



Performance Enhancement of 60GHz Microstrip Antennas Using Metamaterial-Based EBG and Lens

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Abstract

In this paper, metamaterial approaches are used to improve the gain, bandwidth, and radiation efficiency of microstrip patch antennas for 60GHz applications. In order to lower surface wave losses and improve the performance of proposed antennas, this work investigates a variety of techniques, including the use of metamaterials as antenna lens and as electromagnetic bandgap (EBG) structures. To overcome the narrow bandwidth (2 GHz) and low gain (1.9 dB) of a conventional GaAs-based microstrip patch antenna operating at 60GHz, several enhancements were investigated via HFSS simulations, the result were cross validated and compared using CST Microwave Studio. Integrating an Electromagnetic Band-Gap (EBG) structure improved performance to a 7.3GHz bandwidth and 3.5dB gain. The most substantial enhancement was realized by combining the EBG with a lens technique, achieving a 10GHz bandwidth and 4.8dB gain. These results confirm that metamaterial-inspired techniques are highly effective for advancing high-frequency antennas, particularly for 60GHz communication systems.

Keywords – Metamaterials, electromagnetic bandgap, Microstrip patch antennas, Surface waves loss, lens Antenna, 60GHz band.

1. Introduction

The rapid expansion of wireless systems drives demand for high-performance millimeter-wave antennas. The unlicensed 60 GHz band, with over 7 GHz of bandwidth, is critical for high-data-rate applications like 6G, WLANs, and HD video streaming [1, 2]. However, 60 GHz antenna design faces major challenges like narrow bandwidth, low gain, and surface wave losses, especially when integrated with MMICs on high-permittivity substrates such as GaAs [2].

While microstrip patch antennas are popular for their low profile and easy integration [3], conventional designs on high-permittivity materials like GaAs suffer from inherently narrow bandwidth and poor radiation efficiency. These limitations are primarily due to the excitation





of surface waves, which propagate along the substrate-air interface and are a significant source of loss in microstrip antennas, particularly at millimeter-wave frequencies [4]. Surface waves contribute to higher losses, diminished gain, and unwanted coupling among antenna elements in arrays [5]. To mitigate these issues, several methods have been explored, such as multi-resonator designs, altered radiator geometries, layered substrates, and aperture/proximity-coupled feeding techniques, alongside the application of metamaterials [6-9]. Even though these techniques have enhanced the printed antenna performance at lower frequency bands, it is still a challenging task to apply them at millimeter-wave frequencies like 60GHz band.

A metamaterial is an artificially structured material engineered with unique electromagnetic properties not found in nature. These materials can exhibit negative permittivity and permeability, leading to phenomena such as negative refractive index and backward wave propagation [8]. Metamaterials have been extensively investigated for their potential to enhance microstrip patch antennas performance by controlling surface waves, improving directivity, and increasing bandwidth [9]. In order to control the electromagnetic fields surrounding the radiating element, metamaterials are frequently employed as substrates or superstrates in antenna design. Techniques such as electromagnetic defected ground structures (DGS), bandgap (EBG) structures, and split-square resonators (SSRs) have been applied to suppress surface waves and improve radiation characteristics [7-9]. For instance, EBG structures create a stopband for surface waves, while DGS modifies the current distribution on the ground plane to enhance bandwidth and gain [8]. The antenna design proposed in this paper integrates several metamaterial-based approaches to enhance the operational characteristics of a 60 GHz microstrip patch radiator.

2. Conventional Microstrip Patch Antenna Design

The rectangular microstrip patch antenna architecture, illustrated in Figure . 1, is designed for (60GHz) operation using a Gallium Arsenide GaAs substrate (thickness $h=0.4\text{mm}$, relative permittivity $\epsilon_r = 12.9$). The radiating element and (50Ω) microstrip feed line are cheeing from gold with thickness ($t=2\mu\text{m}$) to minimize conductor losses. The GaAs substrate was selected for its compatibility with Monolithic Microwave Integrated Circuit (MMIC) processes, critical for minimizing parasitic effects at millimeter-wave frequencies. The patch-ground plane separation is optimized to suppress surface wave propagation while maintaining mechanical stability under high-frequency excitation

The characteristic impedance of the microstrip feed line was set at 50Ω to ensure effective coupling with the antenna.



The feed line width (WF) was computed using ADS (Advanced Design System) software and determined to be 0.27mm. However, the simulation results showed a significant problem with impedance matching between the feed line and the patch. The reason for this is that the feed line's width (0.27mm) is rather large in comparison to the patch width, which leads to reflections at the boundary and lower power transfer efficiency. The dimensions of the inset feed line and the patch were calculated using established design equations [3] and further optimized using HFSS software and CST software.

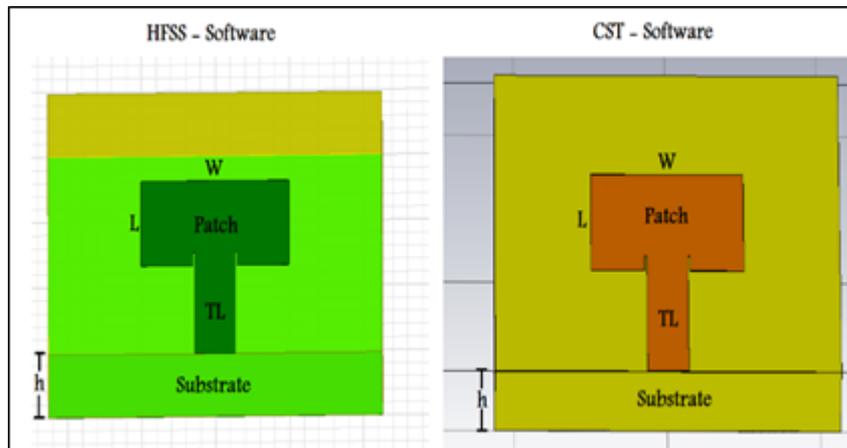


Figure 1 Structure Design Micro-Strip Patch Antenna

The optimization process involved adjusting the patch dimensions, feed line parameters, and inset feed length to get the best matching of the feed line and the patch. Optimized geometry of the antenna dimensions are listed within Table 1

Table 1: Dimensions of Patch Antenna.

Parameters	Dimensions
patch width (W)	1mm
patch length (L)	0.65mm
feed line width (W_F)	0.27mm
feed line length (L_F)	0.55mm
inset fed length	0.1mm
ground plane length (L_s)	1.44mm
ground plane width (W_s)	2.47mm

The antenna demonstrates satisfactory impedance matching characteristics, achieving a return loss (S_{11}) of -16.5 dB at the target frequency of 60 GHz, which complies with the industry-standard -10 dB threshold for efficient power transfer. As illustrated in Figure 2, the operational bandwidth (defined at the -10 dB reference level) spans 2 GHz, corresponding to a fractional bandwidth of 3.33% relative to the centre frequency indicating significant reflections at the feed point. Figure 3 shows 3D antenna gain radiation pattern. Antenna gain is 1.9 dB at resonant frequency, side lobes and back lobes are high due to generate surface

waves.

Analysis of the obtained results indicates that the antenna exhibits inadequate performance at 60 GHz. This is primarily attributed to significant losses arising from surface wave excitation, a consequence of the properties of the employed dielectric substrate. The excitation of surface waves that increases the utilization of the GaAs substrate. Specifically, in the 60GHz frequency band, the first surface wave mode (TM₀) has a zero cut-off frequency, and there is a possibility of exciting another mode (TE₁) which has a cut-off frequency of 54.3GHz.

Furthermore, a substantial disparity exists between the width of the feed line and the antenna width, leading to impedance mismatch between the antenna and its feed network.

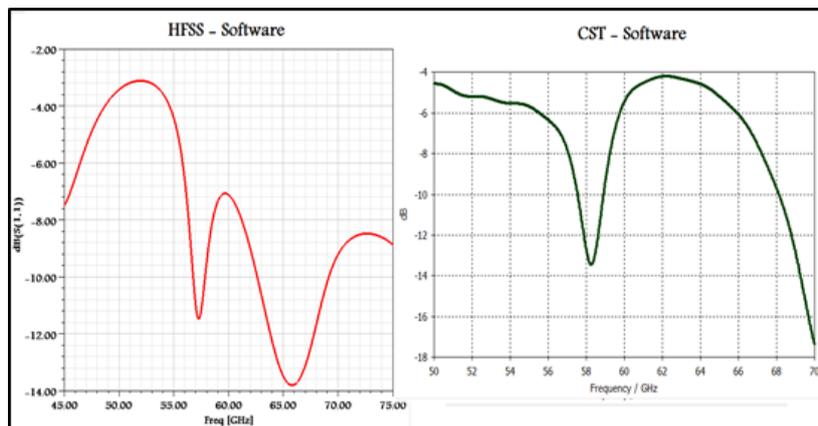


Figure 2 Return Loss of the Patch Antenna

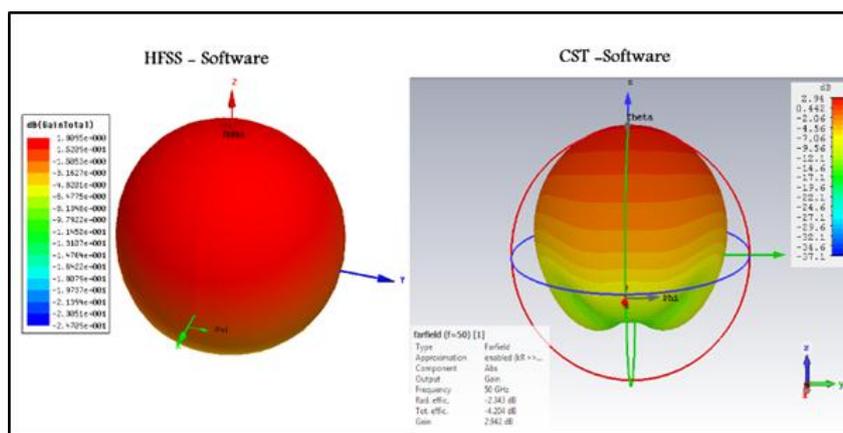


Figure 3 3-D Radiation Pattern of Patch Antenna

3. EBG Antenna

Electromagnetic Band Gap (EBG) structure presented below is comprised of 28 artificially periodical objects that are aimed at regulating the propagation of electromagnetic waves within a designated frequency spectrum. Each of these structures has a square cross-section with a height ($h_c = 0.244$ mm), length and width ($d = 0.04$ mm), and hole spacing ($h_s = 0.25$ mm) between holes. All of these dimensions were optimized carefully using HFSS simulation software and compare with CST software for maximum performance. The EBG structure inhibits or facilitates the propagation of electromagnetic waves at all incident angles and polarization status within the designated frequency spectrum. Figure 4 is the top view and side view of this antenna structure.

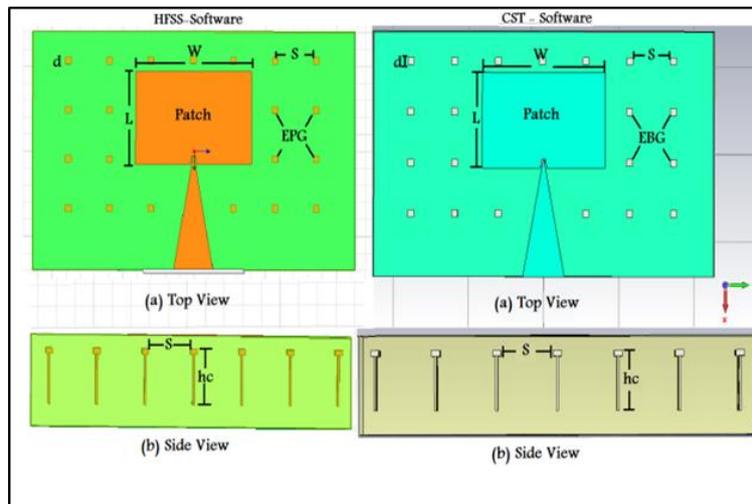


Figure 4 Microstrip Patch Antenna with EBG.

The antenna achieves resonant operation frequency at 60 GHz with a 7.6 GHz bandwidth (13.2%), as shown in Figure 5. The antenna achieves maximum gain of 3.5 dB at the 60 GHz resonant frequency. Radiation pattern analysis confirms excellent stability throughout the operational bandwidth, with less than 0.5 dB gain variation across the entire 7.6 GHz band. The three-dimensional radiation characteristics at resonance are presented in Figure 6. Furthermore, when the design was validated using CST Microwave studio, the antenna exhibited an enhanced Band width of 14.3 GHz and higher maximum gain of 4.1dB „confirming the consistency and reliability of the proposed approach across different simulation platforms.

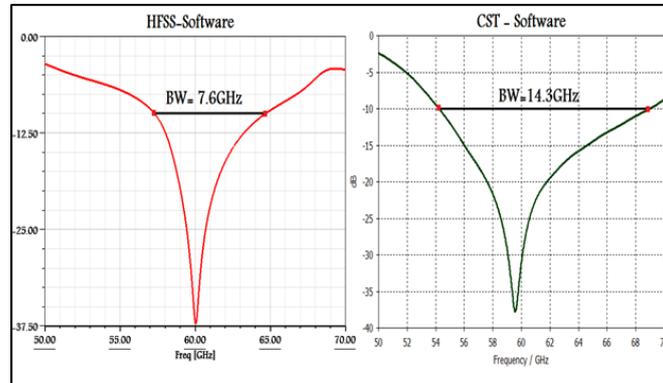


Figure 5 Return Loss of Patch Antenna with EBG

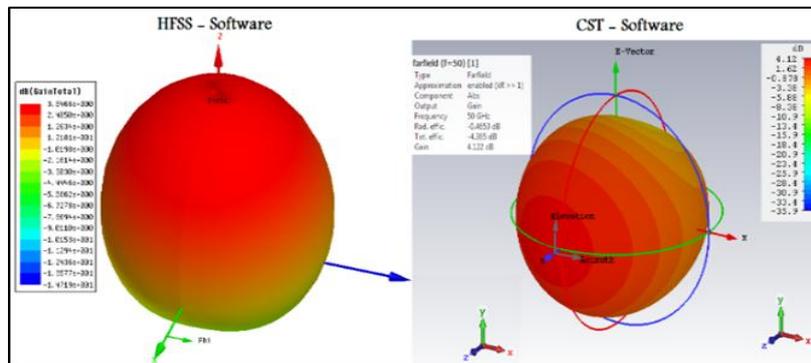


Figure 6 3-D Radiation Pattern of Patch Antenna with EBG

4. LENS Metamaterial Antenna

A metamaterial-based antenna lens was designed and simulated using an 8×6 array of split-square resonators (SSRs) to enhance antenna performance at 60 GHz. Each SSR unit cell, consisting of dual concentric square split patterned on a GaAs substrate, was optimized by adjusting parameters such as height, width, radius, and gap to achieve resonance at 60 GHz. The optimized unit cell was then replicated to form an 8×6 SSR array, which serves as the antenna lens.

The array arrangement ensures that the lens can effectively interact with incident electromagnetic waves, enabling control over their phase and amplitude. The 3D structure of the lens antenna is shown in Figure 7.

Simulation results of Figure 8 show that both effective permittivity and permeability become negative in the vicinity of 60 GHz, confirming the double-negative (DNG) property of the structure. The 8×6 SSR array functions as an antenna lens capable of improving directivity

and focusing, demonstrating its potential for millimetre-wave applications such as 5G communication systems.

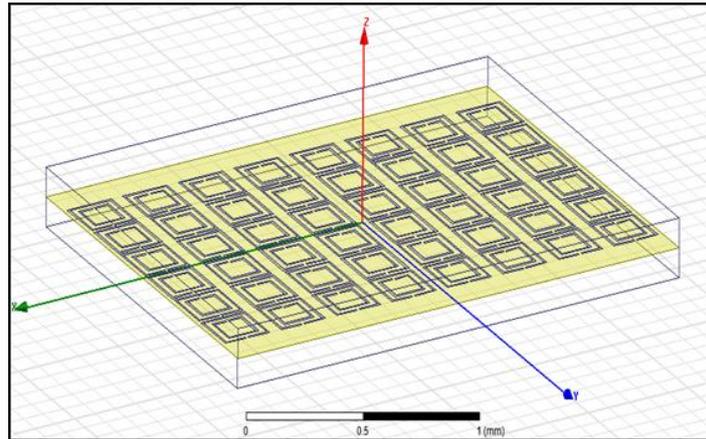


Figure 7. Lens Antenna Structure.

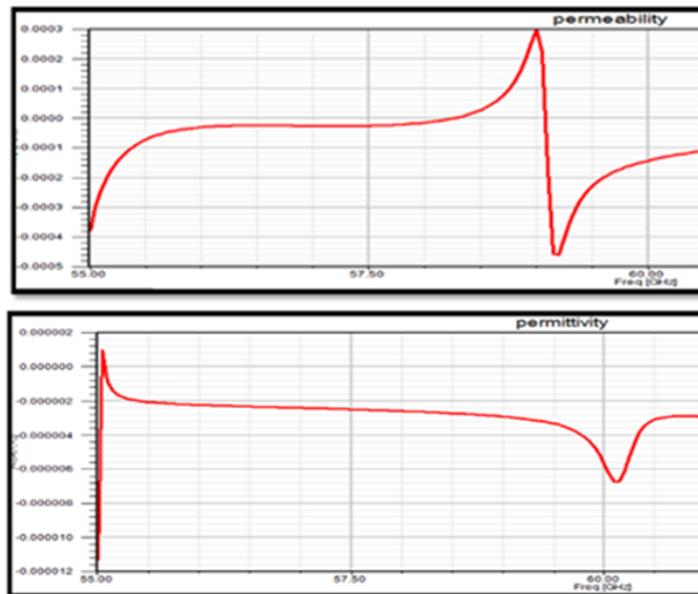
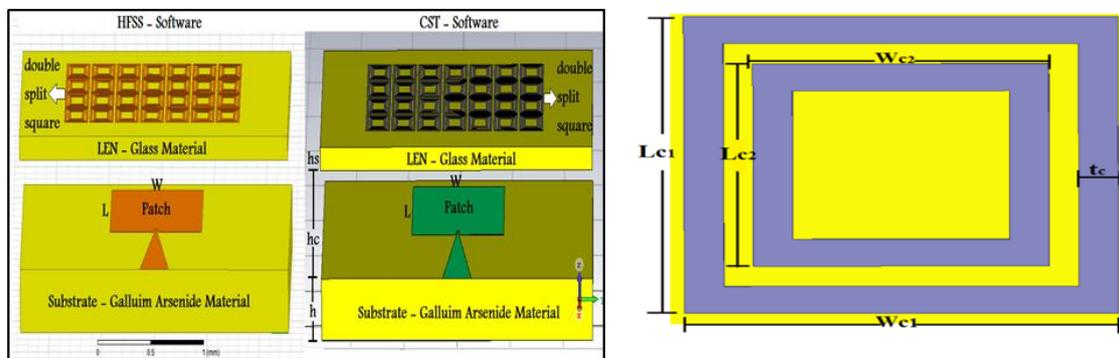


Figure 8 Simulation Results of Permeability and Permittivity at 60GHz

Figure 9 illustrates the configuration of the microstrip antenna integrated with a lens. The lens structure consists of a periodic cell array with a uniform spacing of 0.02 mm in both the x- and y-directions. The antenna is designed for operation at 60 GHz, and its dimensions were optimized using ANSYS HFSS simulation software; the final parameters are summarized in Table 2

TABLE 2: Dimensions of the LENS Techniques Patch Antenna

Parameter Description	Dimensions
The width of the patch (W)	0.87m m
The length of the patch (L)	0.68m m
Length of the ground plane(L _g)	1.4m m
Width of the ground plane(W _g)	2.2m m
The length of the unit cells(Lc1,Lc2)	(0.22, 0.15)mm
The Width of unit cells(Wc1,Wc2)	(0.22, 0.15)mm
The thickness of unit cells	0.02m m
The thickness of Substrate(h)	0.4m m
The thickness of air gap(hc)	0.55m m
The thickness of Superstrate(hs)	0.05m m



(A) 3-D View (B) Structure Double Square Rings
Figure 9 Configuration of Antenna with LENS Techniques

Simulation results as shown in Figure 10 demonstrate a 6.2 GHz bandwidth at the 60 GHz resonant frequency, with an exceptional return loss of -35 dB, indicating highly efficient impedance matching. The antenna achieves a maximum gain of 5.65 dB, with remarkable radiation pattern stability across the entire bandwidth. Figure 11 shows the 3-D radiation pattern of antenna gain. Moreover, when validated using CST Microwave studio, the antenna performance was further enhanced, achieving a wider 12.2 GHz bandwidth and a gain of 5.1 dB. The results show significant performance improvements over conventional designs, validating the metamaterial lens for mm-Wave antenna applications

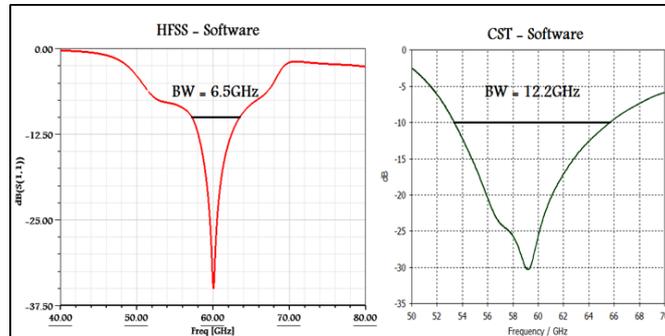


Figure 10 Return Loss of the Patch Antenna with LENS Techniques

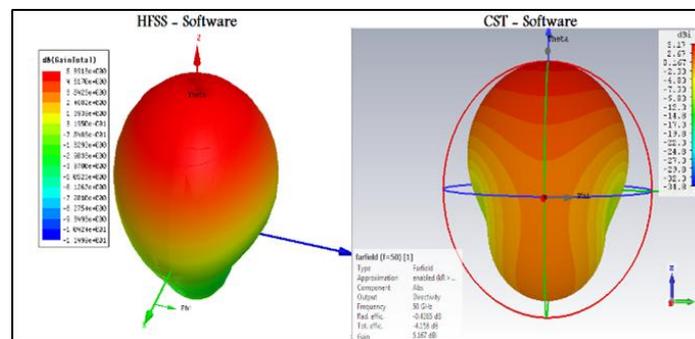


Figure 11 3-D Radiation Pattern of the Patch Antenna with LENS Techniques

5. Antenna Design with LENS Technique Combined with EBG

The proposed antenna geometry and configuration is shown in Figure 12. In this design, the EBG structure and Lens technique are combined to optimize the performance of the microstrip patch antenna. The integration of these two technologies attempts to improve key antenna parameters such as bandwidth, gain, and radiation pattern efficiency, while minimizing surface wave losses of the antenna.

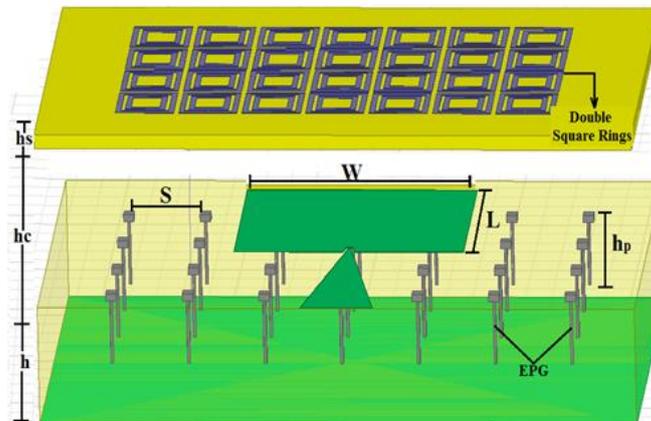


Figure 12 Configuration of Antenna with EPG and LENS Techniques

The simulation results in Figure 13 demonstrate outstanding broadband performance, with a 10 GHz bandwidth at 60 GHz resonance, achieving an exceptional -40 dB return loss, indicating near-perfect impedance matching. As shown in Figure .14, the antenna maintains excellent radiation characteristics with a maximum gain of 4.8 dBi, stable beamwidth ($62^{\circ} \pm 1.5^{\circ}$), sidelobe suppression (< -11.2 dB) across the entire bandwidth

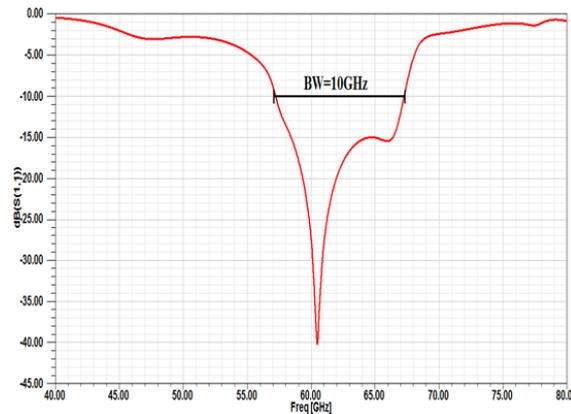


Figure 13 Return Loss of the Patch Antenna with EBG and LENS Techniques

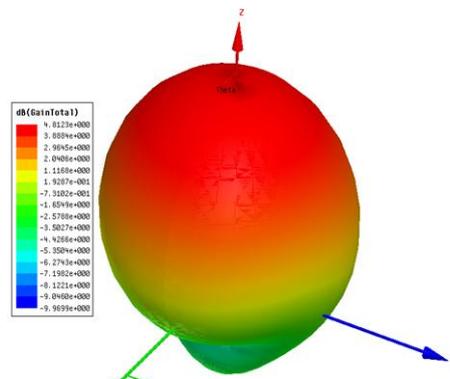


Figure 14 3-D Radiation Pattern of the Patch Antenna with EPG LENS Techniques

6. Performance Comparison

Three different configurations of the microstrip patch antennas on a GaAs substrate have been investigated at the 60GHz band and performance comparison of antennas is listed in Table III. The conventional antenna exhibits a return loss of -16.5 dB, a bandwidth of 2 GHz, and a gain of 1.9 dB. While functional, its performance is limited by surface wave losses and edge diffraction, which reduce radiation efficiency. In contrast, the EBG structure significantly enhances performance, achieving a return loss of -37 dB, a bandwidth of 7.3 GHz, and a gain

of 3.5 dB. The EBG structure suppresses surface waves, reducing losses and improving radiation efficiency.

The Lens technique further improves performance, achieving a return loss of -35 dB, a bandwidth of 6.2 GHz, and a gain of 5.6 dB. By focusing electromagnetic waves, the lens increases gain and directivity. However, the best overall performance is achieved by combining the EBG structure with the Lens technique, which results in a return loss of -40 dB, a bandwidth of 10 GHz, and a gain of 4.8 dB. This configuration demonstrates a significant reduction in surface wave losses, leading to more radiation in the broadside direction, a desirable feature for high-frequency applications.

TABLE 3: Comparing Conventional with EBG and LENS

Antennas	RL (dB)	BW (GHz)	Gain (dB)
Conventional Antenna	-16.5	1.23	1.9
EBG Antenna	-37	7.3	3.5
LENS Antenna	-35	6.2	5.6
EBG with LENS Antenna	-40	10	4.8

The Lens technique demonstrates superior radiation performance compared to the EBG technique, as it focuses electromagnetic waves more effectively. Without the metamaterial superstrate, the antenna's radiation performance drops significantly due to edge diffraction and surface wave losses. The comparison clearly shows that the use of EBG structures and Lens techniques significantly enhances the performance of microstrip patch antennas at 60 GHz. The EBG with Lens technique provides the best overall performance, with a wide bandwidth, high gain, and reduced surface wave losses, making it a promising solution for high-frequency applications such as 6G communications and millimeter-wave systems.

7. Comparison between HFSS and CST Results

The validation using CST microwave studio confirmed the enhancement observed in HFSS simulation, but also revealed notable differences. CST results demonstrated superior performance in terms of bandwidth and gain, achieving a wider bandwidth of up to 12GHz and gain of 5.1dB, which exceeded the HFSS results. However, a slight frequency shift in the resonant frequency was observed compared to the nominal 60GHz obtained in HFSS. These differences highlight the importance of cross validation across different simulation platforms to ensure the reliability and robustness of the proposed antenna design as shown in Table IV.

TABLE 4: Dimensions of Patch Antenna.

Antennas	Return loss (dB)		Bandwidth (GHz)		Gain (dB)	
	HFSS	CST	HFSS	CST	HFSS	CST
Conventional	Not working	Not working	Not working	Not working	1.9	2.1
EBG	-37	-38	7.6	14.3	3.5	4.1
LENS	-37	-30	6.5	12.2	5.6	5.1

8. Conclusion

This paper shows that combining EBG structures and metamaterial-based Lens methods can substantially improve the performance of microstrip patch antennas at 60 GHz. EBG shows the optimum performance with -37.5 dB of return loss, 10 GHz of bandwidth, and 4.8 dB of gain and minimizes surface wave loss. When compared with the ordinary antenna that possesses 2 GHz of bandwidth and 1.9 dB of gain, with HFSS simulation results, the new design makes significant improvements. In conclusion, the combining of EBG structures and metamaterial-based Lens methodologies provides a very promising approach for enhanced performance of microstrip patch antennas at 60 GHz. It addresses significant issues like surface wave loss and low gain and is therefore a very viable candidate for next-generation wireless communications systems

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