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A Low-Profile EBG Based Corrugated 5G Antenna Design for WLAN Communication

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ABSTRACT: The paper introduces a corrugated antenna structure suitable for 5G WLAN application and operates at a frequency of 5.52 GHz. Further, a periodic structure made up of square unit cells is combined with the antenna design, and improvement in gain and impedance bandwidth is observed. The antenna gain without periodic structure is 3.48 dB whereas with periodic structure it is noted as 4.09 dB. The antenna dimensions are 16 mm × 16 mm × 3 mm. Also, the measured bandwidth of the antenna structure without periodic structure is observed to be 210 MHz, and that with periodic structure is 310 MHz.

1. INTRODUCTION

As the population is increasing drastically, the need for high-speed systems is rising exponentially. Many recent applications like smart devices with high definition (HD) streaming abilities, self-driven systems with interconnected vehicles, and augmented reality-virtual reality (AR-VR) gaming require large bandwidth. The developments in 5G technology can suffice the thirst for high data rates, minimum delay, larger bandwidth, and wide coverage capacity. Also, 5G supports a wide spectrum starting from 470 MHz up to 71 GHz [1]. The spectrum below 6 GHz can provide a larger coverage area and better reliability. The performance of a communication system is totally dependent on the antenna design and its performance parameters such as gain, return loss bandwidth, directivity, and radiation efficiency [2]. It can also provide high speed, and designing a 5G network in sub-6 GHz may require carriers that are cost efficient. The sub-6 GHz also provides unutilized spectrum which can be used and explored in near future [3].

Over the last few decades, antennas suitable for 5G applications have been designed and analysed. Single-element antenna structures can provide limited gain and bandwidth which can be further enhanced by designing a multi-element antenna structure. However, the antenna feeding system might be complicated in the case of multi-element antenna designs [4, 5]. Antennas with multi-resonant features can provide constant gain over large bandwidths with reasonably stable radiation patterns [6]. In addition, extensive research is carried out on 5G base station compact antenna designs capable of exhibiting large gain and highly directional patterns. These types of antennas include phased array schemes, stacked patches, and multi-band structures [7].

Recently, researchers have also explored antenna designs based on electromagnetic periodic structures that can provide enhanced performance in terms of gain, bandwidth, electrical size, radiation pattern, and directivity. Electromagnetic periodic structures are artificial materials that are manufactured by changing their electromagnetic properties such as permittivity and permeability. These properties can be adjusted as per the requirement by repeating metallic structures usually called unit cells. The periodic arrangement of these unit cells alters the capacitive and inductive behaviours of the material thereby changing its attributes. In addition, an overview of electromagnetic behaviour of different periodic structures in two dimensional metamaterials generally referred as metasurface is presented. The research focuses on analysis of behaviour of EM waves in periodic structures, controlling thermal emission of a system and use of metalens and optical element to design metasystem [8]. Array of cylindrical microstructures with dimension less than lambda governs the permeability of metamaterials [9]. Different unit cell structures such as electrical dipoles and split rig resonators (SRRs) with dimensions less than one tenth of operating frequency improves antenna performance in terms of gain, bandwidth, and size [10]. Negative refractive index microstructures of subwavelength size with dimension less than lambda/6 is designed [11].

Periodic structures are often referred to as left-handed materials or metamaterials. The available literature on antenna design incorporating periodic structure discusses a wide range of metamaterial structures like electromagnetic periodic structures (EBGs), frequency selective surfaces (FSSs), artificial magnetic conductors (AMCs), and high impedance surfaces (HISs).

A monopole antenna backed with hexagonal slot square unit cells displays improved gain and radiation efficiency at 3.5 GHz and 5.8 GHz, respectively. However, the use of a periodic

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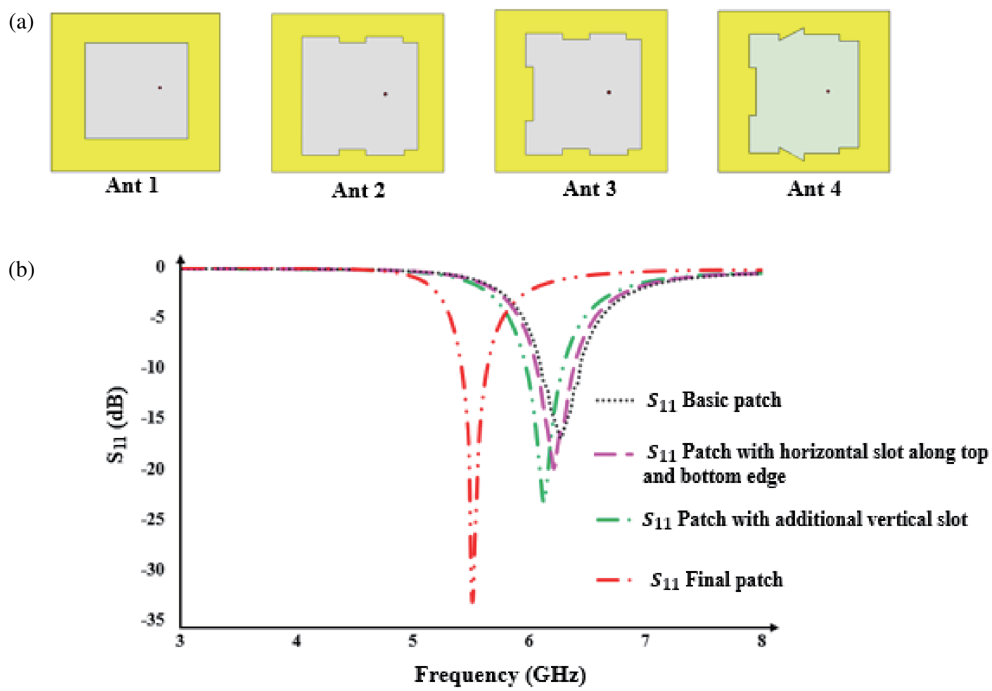

FIGURE 1. (a) Single antenna evolution stages. (b) S parameter for each design stage.

structure increases the overall antenna dimensions [12]. A pair of dipole antennas exhibits dual polarization and dual band feature operating at 3.5 GHz and 4.7 GHz is designed. Its gain and radiation efficiency are enhanced using microstructures printed on an F4BTME-1/2 substrate of 3 mm thickness [13]. An antenna with concentric rings as a periodic structure used as a reflector for 2.51 GHz and 3.36 GHz and as a perfect electric conductor at 5.72 GHz is proposed. The overall design appears large with minimal bandwidth enhancement [14]. Circular ring and square loop unit cell as FSS structures are designed at 2.45 GHz and 2.82 GHz, respectively. The use of a periodic structure along with antenna can be explored. The measured and simulated insertion losses highlight noticeable difference [15]. Vivaldi antenna with periodic structure promotes gain and bandwidth enhancement at 28 GHz but requires 2 layers of FSS microstructures, making the design bulkier. The two layers are rotated by 45 degrees and are made of unit cells (size less than lambda/10) of unequal dimension [16]. Performance of monopole antenna operating at 5.9 GHz is enhanced using an FSS periodic structure. The proposed prototype is relatively bulky and is fabricated on a relatively expensive substrate [17]. Antenna with an EBG structure resonates at 3.5 GHz and is printed on a high dielectric substrate providing volume reduction and gain enhancement [18]. A single layer planar EBG based meandering structure monopole antenna operates at 3.48 GHz and 4.88 GHz, respectively. The EBG structure enriches front to back ratio and improves mutual coupling, but no evidence of gain and bandwidth enhancement is shared [19]. The EBG based antenna designed at 3.6 GHz uses a 2×2 array of rectangular unit cell and provides gain and bandwidth enhancement, but the design is not compact [20]. A two-port multiple-input multiple-output (MIMO) antenna operating at 2.4 GHz is designed using a fractal based traditional mushroom EBG structure for gain enhancement, improved isolation, and marginal bandwidth improvement [21]. The split ring resonator (SRR) unit cell structure with MIMO antenna resonates at 3.5 GHz providing considerable isolation and bandwidth with relatively low gain [22].

All the above structures can suppress the undesired frequencies, reduces the surface wave and unwanted minor lobe radiations thereby enhancing performance of 5G antennas. In addition, the use of periodic structures in antenna design can support a relatively compact low profile wideband antenna structure and explores sub-6 GHz spectrum. Also, according to literature EBG can be used as an AMC, FSS, or HIS structure as per the applications [23]. Comparatively, the EBG structure can perform better in the lower 5G spectrum.

As mentioned in [24], the sub-6 GHz band supports various wireless applications under IEEE 802.11 standard that has a bandwidth requirement ranging from 80 MHz to a maximum of 160 MHz. The proposed 5G antenna design supports WLAN application in sub-6 GHz band providing surface wave suppression, reduced back radiations resulting in enhanced radiation characteristics with a gain of 4.09 dBi and measured bandwidth of 310 MHz. In addition, the overall length and width of the proposed EBG backed prototype are kept the same with minimal increase in the overall height.

2. ANTENNA DESIGN

2.1. Single Element 5G Antenna

The antenna evolution stages along with S-parameter plot for each stage are highlighted in Fig. 1(a) and Fig. 1(b), respectively. Ant 1 represents a simple compact square patch with di-

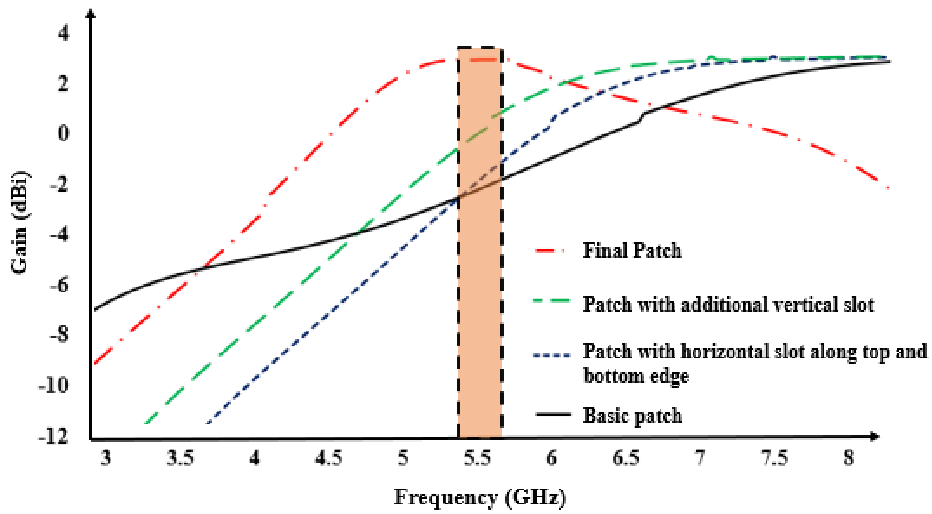

FIGURE 2. Single antenna prototype gain variations.

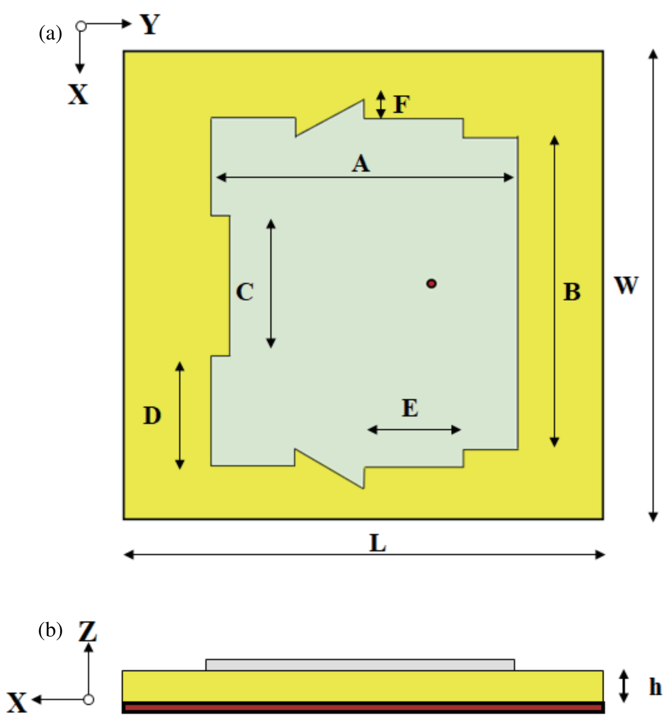

FIGURE 3. Proposed Antenna. (a) Front view, (b) side view.

mension less than $\lambda/4$ at 5.52 GHz resulting in a dip at higher frequency with poor impedance matching. Further inclusion of corrugation (rectangular slots) along the top and bottom edges of the design provides an improved impedance matching at a relatively lower frequency than Ant 1. The proposed antenna is designed to support WLAN application in sub-6 GHz spectrum, hence to decrease the frequency further, additional corrugated structure along the left vertical edge is cut as shown in Ant 3. In the final stage of evolution, a triangular corrugated structure is added that increases the electrical length of Ant 4, thereby shifting the resonant frequency to 5.52 GHz with return loss of -29.45 dB. In addition, a high current density along the radiating edges is also observed which in turn enhances gain as shown in Fig. 2.

As shown in Fig. 3, the proposed antenna is designed on FR4 (substrate 1) with dielectric constant $(\epsilon_r) = 4.4$, $\tan\delta = 0.02$, and height $(h) = 1.5$ mm. The antenna dimensions are 16 mm $\times$ 16 mm $\times$ 1.5 mm and resonates at a frequency of 5.52 GHz with a bandwidth of 210 MHz (5.63 GHz to 5.42 GHz) and a gain of 3.48 dB. The antenna specifications are depicted in Table 1. The antenna design exhibits a corrugated structure, thereby increasing the electrical length of the patch through which the current flows. This enables the structure to resonate at a relatively lower frequency. As the substrate used is FR4 which is easily available, the proposed structure is cost effective.

TABLE 1. Antenna dimensions.

Parameters	Dimensions (mm)	Parameters	Dimensions (mm)
L	16	W	16
A	12	B	13
C	5	D	4.1
E	4	F	0.5

The performance of geometric variations in the antenna parameters is studied, and parametric analysis of left vertical slot width (C) and the horizontal slot width (E) along the top edge and the bottom edge of the proposed antenna are done. From Fig. 4, it has been observed that the width (E) of horizontal slot is increased from 0.4 mm to 1.4 mm in uniform steps of 0.2 mm. The slot width of $E = 1$ mm helps to resonate the antenna at 5.52 GHz. In addition, a high current density along the radiating edges is observed which in turn enhances radiation characteristics.

As shown in Fig. 5, the vertical slot width (C) is varied from 0.6 mm to 1 mm. It is observed that as the slot width increases the electrical size of the proposed radiator increases thereby decreasing the resonating frequency. The desired operating frequency of 5.52 GHz with a return loss of -34 dB is obtained for $C = 0.8$ mm. Thus, the suggested antenna impedance matching can be modified by adjusting the values of C and E, and the operating frequency band can be adjusted accordingly.

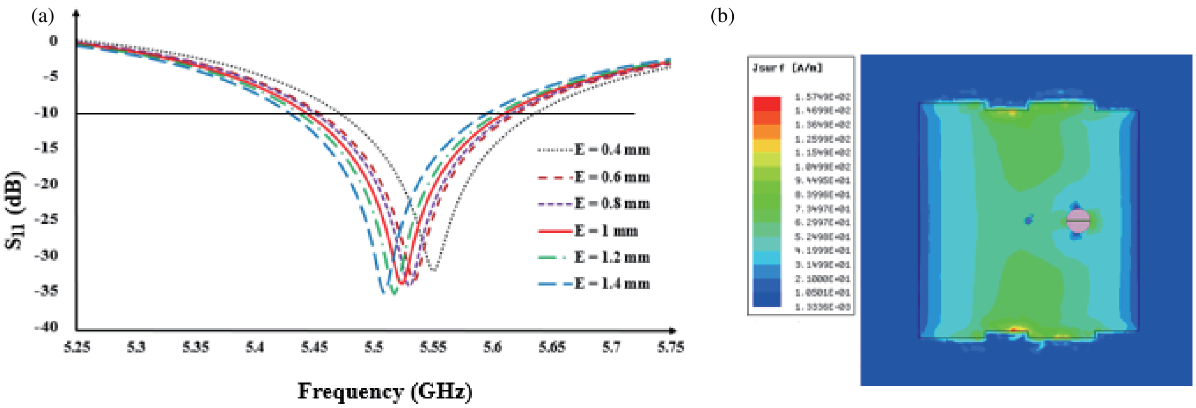

FIGURE 4. (a) Simulated S_{11} of the proposed antenna with different horizontal slot width (E). (b) Current distribution for $E = 1$ mm.

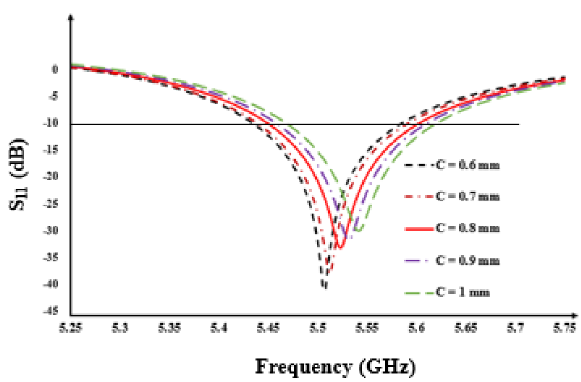

FIGURE 5. Simulated S_{11} of the proposed antenna with different vertical slot width (C).

2.2. Antenna Design with Periodic Structure

As discussed in the literature, the use of periodic structures can enhance the overall antenna performance by tailoring the characteristics of the material. The proposed periodic structure-based antenna geometry is designed and discussed. The EBG structure consists of a 6×6 array of square unit cells. The unit cell size is 1.5 mm $\times$ 1.5 mm with a spacing of 1 mm. The periodic structure is printed on substrate 2 which is an FR4 material with specifications same as substrate 1. This EBG layer is placed below the antenna to suppress surface current. As a result, the back radiations are reflected by the EBG layer, and hence the radiation in the back lobe is suppressed which further boosts the antenna gain [25, 26]. Hence, EBG enhances gain and directivity, thereby increasing the overall efficiency of the antenna. Fig. 7 represents the top view and side view of the prototype. The two layered antenna structure helps in enhancing antenna gain and bandwidth.

Figures 6(a) and (b) describes the unit cell analysis. As shown in Fig. 6(a), the square unit cell (UC) dimension is incremented in steps of 0.1 mm and is varied from 1.3 mm to 1.7 mm. As the UC dimension increases, it reduces the spacing between the unit cells thereby affecting the distributed inductance and the capacitance of the periodic structure. For UC of dimension 1.5 mm $\times$ 1.5 mm with a uniform spacing of 1 mm, it is observed that the periodic structure resonates at 5.52 GHz with return loss of -21.60 dB and impedance bandwidth of 310 MHz, thereby providing a better performance than other UC. The selected unit cell dimension provides a passband throughout the operational band of 310 MHz and exhibits strong attenuation over undesired frequencies. Fig. 6(b) represents Floquet port analysis of the EBG unit cell. The EBG unit cell of dimension 1.5 mm $\times$ 1.5 mm with a substrate height of 1.5 mm is placed in an airbox, and the surface current distribution of the unit cell at the operating frequency is represented in Fig. 6(c). It can be observed that the unit cell offers high impedance and suppresses surface wave propagation. This feature enables the EBG layer placed below the antenna to reduce back radiation, thereby enhance the radiation characteristics of the prototype. Further, the square metallic unit cells in the periodic structure add the inductive effect, and the uniform spacing contributes towards the capacitive effect. The array of 6×6 uniformly spaced square unit cells provides the equivalent inductance and capacitance with desired filtering response. Also, the EBG structure behaves as a high impedance surface, thereby providing surface wave attenuation over the operational band of 310 MHz.

3. RESULTS AND DISCUSSION

The antenna structures are designed and simulated using Ansys HFSS software. The performance of proposed structures in terms of gain, return loss, impedance bandwidth, and current distribution is observed.

3.1. Corrugated Antenna Design

The proposed structure discussed consists of a probe feed corrugated antenna geometry. As shown in Fig. 8, the designed antenna provides good impedance matching with simulated and measured return losses of -33.98 dB and -29.45 dB respectively at 5.52 GHz. The measured impedance bandwidth obtained is 210 MHz (5.42 GHz–5.63 GHz) with the maximum gain of 3.48 dBi at the operating frequency.

3.2. Corrugated Antenna Design with Periodic Structure

The corrugated antenna structure is backed by an EBG structure which consists of an array of 6×6 square unit cells. Further, the

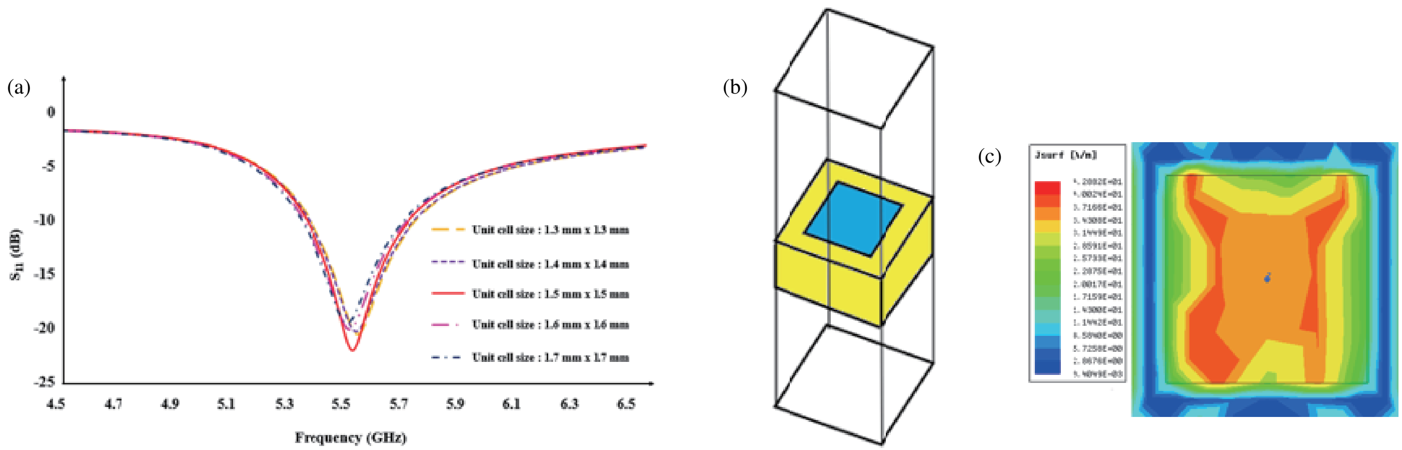

FIGURE 6. (a) EBG unit cell parametric analysis. (b) Floquet port analysis, (c) surface current distribution at 5.52 GHz.

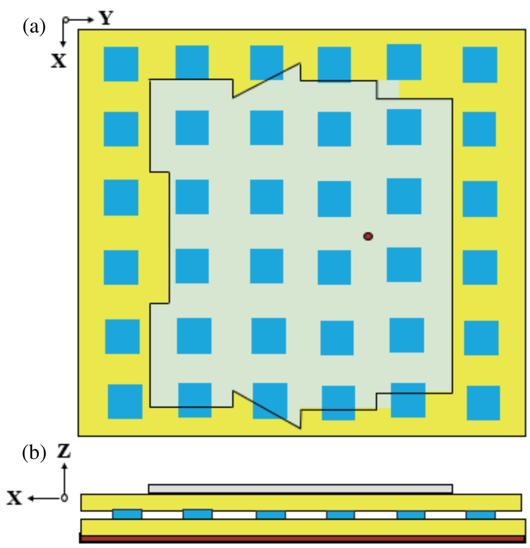

FIGURE 7. Proposed antenna with periodic structure. (a) Front view, (b) side view.

performance of the antenna with a periodic structure in terms of gain and return loss is enhanced. As depicted in Fig. 8, the peak simulated and measured reflection coefficients at 5.52 GHz are 29.2 dB and −25.45 dB, respectively. The proposed antenna provides a relatively wide measured return loss bandwidth of 310 MHz from 5.36 GHz to 5.67 GHz whereas the simulated bandwidth is observed in 304 MHz (5.41 GHz–5.62 GHz).

The radiation pattern for the designed antenna is shown in Fig. 9, Here, the variations in the electric field and magnetic field with respect to Φ represent a relatively directive pattern with minimum radiation in the undesired direction. The measured results are in good agreement with the simulated ones except slight variations due to measurement setup limitations. Fig. 10 represents 3D gain plot of the proposed antenna design with a gain of 3.48 dBi and 4.09 dBi, respectively.

Figure 11 shows the 2D gain plot of the proposed antenna. From Fig. 11, it can be inferred that the developed EBG prototype structure provides a steady improvement in the overall gain of the antenna throughout the operating range without compromising the size and complexity of the antenna. Hence, the EBG layer can be scaled to achieve greater gain enhancement [25, 26]. In addition, the EBG layer is placed below the antenna structure without any air gap between the two substrates. The proposed antenna gain can be further enhanced by introducing an air gap between the EBG structure and the antenna.

Also, Fig. 12 presents the current distribution pattern for the designed antenna, highlighting the variations in the current density over the surface of the antenna at 5.52 GHz. Table 2 summarizes the performance in terms of number of substrate layers, gain, bandwidth, and dimension for proposed design with and without a periodic structure.

TABLE 2. Antenna parameters with and without EBG.

Number of Substrate layers	Gain (dBi)	Bandwidth (MHz)	Dimension (mm^2)
Single layer without EBG	3.48	210	16×16
Double layer with EBG	4.09	310	16×16

Figures 13(a) and 13(b) present the fabricated prototype of the proposed antenna structure. It demonstrates top view of the antenna prototype and periodic structure, respectively. The two layered antenna structure with bottom layer as EBG structure and patch printed on the top layer is fed using SMA connector, also depicted in Fig. 13(c). As shown in Fig. 14, the fabricated antenna is tested, and the antenna measurements are done at Terna College of Engineering, Nerul, Navi Mumbai.

A compact wideband corrugated radiating structure has been proposed. The EBG structure consisting of an array of 6×6 unit cells not only enhances the gain but also provides a bandwidth improvement of 100 MHz. A two layered fabricated prototype is in good agreement with simulated structure. The proposed antenna resonates at 5.52 GHz and is best suited for 5G application in sub-6 GHz range. The performance of the designed antenna prototype is compared with the literature in terms of size, gain, operating frequency, bandwidth, and substrate used. Table 3 shows that the proposed antenna structure highlights a

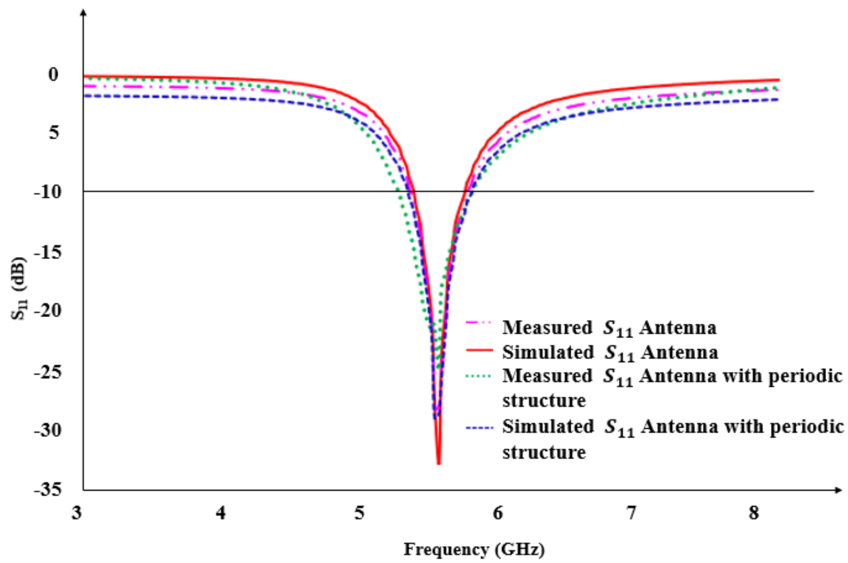

FIGURE 8. Measured and simulated S-parameter plots of the proposed antenna.

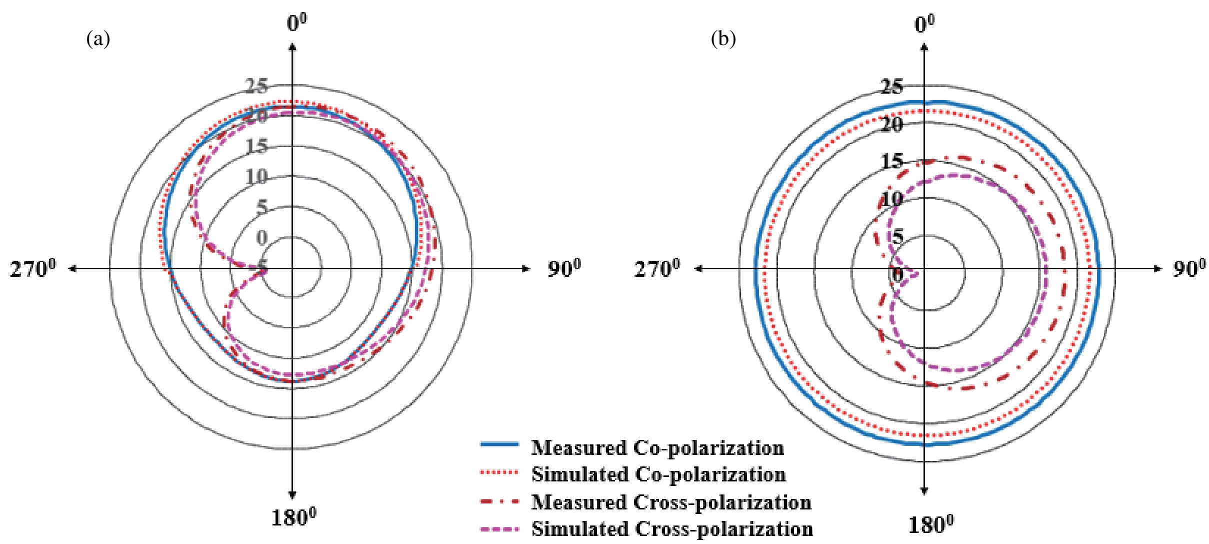

FIGURE 9. Radiation pattern of the proposed antenna at 5.52 GHz. (a) H-Plane pattern. (b) E-plane pattern.

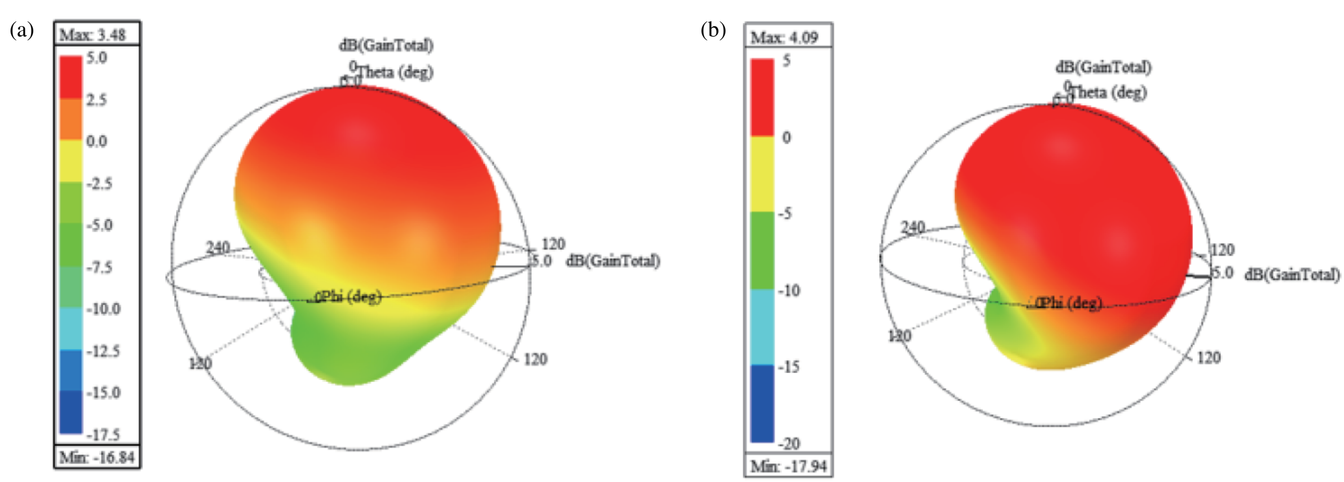

FIGURE 10. 3D-gain plot of proposed antenna. (a) Corrugated antenna. (b) Corrugated antenna backed with periodic structure.

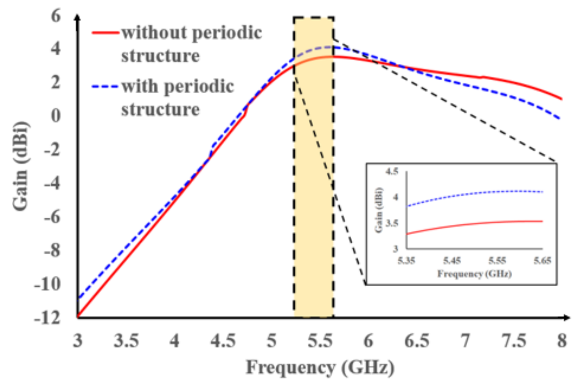

FIGURE 11. 2D-gain plot of proposed antenna. (a) Corrugated antenna. (b) Corrugated antenna backed with periodic structure.

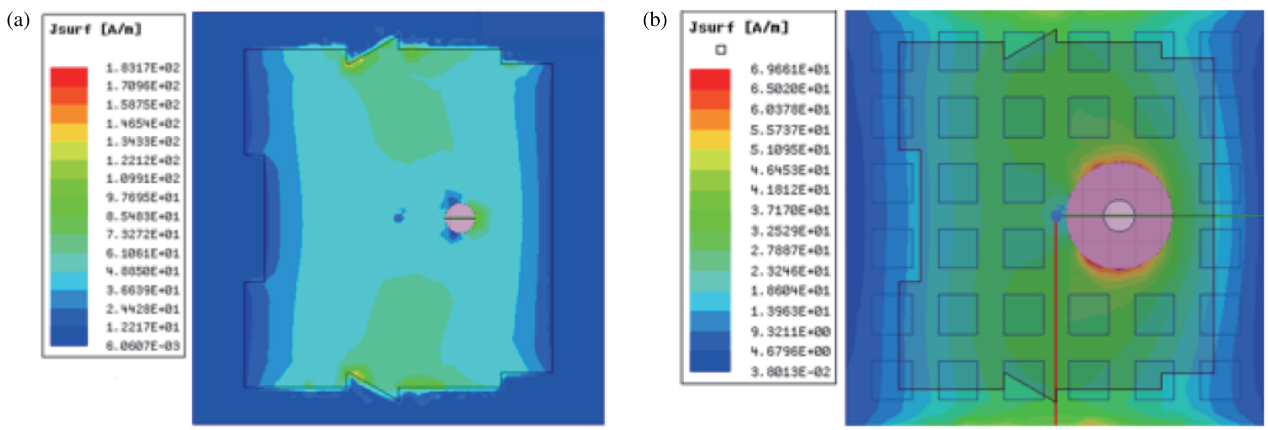

FIGURE 12. Current distribution of proposed antenna. (a) Corrugated antenna. (b) Corrugated antenna backed with periodic structure.

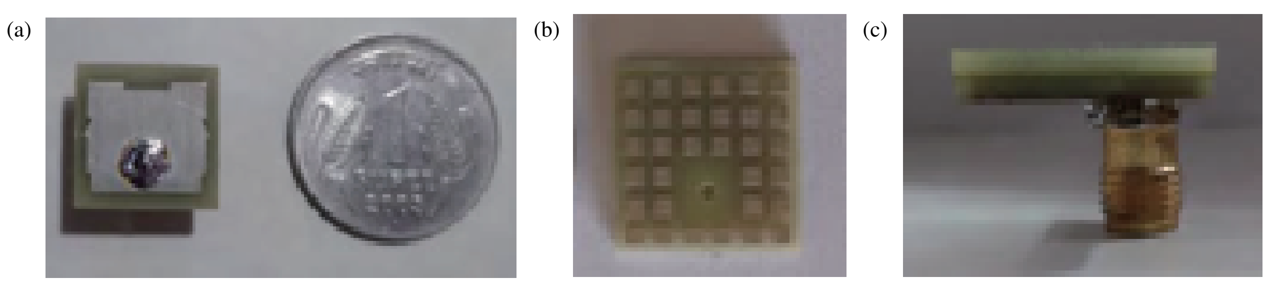

FIGURE 13. Fabricated antenna prototype. (a) Top view of antenna. (b) Top view of periodic structure. (c) Sideview of antenna with connector.

low-profile design compared to references [14, 17] and also exhibits a relatively better gain than [18, 22]. In addition, the proposed EBG-backed antenna prototype exhibits a bandwidth of 310 MHz, which is better than and comparable to the bandwidth obtained in [14, 18, 20, 21]. Also, the use of an EBG structure suppresses the surface wave and enhances the radiation pattern.

Salient features of the prototype designed:

1. A simple planar EBG layer backs the antenna prototype to enhance the gain and bandwidth of the antenna. The EBG unit cell is kept to be a simple square of dimension $1.5 \times 1.5\,\text{mm}^2$ with a gap of 1 mm between the unit cells which suppresses surface waves, reduces the back lobe, and increases the directivity compared to the prototype without EBG.
2. The size of the antenna and EBG layer is kept the same as the total dimensions of $0.29 \times 0.29 \times 0.055\lambda_0^3$, and hence the EBG backed antenna prototype exhibits a minimum compactness of 34% compared to [14, 17, 20].
3. The measured bandwidths of the proposed prototype with and without EBG are 310 MHz (5.62%) and 210 MHz (3.8%) which are comparable with [14, 18, 20, 21], and the EBG enhances the fractional bandwidth by 32.4%.
4. The developed EBG prototype structure also provides a steady improvement in the overall gain of the antenna

TABLE 3. Performance comparison with the current state of art.

Ref.	Size (λ_0^3)	Frequency (GHz)	Bandwidth (MHz)	Gain (dBi)	Substrate	Comment
[18]	$0.24 \times 0.3 \times 0.03$	3.5	80	3.6	$BiNbO_4$ (V_2O_5)	Built on substrate with high ϵ_r, provides low gain.
[14]	$0.79 \times 0.79 \times 0.029$	2.51, 3.36, 5.72	240, 110, 230	5.6, 6.5, 9.6	FR4	Prototype is of large size, providing less bandwidth.
[17]	$0.98 \times 0.98 \times 0.14$	5.9	830	8.93	Rogers 5880	comparatively large prototype, built on a costlier substrate.
[20]	$0.45 \times 0.44 \times 0.036$	3.6	80	4.8	FR4	Prototype is of large size providing narrow bandwidth.
[21]	$0.23 \times 0.76 \times 0.013$	2.4	70	4.25	FR4	Prototype is compact providing narrow bandwidth.
[22]	$0.55 \times 0.467 \times 0.019$	3.5	430	3.5	FR4	Metamaterial based antenna design provides good bandwidth with less gain.
This work	$0.29 \times 0.29 \times 0.055$	5.52	310	4.09	FR4	Relatively high bandwidth, compact and cost efficient.

FIGURE 14. Proposed antenna measurement using VNA.

throughout the operating range without compromising the size and complexity as compared to [18] and [22].

5. The designed antenna structure is fabricated on an FR4 substrate which is relatively cost efficient as compared to [18] and [17], and it does not include vias or any other components which could have made the prototype bulkier.

4. CONCLUSION

The proposed work describes a corrugated antenna structure designed for 5G application backed by an EBG structure. Since the antenna prototype is designed in the sub-6 GHz band, it can support wide coverage areas. The proposed design provides a gain of 4.09 dBi with an enhanced bandwidth of 310 MHz. In addition, the use of a periodic structure minimizes back radiations and thereby exhibits a directional radiation pattern. The 5G antenna resonates at a frequency of 5.52 GHz and can be considered a suitable candidate for WLAN applications.

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