain measurement is conducted using the S_{21} measurement method in VNA. Assuming the S_{21} is equal to the overall gain and loss existing on the power link budget calculation, a gain value of 4.3 dBi is obtained. The result conforms to the simulation gain value of 4.229 dBi. In conclusion, the overall measurement results show good agreement with the simulation, both in circuit parameters such as S11 and radiation parameters like radiation pattern and gain.

4. Conclusions

This study successfully demonstrated the efficacy of utilizing EBG as a reflector to enhance the parameters of an antenna with a circular patch. The incorporation of EBG resulted in a substantial 59% gain improvement, from 2.64 dBi to 4.2 dBi. The analysis conducted using the reflection diagram method highlighted the importance of achieving 0° phase in the unit cell for constructive interference. Moreover, the utilization of EBG not only enhanced the antenna gain but also proved effective in minimizing back radiation. These findings underscore the potential of EBG technology in improving antenna performance, presenting promising opportunities for advancements in wireless communication systems.

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Additional Information