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DESIGNING A COMPACT SINGLE FEED BROADBAND MM-WAVE ANTENNA FOR WIRELESS MOBILE APPLICATION USING HYBRID EBD AND DGS TECHNIQUE

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Abstract

This paper introduces a compact high-gain microstrip patch antenna designed to enhance bandwidth and cater to 5G applications. The antenna comprises five layers and utilizes a single-feed off-centered microstrip transmission line, operating within the 32 GHz to 40 GHz millimeter-wave band. To boost its performance, a hybrid Electromagnetic Band Gap (EBG) and Defected Ground Structure (DGS) are incorporated. The design enhancements involve the integration of two L-shaped elements on the radiating element, as well as the addition of four-square elements and two rectangular element slots at the center and edge of the ground plane. The antenna is constructed using Rogers RT Duroid 5880 as the substrate material, possessing a dielectric constant of 2.2 and a loss tangent of 0.0009, with a height of 0.254 mm. The antenna's compact structure measures 4.9 mm × 4.9 mm × 0.254 mm, equivalent to $0.92\times \lambda g \times 0.05\lambda g$. This compact size is ideal for miniaturization. Simulations were performed using Computer Simulation Technology Microwave Studio 2019 (CST MWS). The simulation results demonstrate that the proposed antenna achieves a maximum gain of 6.97 dBi and boasts a wide bandwidth spanning 7.9 GHz while maintaining a return loss of less than -10 dB. This research findings address the demand for increased gain and extended bandwidth in millimeter-wave bands, aligning perfectly with the requirements of 5G applications.

Keywords: CST, EBG, DGS, 5G, Antenna

INTRODUCTION

Mobile wireless technologies have undergone phases of evolution, starting from the first generation (1G), second generation (2G), third generation (3G), fourth generation (4G), and now fifth generation (5G) technology. From 1G to 4G, mobile communication systems have been using the spectrum below 3 GHz, which has become overcrowded. The rapid increase in mobile data growth and the use of smartphones are creating unprecedented challenges for wireless service providers, as they are limited to a carrier frequency spectrum ranging between 700 MHz and 2.6 GHz. In this carrier frequency spectrum, each major wireless provider has approximately 200 MHz across all the different cellular bands of spectrum available to them [1]. Additionally, the demand for capacity in mobile broadband communication increases dramatically every year and is expected to experience a thousand-fold increase in total traffic by 2020 [1]. Meeting these modern system specifications can be achieved with the advent of 5G communication systems, which provide a solution for the growing data traffic [2]. 5G is expected to provide higher data transmission rates and broader coverage than the currently allocated 4G spectrum, which faces spectrum shortage. To support the fifth-generation mobile network, service providers require a more useful spectrum and efficient radio access technology to deliver the expected mobile traffic and high data rates in the order of multiple Gbps [3]. This can be achieved by utilizing the advantages offered by millimeter-wave antennas. Millimeter-wave (mm-Wave) refers to the frequency band between 30 GHz and 300 GHz, which has attracted considerable attention recently for next-generation cellular networks. The mm-Wave bands offer orders of magnitude higher spectrum availability than current cellular allocations [4]. The millimeter-wave spectrum has become increasingly interesting to service providers and system designers due to the wide bandwidths available for carrying communications in this frequency range. Such wide bandwidths are valuable in supporting applications such as high-speed data transmission and video distribution. Radio astronomy, radars, airport communications, and many military applications have already been using the mm-Wave bands for the last few decades. Even a small fraction of the available mm-Wave spectrum can support hundreds of times more data rates and capacity compared to the current cellular spectrum. Thus, the availability of a large amount of mm-Wave spectrum is opening up new horizons for spectrum-constrained future wireless communications [6]. However, mm-Wave is saddled with losses such as severe path loss, high penetration loss, and free space attenuation. To overcome these limitations, antenna designs for the mm-Wave band should cover a wider range of operation with high gain. Patch antennas are the most popularly used antennas due to their excellent features and their design meeting the requirements of modern-day wireless communication. However, conventional patch antennas are characterized by low gain and small bandwidth, which can affect their potential application in the mm-Wave frequency band. To address the challenge of conventional microstrip patch antennas at high frequencies, this research work aims to modify the compact single-feed broadband mm-Wave antenna designed in the work of [7] by exploring the use of DGS and EBG to further enhance the antenna's performance in terms of bandwidth and gain, making it a suitable candidate solution for 5G wireless and mobile communication.

REVIEW OF SIMILAR WORK

Developed a small dual-band (28/38 GHz) elliptical antenna for 5G applications with DGS. In their work, they presented a compact elliptical dual-band microstrip antenna fed with a coplanar waveguide. The proposed antenna was designed and analyzed using a 3D full-wave electromagnetic software named High-Frequency Structure Simulator (HFSS), based on the Finite Element Method (FEM). The design adopted a bi-layer substrate configuration, where the elliptical radiating patch was printed on a Rogers RO3010 substrate with dimensions of 2.265x2x0.75 mm^3, having a dielectric constant of 10.2 and a loss tangent of 3.5x10^-3 at 9.4 GHz. The radiating patch occupied a surface area of 0.754 mm^2. Additionally, the Rogers RO3010 substrate was placed on top of another dielectric, namely Rogers RO4350B, with a relative permittivity constant of 3.66 and a loss tangent of 4x10^-3 at 9.4 GHz. The antenna operated at 28 GHz and 38 GHz, which are two of the selected bands allocated to 5G by the International Telecommunications Union. The simulation results showed that the antenna achieved a minimum wide bandwidth of 4.14 GHz and a constant gain of 6 dB over the operating frequency range. As a miniaturized antenna, its electrical characteristics, along with the antenna's size, were chosen as comparison parameters with those found in recent research works. In addition, previous electrical parameters, together with the return loss and VSWR, were selected for the proposed elliptical antenna, which were improved by inserting two F-shaped slots in the ground plane. However, the development of the small dual-band and the use of a bi-layer substrate configuration limited the achievable magnitude frequency with elliptical antennas [5]. A millimeter-wave antenna with enhanced bandwidth for 5G wireless applications [8]. In their study, the researchers designed and fabricated a new rectangular antenna that has high bandwidth in the millimeter-wave range, stable radiation patterns, and an improved reflection coefficient at 28 GHz for future 5G applications. They used an FR-4 substrate with vaery compact dimensions of 5.5 × 4.35 mm^2, a dielectric constant of 4.4, a thickness of 1.6 mm, and a loss tangent of 0.002 for the design and fabrication of the proposed antenna. The proposed configuration was designed and simulated using HFSS (High-Frequency Structure Simulator), a simulator based on the finite element method. The designed antenna achieved an impedance bandwidth of about 4.10 GHz (25.8 GHz to 29.9 GHz) and had a reflection coefficient of about -39.70 dB, with a maximum gain of 5.32 dBi. The results showed good agreement between the measured values and the simulated results. However, a shortcoming of this work is the use of compact dimensions for the substrate. While the substrate has compact dimensions, the ground structure adopted in the study limited the degree of enhancement recorded by the authors.

Designed a single-feed dual-band millimeter-wave antenna for future 5G wireless applications to improve performance. The antenna was designed and simulated using the Computer Simulation Technology (CST) platform, with an FR-4 substrate having a height of 0.8 mm, a dielectric constant of 4.67, and a loss tangent of 0.002. The total size of the antenna was 8 × 8 mm^2, and the rectangular radiator of the antenna was 3.4 × 3.4 mm^2 in size. An inverted-L was introduced into the radiator to achieve dual-band capability, and the antenna was fed through a 50 Ω feed line probe with dimensions of approximately 2.3 × 0.4 mm^2. The simulation results showed that the antenna achieved a wide bandwidth in the upper band (38 GHz) of about 3.54 GHz (35.56 GHz to 39.12 GHz) with over 6 dB gain, and the lower band (28 GHz) produced a bandwidth of about 1430 MHz (27.27 GHz to 28.70 GHz) with a 2.7 dB gain suitable for 5G applications. The major drawback of this work is seen in the use of a conventional ground structure for implementing a single-feed dual-band millimeter-wave antenna. Research has shown that the use of improved ground structures has a positive effect on the achievable bandwidth, especially for 5G applications. Hence, the authors' work can be improved by adopting a more efficient ground structure in the single-feed dual-band millimeter-wave antenna.(Darboe, Konditi, & Manene, 2019), proposed a Rectangular Microstrip Patch Antenna for 5G applications. The antenna is design with the following parameters; ground plane length of 6.258mm and width of 7.235m, patch height of 0.5mm, length 3.4mm, width of 4.1mm. An inset feed transmission line technique is used for matching the radiating patch and the 50 Ω microstrip feed line. The antenna is intended to have a resonant frequency of 27.954GHz, with return loss of -13.48dB, bandwidth of 847MHz. The antenna has a relative high gain of 6.63 dB which is considered very good for compact microstrip antenna and a half power beam width of 66.0°. Although, the antenna was designed for 5G mobile application, the bandwidth is relatively low for most 5G applications. This work can further employ enhancement techniques such defected ground structure to improve the bandwidth for millimeter wave applications.

From the work reviewed so far, it can be observed that various attempts have been made to improve the performance of the patch antenna. Some works have considered the use of DGS, but the designed antenna is not suitable for millimeter-wave frequency applications, as seen in the works of [11] and [12]. Additionally, some researchers have used DGS, but with high overall antenna dimensions, as shown in the work of [3] and [12]. Furthermore, some work has considered the use of EBG, but the designed antennas are not suitable for the millimeter-wave frequency band [12]. Some work has considered the use of EBG for the millimeter-wave, but additional performance can be achieved when combined with DGS [7]. Finally, some work has combined EBG and DGS, but the overall dimensions are high, making them unsuitable for size-constrained applications, as seen in the work of Rahman et al. (2019). Thus, this research work proposes to improve the work of [7] by using a Defected Ground Structure (DGS) to make the antenna a suitable candidate solution for 5G communications. The proposed improvement is expected to enhance the bandwidth and gain of the microstrip antenna for higher frequency applications.

ANTENNA DESIGN

In the design of a microstrip patch antenna, it is essential to first select the substrate to be used since its basic parameters, such as thickness and dielectric constant, have a great influence on the antenna characteristics. This design work employed Rogers RT5880 with a height of 0.254 mm thickness and a relative dielectric constant of 2.2. Copper material is used as the patch conductor and ground plane. Popular models, such as the transmission line model, cavity model, and the full-wave model, are employed in analyzing microstrip patch antennas [13]. Among the aforementioned models, it is said that the transmission line model is the easiest [13]. The dimensions of a single patch element are calculated using the transmission line model accordingly:

$$w_p = \frac{c}{2f_o}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad 1$$

The patch width is wp and ε_r is the relative dielectric constant and f_o represents the frequency at which the antenna resonates.

The effective dielectric constant is expressed as:

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{w}\right)^{\frac{-1}{2}} \qquad 2$$

As a result of fringing, the length of the patch is extended by a distance equal to:

$$\Delta_{Lp} = 0.412h\frac{\left[\varepsilon_{reff}+0.3\right]\left[\frac{w}{h}+0.264\right]}{\left[\varepsilon_{reff}-0.258\right]\left[\frac{w}{h}+0.8\right]} \qquad 3$$

The length is determined by:

$$L = L_{eff} - 2\Delta_L \quad 4$$

$$L_{eff} = \frac{c}{2 f_o \sqrt{\varepsilon_{reff}}} \quad 5$$

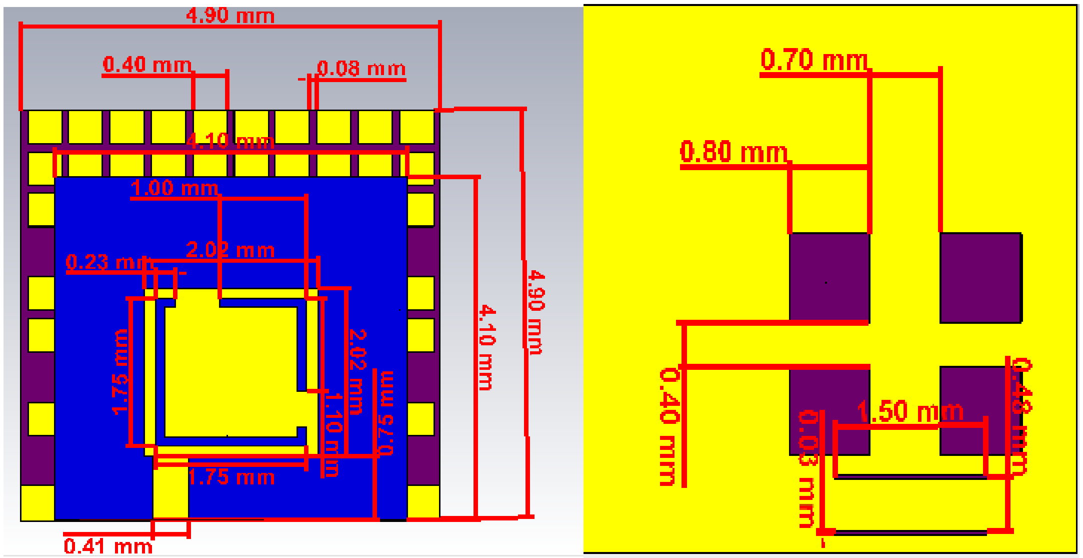
The length (Lp) and width (wp) of the radiating patch for the design was calculated to be 3.12 mm and 2.59 mm using the mathematical equations described above. The simulation model for the single element antenna implemented in CST-MWS and the hybridize EBG and DGS based antenna as shown in Fig.1(a). This arrangement enables to improve the antenna performance. A simulation model for the hybridize EBG and DGS based antenna implemented in CST-MWS is shown in Fig 1.

METHODOLOGY

The following are the steps taking to develop the hybrid EBG and DGS patch antenna design.

Hybrid EBG and DGS Patch Antenna Design

In order to exploit the benefits of EBG and DGS in enhancing antenna performance, it is necessary to design an antenna based on a hybrid EBG and DGS structure. In this work, the design procedure begins by designing an EBG structure on a slotted patch based on the work of [7]. In the EBG-based slotted patch antenna structure, two substrates (Rogers RT5880 and Rogers RT4003c) were employed. The Rogers RT5880 has a dielectric constant of 2.2 and a thickness of 0.254 mm. The Rogers RT4003c has a dielectric constant of 3.38 and a thickness of 0.203 mm. The EBG consists of a linear arrangement of squares measuring 0.4 mm. The square elements are located on the Rogers RT5880 substrate and are 0.0818 mm apart from each other. The defected ground structure was designed using combinations of rectangular and square slots on the ground. This is done to achieve better performance. Two rectangular slots were designed with dimensions of 0.03 mm by 1.5 mm and are 0.48 mm apart. The square elements number four, and each one of them has dimensions of 0.8 mm by 0.8 mm. They are separated by distances of 0.7 mm on the horizontal axis and 0.40 mm on the vertical axis. The design parameters for the feed line, EBG, radiator, and ground plane are clearly shown on the antenna structure, and the overall design is shown in Figure 1. The hybrid EBG and DGS-based patch antenna was modeled in CST MWS using the dimensions shown in Figure 1. The model view of the hybrid EBG and DGS slotted patch antenna in CST MWS workspace is shown in Figure 1.



(a) Front view (a) Back view

Figure 1: Front and Back View of the Hybrid EBG and DGS Based Patch Antenna

Software Used

CST MWS is a specialist tool for the 3D EM simulation of high frequency components. CST MWS enables the fast and accurate analysis of high frequency (HF) devices such as antennae (including arrays), filters, transmission lines, couplers, connectors (single and multiple pin), printed circuit boards, resonators, etc. CST employs Finite Integration in Technique (FIT) and is also popular among antenna designers due to ease in simulations The name CST ® (CST MWS) stands for Computer Simulation Technology microwave studio. CST time domain solver is suitable for wide band problems [14].

RESULTS

A. Return Loss Plot for the Developed Hybrid EBG and DGS

The return loss plot for the proposed hybrid EBG and DGS based slotted patch antenna is shown in Figure 4. It was observed from the plot that the proposed antenna operates in the frequency range of 32.1 GHz – 40 GHz with minimum resonant point at 35 GHz with a return loss of -30 dB.

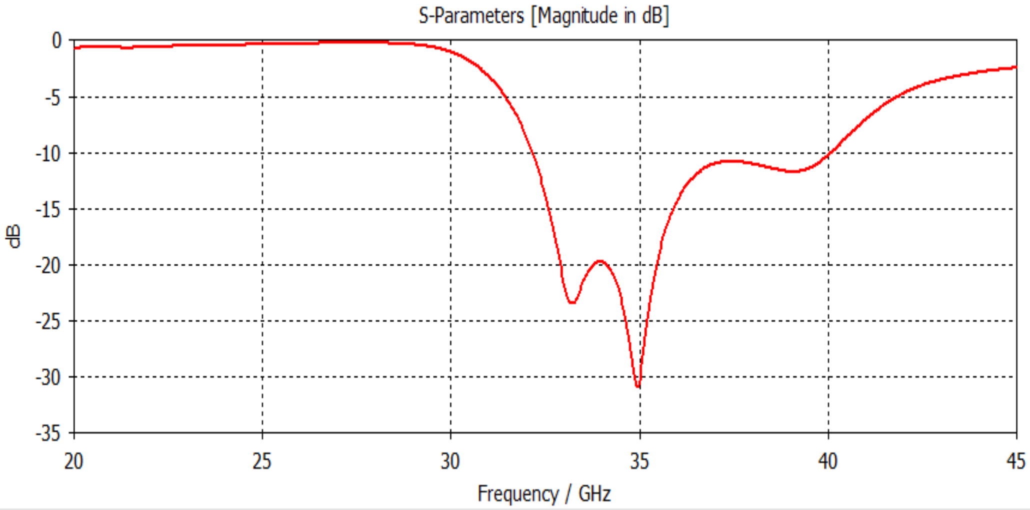


Figure 2: Return loss plot for the proposed hybrid EBG and DGS Based Slotted Patch Antenna

The overall bandwidth of the proposed antenna is 7.9 GHz which is higher than the bandwidth of the other designed antenna. This shows that the hybridization of EBG and DGS structure improve the performance of the patch antenna in terms of return loss and bandwidth.

B. Radiation Pattern Simulation Result

The radiation of an antenna shows the graphical orientation of the radiated beam and the antenna gain. The polar plot radiation patterns for the proposed hybrid EBG and DGS based patch antenna are shown in Figure 3.

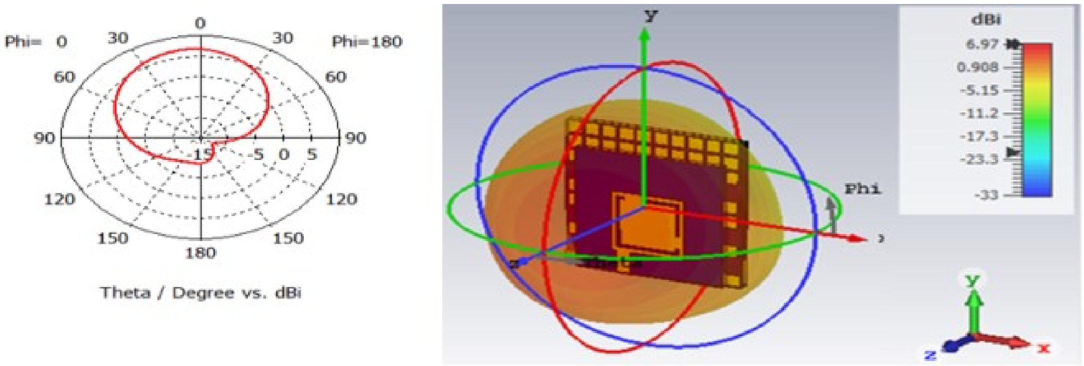


Figure 3: 2D and 3D Radiation Pattern the Proposed Antenna

The designed antenna gain was observed at 38 GHz which is the designed frequency of the single patch antenna. It was observed

that the hybrid EBG and DGS based patch has a maximum gain of 6.97 dBi at 40 GHz and a minimum gain of 5.25 dBi at 32 GHz as shown in Figure 5, likewise it has a maximum HPBW of 88^0 at 36 GHz and minimum HPBW of 81^0 at 40 GHz as shown in Figure gain of 6.97 dBi. This gain was achieved due to advantage offered by EBG and DGS. It is evident from the plot that the hybrid EBG and DGS has the highest gain compared to the work of Usman *et al* 2018. The achieved improvement in gain is due to the combine effects of using both EBG and DGS structure.

C. Gain against Frequency of Operation Figure 5. Shows the gain distribution for the developed antenna shows the gain distribution of the designed antenna with a maximum gain of 6.97 dBi. it can be observed that the developed work exhibit good gain this is due to the use of both EBG and DGS which improved the performance of the antenna. Figure 5 shows the graph gain against frequency of operation and the developed work.

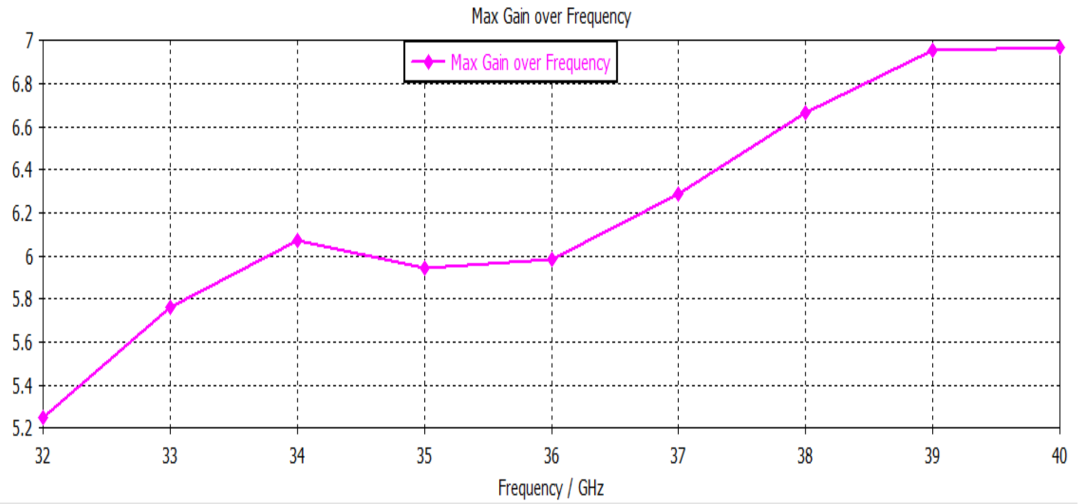


Figure 4: Gain against Frequency of Operation.

The gain for the designed antenna is slightly increased between the frequency 37 GHz and 40 GHz as shown in figure 4. In addition, the gains also increased for frequency at 32 GHz, 33 GHz and 34 GHz, accordingly. The effect of the DGS structure that was introduced in the ground plane of the of the developed antenna has changed the input impedance of the feed. Thus, the impedance of the developed antenna is mismatched at 35 GHz as a result of which the designed antenna decreases at 35 GHz and 36 GHz.

CONCLUSION

This research work presented the development of an improved compact millimeter-wave antenna using hybrid energy band gap and defected ground structure. The hybridize EBG and DGS structure were designed and simulated in CST studio to evaluate their performance. The results obtained from the CST simulation shows the EBG based and DGS based antenna improves the performance patch antenna in terms of gain and bandwidth. The size of the antenna is very compact and thus is a suitable for miniaturization.

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