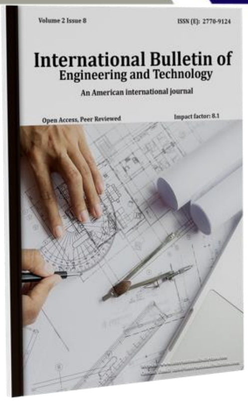

DEVELOPMENT AND ANALYSIS OF METASTRUCTURE BASED MICROSTRIP ANTENNAS

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The rapid advancement of communication technologies is evident across the globe. The emergence and widespread deployment of 5G networks, in particular, have significantly heightened the demand for high-speed and dependable wireless connectivity. These evolving technologies extend beyond mobile devices, playing a critical role in sectors such as industry, healthcare, transportation, smart cities, and many others. Uzbekistan is actively participating in this global wave of digital transformation by developing the foundational infrastructure required for next-generation networks. At the core of these systems lies the antenna, often regarded as their most vital component.

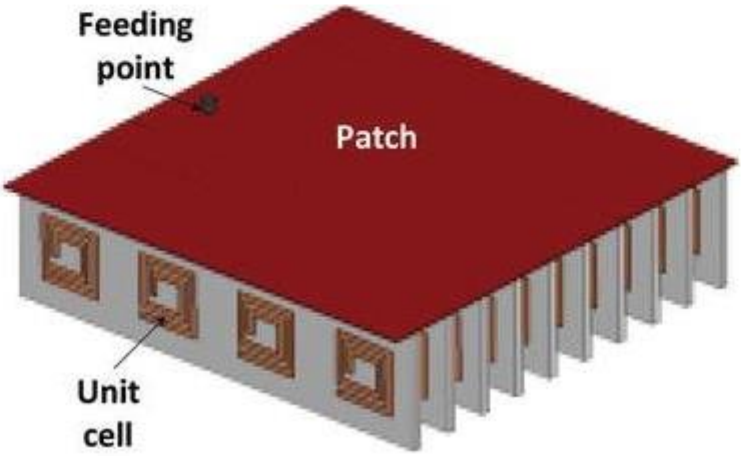


Figure 1. Appearance of the antenna made with the help of metastructures.

To the general public, the term “antenna” often evokes the image of a basic technical device, such as a metal rod or a small plastic element mounted on a television or mobile phone. In actuality, however, an antenna is a highly sophisticated technological component that plays a vital role in enabling information transmission via electromagnetic waves. As a central element of all wireless communication systems, the antenna functions by transforming electrical signals into electromagnetic waves that travel through the air, and vice versa, by capturing incoming electromagnetic waves and converting them back into electrical signals.

The question "What is an antenna?" can be concisely addressed by defining it as a communication component that facilitates the bidirectional conversion between electrical and electromagnetic energy. Nevertheless, this seemingly straightforward definition encompasses a range of intricate physical phenomena, rigorous mathematical modeling, and advanced engineering solutions. In high-frequency communication systems, such as 5G networks, the antenna's quality and compatibility are pivotal to the overall system performance.

Several key parameters determine the effectiveness of an antenna. Among the most critical are:

- Operating frequency range – the specific frequency band for which the antenna is designed;
- Radiation pattern (directionality) – the spatial distribution of the radiated or received energy;
- Gain – a measure of the antenna's capability to direct energy efficiently in a given direction;
- Polarization – the orientation of the electric field of the transmitted or received wave;
- S_{11} or return loss – an indicator of impedance matching, reflecting the extent to which the antenna resists signal reflection.

These parameters form the basis for antenna design, selection, and performance analysis. In 5G systems, which operate in the millimeter-wave spectrum (e.g., around 28 GHz), factors such as antenna geometry, substrate material, and electromagnetic behavior become particularly significant. As a result, microstrip antennas have gained popularity in modern engineering due to their compact size, lightweight nature, structural adaptability, and high-frequency operation capabilities.

The antenna design process is based on theoretical knowledge, which includes geometric shape, frequency range, dielectric constant, substrate thickness, and other important physical parameters. Especially in the production of microstrip (patch) antennas, the precise determination of these parameters and formulas defines the operational efficiency of the antenna.

In the process of designing antenna systems, the central operating frequency plays a crucial role. Particularly for microstrip patch antennas, determining the resonant frequency is one of the essential steps necessary for the antenna's effective operation. The central operating frequency refers to the frequency at which the antenna has the best capability to transmit or receive electromagnetic waves. This frequency usually depends on the geometric dimensions of the antenna, especially the patch length, as well as the properties of the substrate material.

For rectangular microstrip patch antennas, the central operating frequency can be determined using the following formula:

$$f_0 = \frac{c}{2L\sqrt{\varepsilon_e ff}} \tag{1}$$

f_0 - Center operating frequency (Hz)

$c \approx 3\times10^8$ m/s – speed of light

L - Patch length (m)

$\varepsilon_e ff$ - Effective dielectric permittivity

The following formula is used to calculate the length of a patch antenna:

$$L = \frac{c}{2 f_0 \sqrt{\varepsilon_0 ff}} - 2\Delta L \qquad (2)$$

L – patch antenna length (metr)

f_0 – Antenna center operating frequency (Hz)

$\varepsilon_e ff$ – Effective dielectric permittivity of the substrate material

ΔL – Antenna fringing effects (fringing effect), i.e., a size correction arising from the propagation of an electromagnetic field at the edges of the patch.

In the process of determining the length of a patch antenna, it is essential to account for the fringing effect (ΔL), which arises due to the extension of the electromagnetic field beyond the physical boundaries of the patch. This effect is influenced by several factors, including the substrate thickness, the dielectric constant of the material, and the overall geometry of the antenna. Although the correction introduced by the fringing effect is relatively small, it becomes critically important in high-frequency applications, such as 5G systems, where precision is paramount.

Accurate calculation of the patch length L is fundamental to achieving resonance at the target operating frequency. This parameter plays a vital role in optimizing antenna performance and is a key element in the design process. In addition to the length, other parameters must also be carefully evaluated to ensure optimal functionality.

Among these, the patch width W holds particular significance. As a primary geometric dimension, the width directly influences the antenna's radiation characteristics and defines its behavior across a given frequency band. To compute the width effectively, engineers commonly apply the following empirical formula:

$$W = \frac{c}{2 f_0} \cdot \sqrt{\frac{2}{\varepsilon_r + 1}} \qquad (3)$$

Here:

W – Width of the patch antenna (m),

c – speed of light (≈3×10^8 m/s)

f_0 – Central operating frequency (Hz),

ε_r – Dielectric permittivity of the substrate material.

The width calculated using the given formula enables the optimization of key electrical parameters of the antenna, such as radiation efficiency and input impedance. Typically, the width is slightly larger than the length, which plays a crucial role in expanding the radiating surface and enhancing the overall efficiency of the antenna. If the width is improperly chosen, the radiation efficiency may significantly decrease, or the antenna may fail to operate at the desired frequency.

The thickness of the substrate (base material) also has a direct impact on the antenna's characteristics. A thicker substrate can enhance the gain of the antenna; however, it may also increase radiation losses. In microstrip antenna design, the substrate material and its physical and parametric properties play a crucial role. In particular, the substrate thickness h is one of the key geometrical parameters that influence electromagnetic field propagation, control of dielectric properties, and overall performance efficiency.

The substrate thickness h is typically measured in fractions of a millimeter (e.g., from 0.2 mm to 1.6 mm) and directly affects critical parameters such as the effective dielectric permittivity, fringing effects, bandwidth, and radiation efficiency.

A thick substrate (i.e., when h is large) can provide a wider bandwidth for the antenna; however, in such cases, surface waves become more pronounced, which may lead to a reduction in the antenna's directionality and overall efficiency.

Conversely, an excessively thin substrate minimizes fringing effects but can significantly limit the antenna's bandwidth.

In practical design processes, the substrate thickness is typically selected based on the following considerations:

$$h = \frac{c}{2f_0\sqrt{\varepsilon_r}} \tag{4}$$

Using this equation, the substrate thickness is selected within an optimal range based on the operating frequency and dielectric permittivity.

In high-frequency antennas, particularly in 5G systems, accurate selection of the substrate thickness is essential to increase bandwidth and minimize radiation losses. Thus, the substrate thickness h serves as a critical design parameter that directly influences the electromagnetic behavior of the microstrip antenna and plays a key role in defining its overall performance. These formulas serve as the foundation for determining the geometric dimensions of microstrip patch antennas. The resonant behavior of a patch antenna is primarily governed by the relationship between its length L and the central operating frequency f_0. When the antenna operates at resonance, it is capable of receiving or transmitting energy at maximum efficiency.

Therefore, accurate calculation of L is critical to ensuring the optimal performance of the antenna.

The patch width WWW plays a critical role in shaping the antenna's radiation characteristics, including its radiation pattern, directivity, and overall efficiency. Increasing the width typically leads to a broader radiating surface, which can enhance the communication quality by expanding the coverage area. However, as the width increases, it is also important to consider its influence on effective dielectric permittivity and input impedance, as these parameters may be significantly altered.

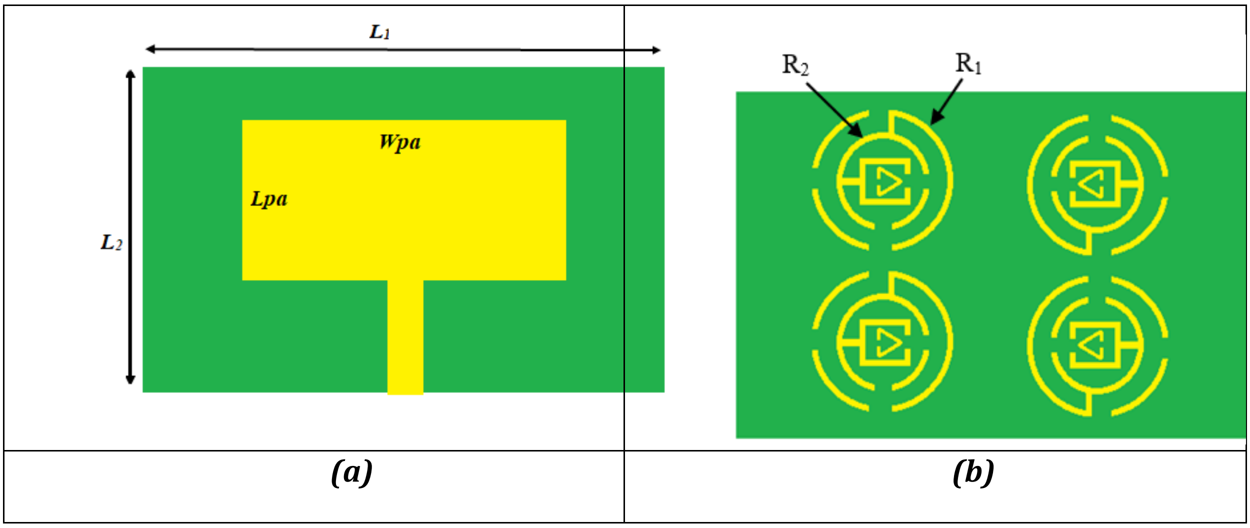
Similarly, the substrate thickness hhh has a profound impact on the propagation of electromagnetic waves through the antenna structure. If the substrate is too thin, the electromagnetic field becomes overly confined, potentially resulting in an extremely narrow operational bandwidth. On the other hand, an excessively thick substrate can increase the excitation of surface waves, thereby reducing the overall efficiency of the antenna. Consequently, the selection of an appropriate substrate thickness requires a careful trade-off to balance performance parameters and achieve optimal antenna functionality.

Table 1 below presents the dimensions of the designed antenna. Here, L_1 and L_2 represent the dimensions of the dielectric substrate, while W_{pa} and L_{pa} denote the width and length of the patch antenna, respectively. R_1 and R_2 correspond to the radii of the metastructures located on the backside of the antenna.

Table 3.1

Parameters	Values
L_1	**16**
L_2	**10**
Wpa	**8.1**
Lpa	**6.3**
R_1	**1.6**
R_2	**1.3**

2. Formation of the Antenna Array and Modeling in CST Studio Suite Environment

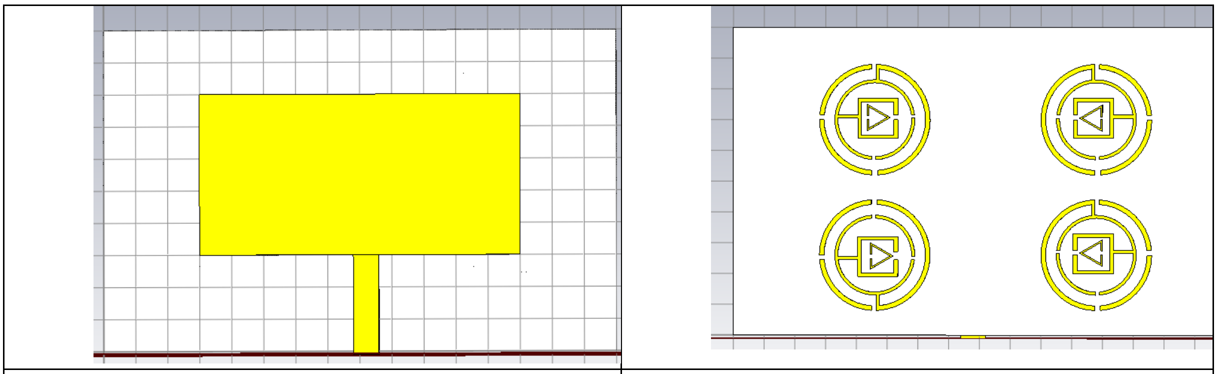


(a) *(b)*

Figure 2. Front (a) and back (b) views of the patch antenna with four metastructures.

The figure above illustrates a patch antenna consisting of four metastructures. In Figure 2(a), the front view of the antenna is shown, where the main patch element and the feed network for signal transmission are visible. Figure 2(b) presents the rear view of the antenna, displaying the arrangement of the metastructures.

Each metastructure is composed of two concentric circles centered on the same axis, along with an inner rectangle and triangle. These metastructures are defined by radii R_1 and R_2, which serve to control the propagation of electromagnetic waves. Through the incorporation of these metastructures, both the operating frequency and overall efficiency of the antenna have been improved.



(a) *(b)*

Figure 3. Front (a) and rear (b) views of the simulated model of the antenna with four metastructures.

During the simulation process, the geometrical dimensions of the patch antenna and metastructures were selected based on the values provided in the table. The primary objective of this study was to analyze the performance efficiency of the antenna and investigate its key characteristics. To achieve this, fundamental parameters such as the $\mathbf{S_{11}}$ parameter, radiation pattern, and return loss were analyzed.

3. Results and Analysis

The results obtained for the S-parameter during the simulation are presented in Figure 4. The $\mathbf{S_{11}}$ parameter is defined as the reflection coefficient for the antenna, indicating how much of the input signal is reflected back due to impedance mismatch. A lower S_{11} value signifies higher antenna efficiency, as it implies reduced energy loss and improved power transfer.

Based on the simulation results, it can be concluded that the incorporation of metastructures enables an expansion of the antenna's effective operating frequency range. The metastructures contribute to the optimization of the antenna design, enhancing its performance at higher frequencies and broadening its operational bandwidth. This, in turn, provides a significant advantage in the development of more efficient antenna systems for technologically advanced telecommunication applications.

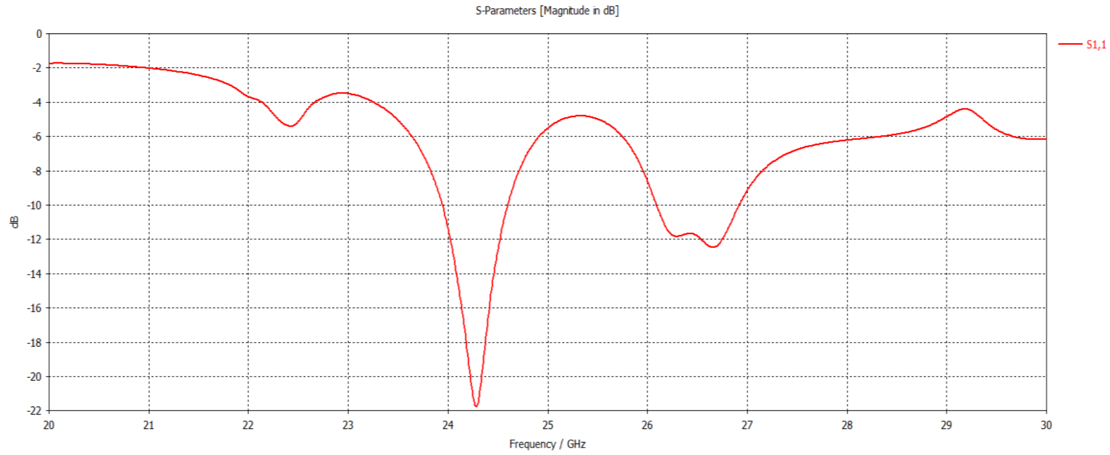


Figure 3.4. S-Parameter Result of the Antenna

The graph above illustrates the magnitude of the S_{11} parameter (in dB) for the patch antenna across the 20–30 GHz frequency range. The analysis of the graph indicates that the antenna exhibits optimal performance within the 24–25 GHz range, where the S_{11} parameter drops to approximately –22 dB, signifying excellent impedance matching.

At frequencies below 22 GHz and above 28 GHz, the impedance matching deteriorates significantly. The observed fluctuations in the graph represent the resonant behaviors of the antenna at specific frequencies. These results demonstrate that the proposed antenna design operates effectively in the millimeter-wave band, particularly within the 24–25 GHz range, which is highly relevant for 5G applications.

The operational bandwidth and matching characteristics of the antenna are critical for practical implementations, and the graph clearly identifies the frequency ranges where the antenna performs most efficiently.

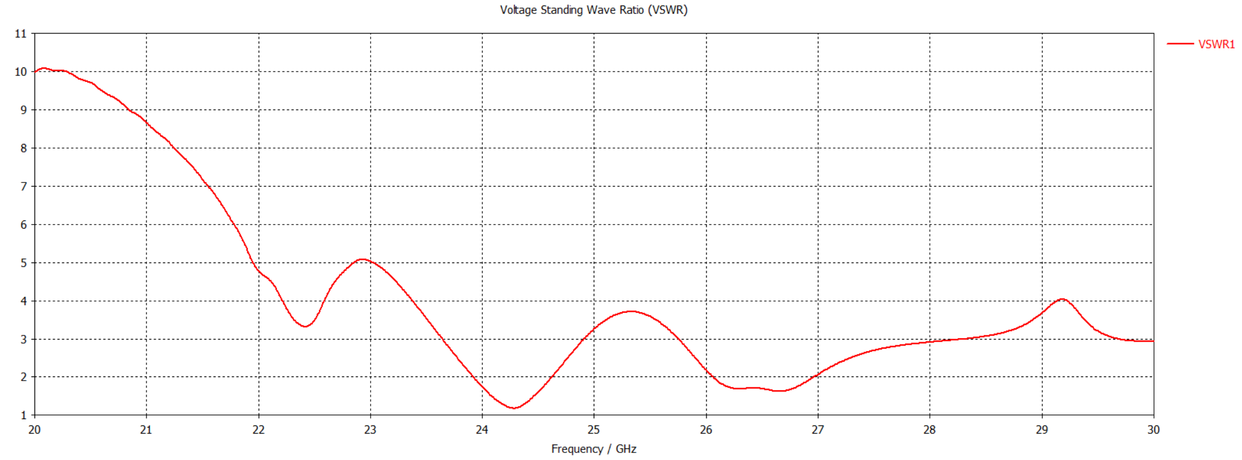


Figure 5. Voltage Standing Wave Ratio (VSWR) Result of the Antenna

The graph above illustrates the Voltage Standing Wave Ratio (VSWR) characteristics of the patch antenna within the 20–30 GHz frequency range. Analysis of the graph reveals that the antenna demonstrates optimal performance in the 24–25 GHz range, where the VSWR drops to approximately 1.5. Within the broader 23–27 GHz band, the VSWR remains below 3, indicating the antenna’s capability for wideband operation.

A minimum VSWR value of 1.5 is observed near 24 GHz, representing the primary resonance frequency. Additional secondary resonances occur around 25.5 GHz and 27 GHz. At frequencies below 22 GHz and above 28 GHz, the VSWR rises sharply, indicating a decline in the antenna's operational efficiency.

These results demonstrate that the proposed antenna is well-suited for millimeter-wave (mmWave) applications, particularly within the 24–27 GHz band used in 5G communication systems. The low VSWR values confirm the antenna’s efficient energy transmission capability, making it a reliable candidate for practical implementation in broadband wireless devices.

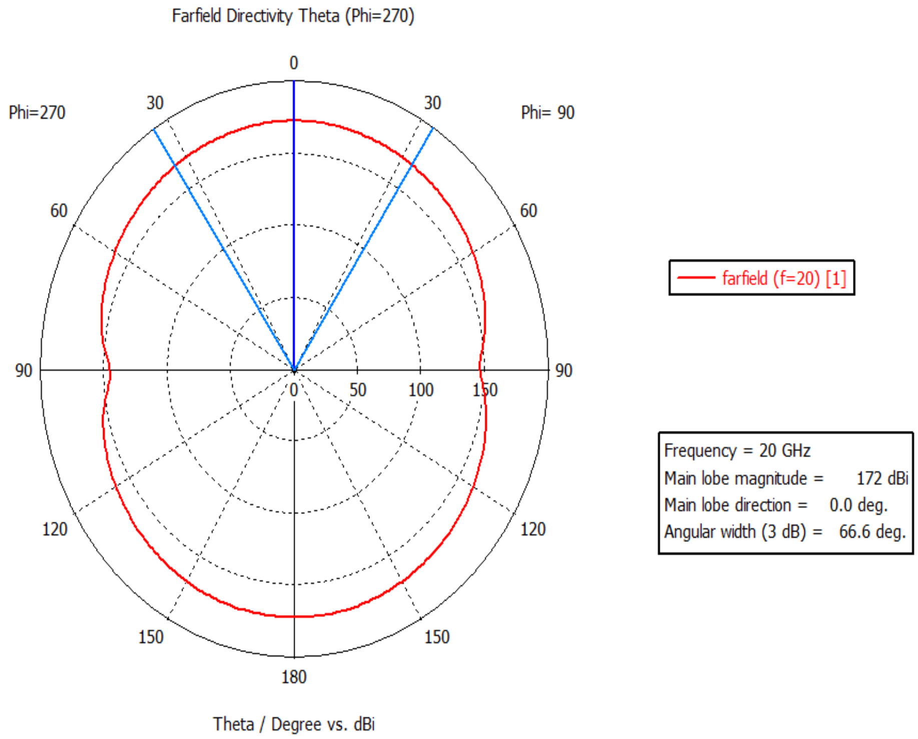


Figure 6. Radiation Pattern Parameters of the Antenna at 20 GHz

This figure presents the far-field radiation pattern of the antenna operating at 20 GHz, displayed as a polar diagram in the Theta angle along the Phi = 270° plane. The antenna's main lobe is directed at 0°, where the maximum radiation intensity reaches approximately 172 dBi. The 3 dB beamwidth is measured to be 66.6°, indicating a relatively wide radiation pattern.

The 20 GHz frequency falls within the millimeter-wave (mmWave) band and is commonly utilized in applications such as high-speed data transmission, 5G networks, radar systems, and satellite communications. As shown in the diagram, the antenna exhibits strong forward radiation (0°) and significantly reduced back radiation (180°), which is favorable for directional communication systems.

Conclusion

In this study, a metastructure-based microstrip patch antenna operating in the 20–30 GHz frequency range was modeled and its electromagnetic performance was analyzed using CST Studio Suite. The geometric parameters (L, W, h) and the design of the metastructures were carefully selected to enhance the antenna's performance. Simulation results demonstrate that the antenna operates optimally within the 24–25 GHz frequency band.

The S11 parameter reaches approximately −22 dB in the target band, indicating excellent impedance matching and minimal reflection losses. The Voltage Standing Wave Ratio (VSWR) remains around 1.5, confirming wideband characteristics. Far-field radiation pattern analysis shows that the antenna exhibits a main lobe directed at 0°, with a 3 dB beamwidth of 66.6°, which supports directional communication applications. Furthermore, the inclusion of concentric metastructures effectively manages the propagation of electromagnetic waves and contributes to the extension of the antenna's operational bandwidth. This design approach demonstrates significant potential for use in advanced 5G systems, radar technologies, and satellite communications. Overall, the proposed antenna design offers high efficiency, wideband capability, and directional radiation properties suitable for millimeter-wave (mmWave) applications, making it a technically sound and practical solution for next-generation telecommunication systems

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