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Intelligent RS Antenna Array Systems for Modern Communication Networks

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Abstract:
5G cellular networks will require providing significantly higher system capacity and user data rates. This potential growth along with today's shortage of spectrum increases the need for new frequency spectrum. The new millimeter wave spectrum is emerging as a suitable candidate with a large amount of available bandwidth (around 60 GHz). The new spectrum places a new requirement for single element antenna and array design. This paper addresses the issues of mm-wave antenna design and the problems that designers may face during the designing process. The proposed antenna has a resonating frequency of 26 GHz and 2 GHz bandwidth. Beam squint problem is also analysis in this paper. The results showed that the gain of the mm-wave antenna array becomes a function of frequency which significantly reduces the performance of mm-wave communication system. Millimeter wave (mmWave) wireless technology has become a part of human life for high-speed and secure data transmission. This paper proposed a square microstrip patch antenna at 26GHz resonant frequency for mmWave wireless communication. The antenna consists of one square radiating element. The proposed antenna has been designed and investigated on Rogers RO 3003 lossy substrate with relative permittivity 3 using Electromagnetic Simulation Software CST Microwave Studio. The result of this paper shows minimal return loss −19.34 dB, gain 6.97dBi, and bandwidth 2GHz at 26 GHz resonant frequency. The element is converted to a uniform linear array of 8 elements the proposed array increases the gain to 16dBi with high radiation efficiency.

Keywords: AI, ML, RIS, antenna, communication, 6G, mmWave, 5G.

I. INTRODUCTION

Intelligent Reconfigurable Surface (IRS) antenna array systems are a new technology that might change the way we communicate. As the need for faster data rates, better coverage, and reduced energy use develops, conventional wireless communication systems start to run into problems. IRS antenna arrays are a new way to improve wireless communication systems by using the idea of reconfigurable surfaces. The next standard for 6G networks will include more complex Key performance indicators [1] and enable a wider range of new use cases. Sixth generation (6G) networks require a new way to transmit and receive data, as well as to sense, communicate, process, and, most critically, operate together in a programmable environment [2]. Over the last several decades, a number of technological advancements have moved mobile communications forward [3]. Designers have been making high-efficiency transceivers for years to make up for signal loss at the ends of a radio channel. Now, as they get ready for 5G technology, they are starting to realize that they have hit the realistic limits of transceiver efficiency [4]. The fifth generation of communication systems must fulfill a lot of criteria, such very high data rates, great mobility, and low latency, which are not accessible in older networks [5]. Tele education, virtual reality workplaces, social networking, telemedicine, e-governance, e-commerce, and many more new applications that use a lot of data will need these standards [6]. For such a broad variety of uses, a high-gain antenna array is quite useful [7]. To meet the huge demand for high-volume data transmission over the communication channel, multiple-input multiple-output (5G) antennas are used. This is because they are immune to multipath fading, use less power than the data rate, and allow for quick data use [8].

In 5G networks, allocating resources might be a difficult optimization issue that needs efficient methods to handle it [9]. One of the most common methods is distributed optimization, which is when many nodes in the network work together to solve the optimization issue [10]. The Alternating Direction Method of Multipliers (ADMM) [11] is one of these algorithms. ADMM is a distributed optimization technique that works effectively for issues in communication networks where resources need to be shared [12]. It is especially helpful when the optimization issue can be broken down into smaller parts [13]. ADMM may be used to provide various users in a 5G network radio resources like bandwidth and power [14]. This challenge may be framed as a constrained optimization problem, with the goal of maximizing network performance while adhering to resource limitations [15]. The ADMM algorithm has these steps: Break the issue down into smaller parts, each of which may be tackled by a different node in the network [16]. Each node works on its own subproblem and then tells its neighbors what it found [17]. The nodes next to each other share information and adjust their solutions as needed [18]. The procedure continues until it converges [19]. ADMM has proven effective in addressing resource allocation challenges in 5G networks, ensuring minimal communication overhead and rapid convergence [20]. Additionally, other distributed optimization algorithms, including the primal-dual gradient method and the distributed subgradient method, are applicable for resource allocation in 5G networks [21].

II. Methodology and Details

Using a virtual simulation environment to model and improve how the IRS antenna array works is what the numerical technique does. CST MWS is a popular electromagnetic simulation tool that can be used to accurately analyze and build complicated structures. This makes it a good choice for IRS applications. Using CST MWS, the design philosophy for Intelligent IRS entails creating a virtual simulation environment to model, optimize, and study how the IRS antenna array works. The design theory's goal is to use accurate electromagnetic simulations to enable exact wavefront manipulation, adaptive beamforming, energy efficiency, and interoperability with current communication networks. Before putting Intelligent IRS systems into use, CST MWS is a strong tool for creating and testing them. Figure 1 shows the suggested technique in greater detail. This flowchart shows how to create Intelligent IRS antenna array systems that use CST MWS for numerical simulations. The first step is to define the geometry and material parameters. The second step is to simulate how electromagnetic waves move through the material. The use of reconfigurable element models and smart control algorithms makes it possible to simulate wavefront modification, beamforming, channel estimation, and feedback. The approach improves the IRS's performance repeatedly and tests how well it functions with communication networks, energy efficiency, and security and privacy aspects before finishing the design.

The flowchart outlines a mmWave-oriented IRS array design workflow, consisting of two parallel paths: an IRS path to optimize characteristics for mmWave bands, and an array path to optimize the array's performance for mmWave operation and match it to intended applications. Each path includes a decision point to verify if the optimization meets requirements. If successful, the process moves to combine the proposed IRS array, and a final decision checks if the combined design provides excellent enhancements. The figure features a clean blue-and-white theme with clear rectangular process boxes and diamond-shaped decision nodes. The flowchart in Fig. 1 illustrates a workflow for designing an IRS array focused on mmWave technology.

- ✓ The process begins with two parallel pathways: one for the initial IRS design and another for the initial array design.
- ✓ Optimize the IRS characteristics for mmWave bands, followed by testing the IRS in an array configuration.
- ✓ Optimize the array's performance for mmWave operation and align it with intended applications.
- ✓ Each path contains a decision point to assess whether optimization satisfies the requirements.
- ✓ Upon the successful completion of both paths, the process advances to integrate the proposed IRS array.
- ✓ A conclusive assessment evaluates the extent to which the integrated design offers significant improvements. If affirmative, the process concludes; if not, additional optimization is required.
- ✓ The figure presents a blue-and-white color scheme, incorporating rectangular process boxes and diamond-shaped decision nodes to enhance readability and ensure a professional appearance.

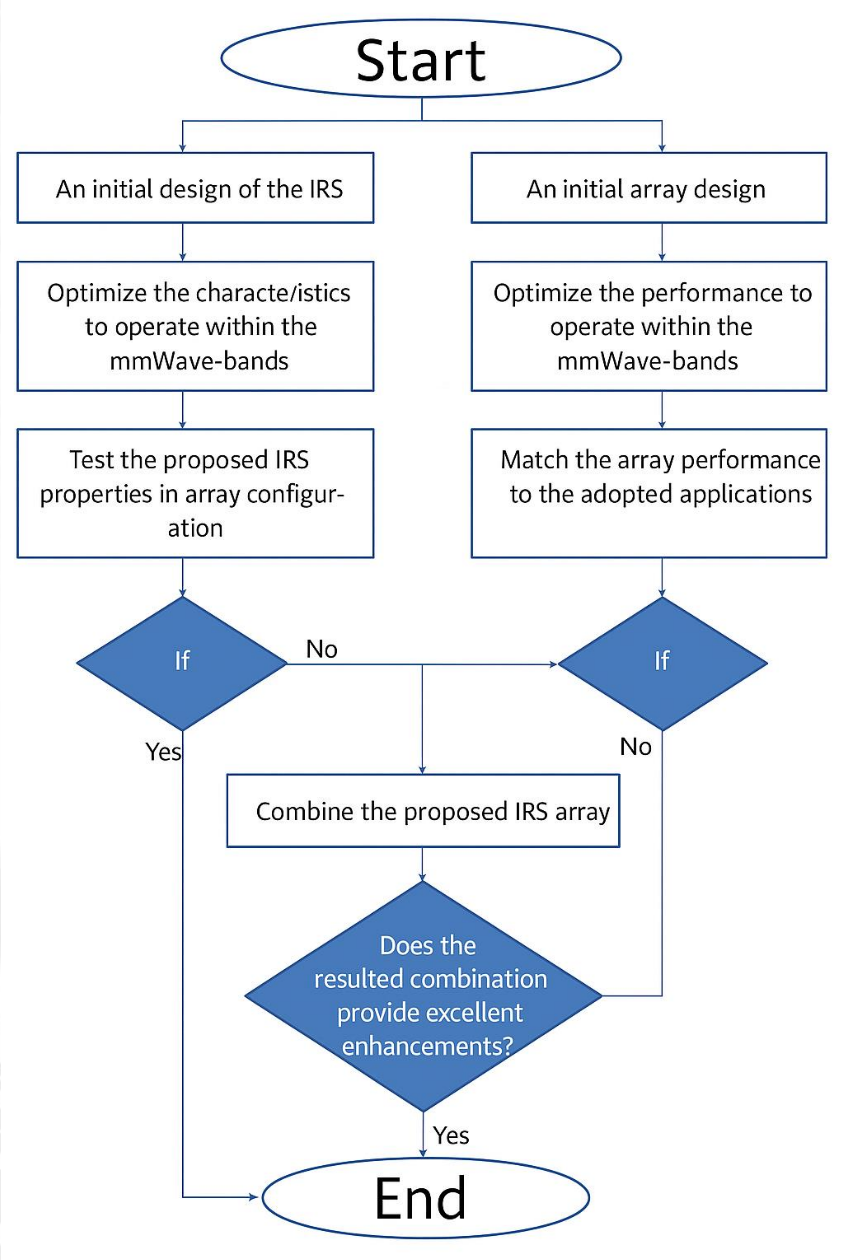


Fig. 1; Methodology and details.

III. IRS Design Geometrical Details

The proposed IRS design is as Sikrpency quadrature flower-based bowtie unit cells. The proposed unit cell occupies a size of 5mm2 to provide a frequency resonance at 26GHz with a bandwidth of 2GHz bandwidth. The individual unit cell provides a gain of 4dBi. The proposed unit cell is arranged inside a 2D array of 100×100 configuration. Also, the resulted array performance can be controlled using varactor diodes that realize a phase shit progressive to maintain the ability of beam forming and steering to the desired location. In such geometry the proposed unit cell is designed as Sikrpency quadrature flower bowtie [22], see Fig. 2, to ensure bandwidth enhancement and gain improvements. The proposed structure based on a Sierpinski fractal antenna design is implemented in MATLAB. In this design, we have to keep in mind that this code is a basic example and might require further refinement for specific applications.

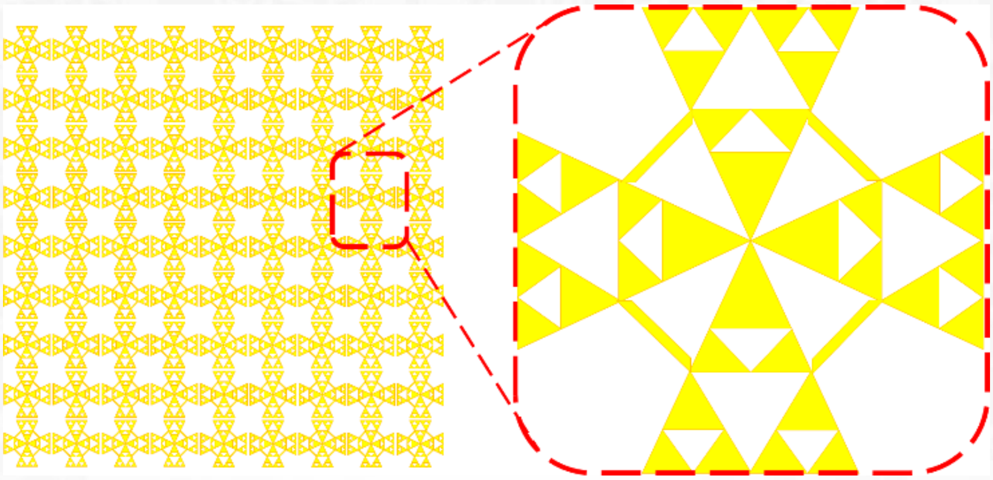


Fig. 2: IRS layer based on array configuration from CST MWS.

A- Single element

The single element is designed to operate at 26GHz frequency resonance. The geometry of the proposed single antenna patch element is shown in Fig. 3(a) and Fig. 3(b). The proposed patch design is mounted on 1mm substrate thickness from the Rogers family RO 3003 lossy with dielectric constant of 3. The rear board of the suggested antenna is fully supported by a ground plane with dimensions of (4×4 mm2) that is expected copper material with 0.035mm wideness. The antenna patch occupies an area of 5mm2 from copper with thickness 0.035 mm. The geometrical parameters of the proposed antenna are listed in Table I. The antenna element is exited with a co-axial prob feed. The feed location is fixed to the x-axis of the antenna at 0.45mm from the patch edge. The co-axial prob input impedance is fixed to 50 ohms at the frequency-band of notice. The sizes of the antenna element are calculated analytically from the fallowing equations [23].

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}[1 + \frac{12h}{w}]^{-1/2} \quad (1)$$

$$\Delta L = h\ x\ 0.421 \frac{(\epsilon_{reff}+0.3)(\frac{w}{h}+0.264)}{(\epsilon_{reff}-0.258)(\frac{w}{h}+0.8)} \quad (2)$$

Where ϵ_r is the dielectric continuous, w is the thickness of the radiating part, and h is the height of the substrate. The actual length of microstrip patch is stated as [24].

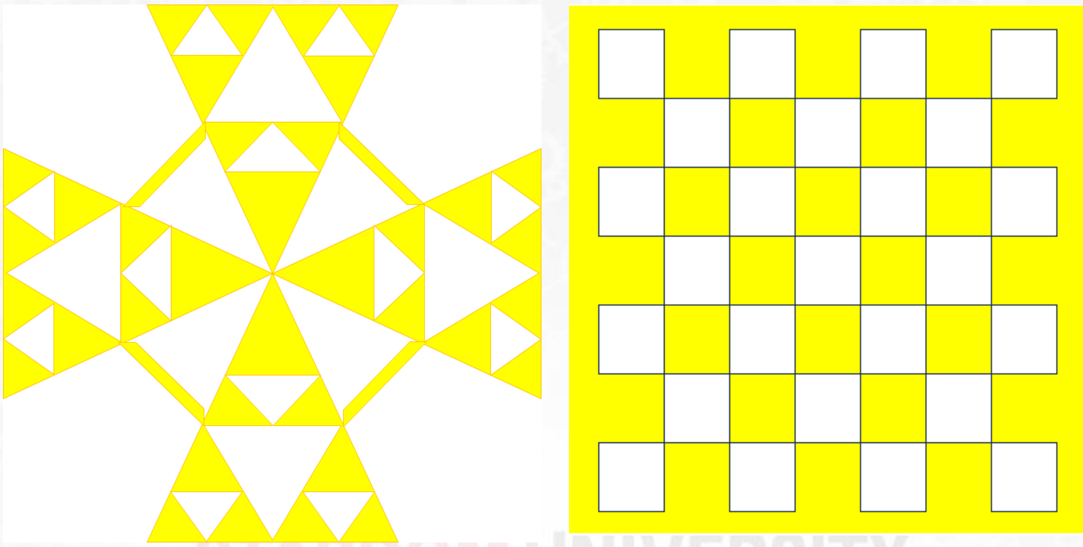
$$L = L_{eff} - 2\Delta L \quad (3)$$

Finally, the effective length and width of the patch are calculated as [25]

$$L_{eff} = \frac{v0}{2f_r\sqrt{\epsilon_{reff}}} \quad (4)$$

$$W = \frac{vo}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \quad (5)$$

These limits are used as initials to behavior a parametric study based on the numerical analysis to be enhanced to achieve the wanted presentation. All these dimensions values have a remarkable effect on the antenna performance.



(a) (b)

Fig. 3 Unit cell design from CST MWS: (a) Front view and (b) Back view.

Table I: Geometrical parameters of the antenna.

Parameter	Value (mm)
Substrate thickness	1
Substrate length	6
Substrate width	6
Patch length	5
Patch width	5
Patch thickness	0.035
Ground thickness	0.035

B- Array configuration

Antenna array technology is one of the most alluring applications since modern communication systems necessitate steerable antenna systems, high gain arrays, and effectively increased radiation patterns. The proposed antenna element, shown in Fig. 4, reaches a peak gain of 6.97dBi at 26 GHz in our design. Due to propagation restrictions, such gain is insufficient for mm-wave technology. As a result, a 1D array structure is suggested to get around the antenna gain limitation [26]. The eight elements that make up the proposed antenna element are spaced out randomly along the x-axis. The chosen distance between the elements is (/2). Fig. 4 depicts the array's geometry [27]. To determine the overall pattern and gain, the findings of the antenna elements were merged [28].

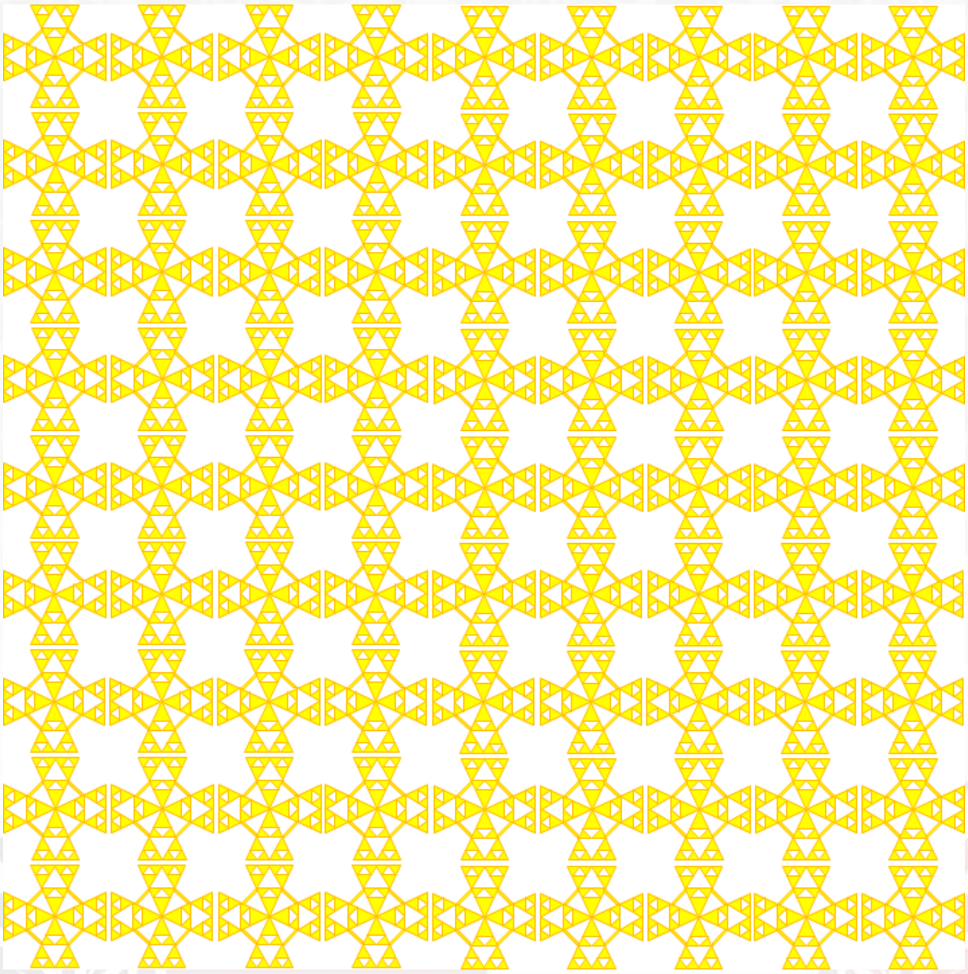


Fig. 4: The resulted IRS array based on the proposed unit cell from CST MWS.

VI. Results Discussion

A. Single IRS Results

The S11 (Reflection Diagram) curve of the single element is shown in Fig. 5. The solver was set to show only the points below -10dB which represent the bandwidth. The parameters are calculated according to the channel performance that was discussed previously.

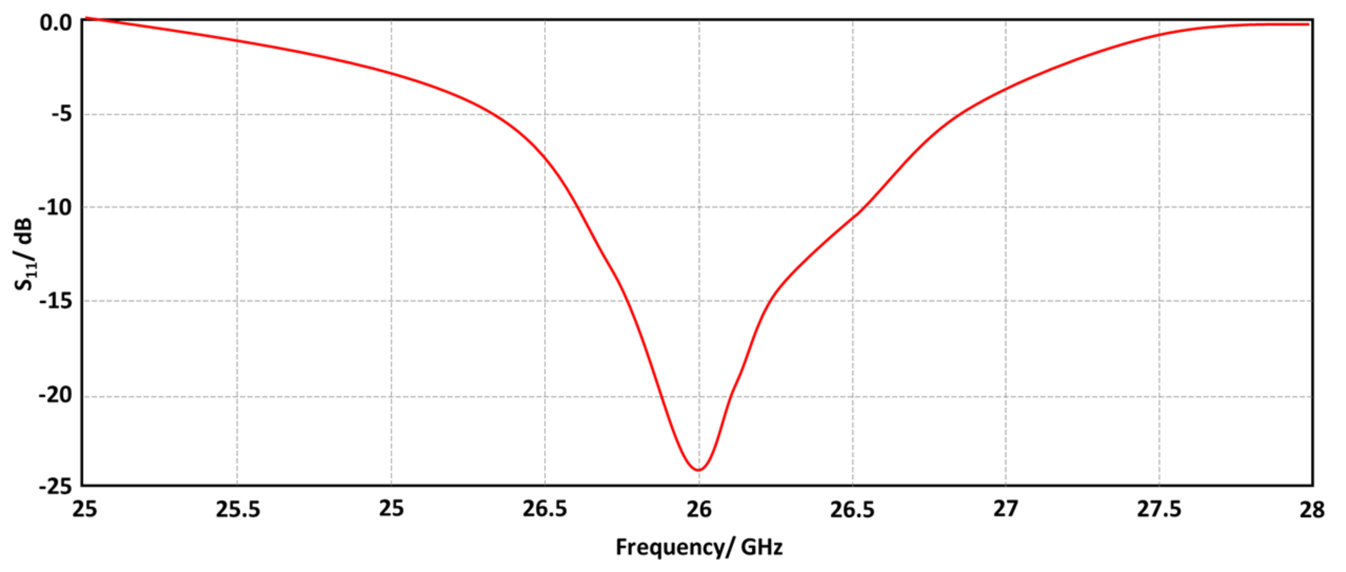


Fig. 5; S11 curve of single element from CSTMWS.

It can be seen that the bandwidth ranges from 25 GHz to 27 GHz with center frequency 26 GHz. The Farfield radiation pattern of the single element is demonstrated in Fig. 6.

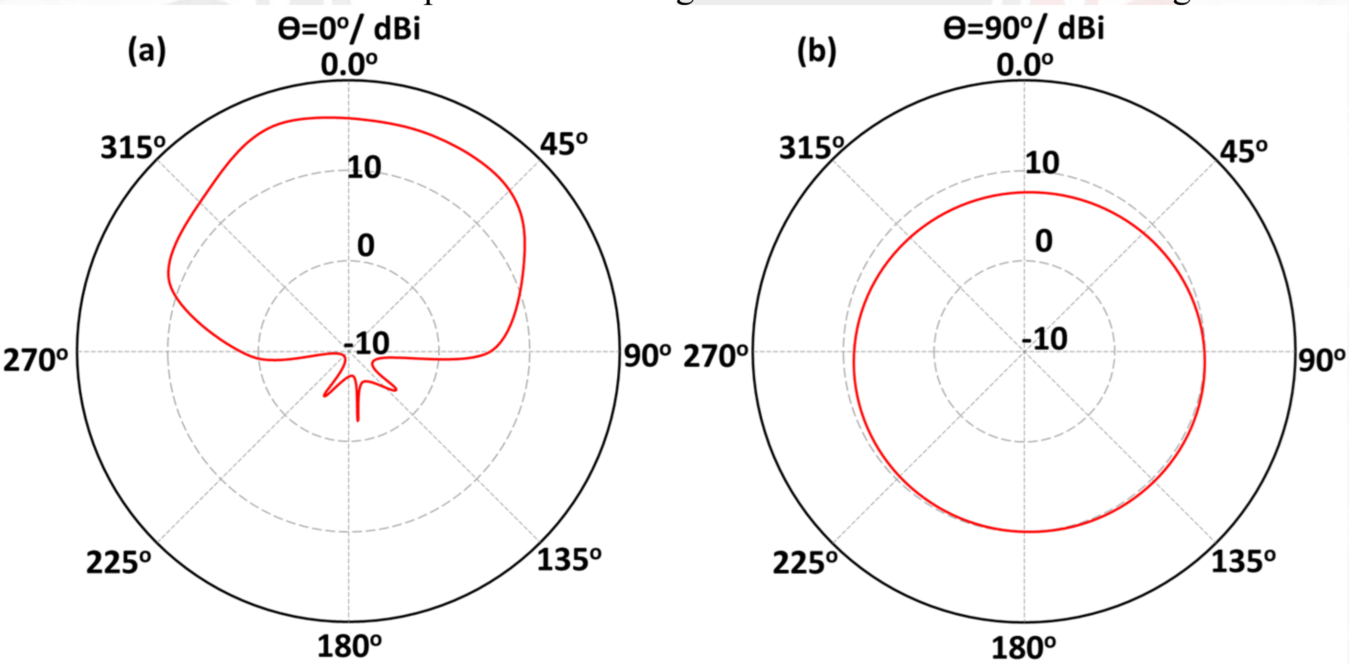


Fig. 6; Farfield pattern 2D at f=26 from CST MWS.

The main lob direction at the 0.0 degree. And the main lob magnitude is (6.94dBi) which represents the gain (IEEE). The proposed antenna gain variation across frequencies are shown in Fig. 7.

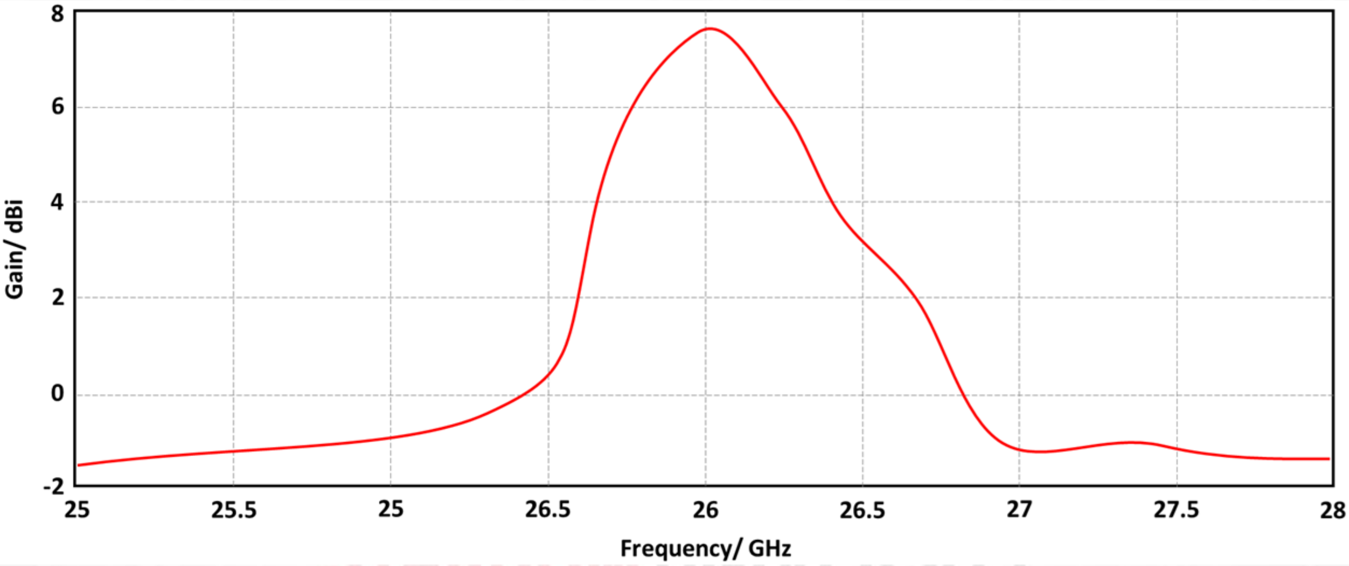


Fig. 7 gain variation over frequencies from CST MWS.

4.1Array Results

The proposed array is simulated element by element and then the results were combined to show the total results. The array Farfield radiation pattern at 26GHz is shown in Fig. 8(a). The resulting pattern is very directive with gain 41.6dBi and since the phase shift was set to zero it can be seen that the main lob direction is still at zero as shown in Fig. 8(b).

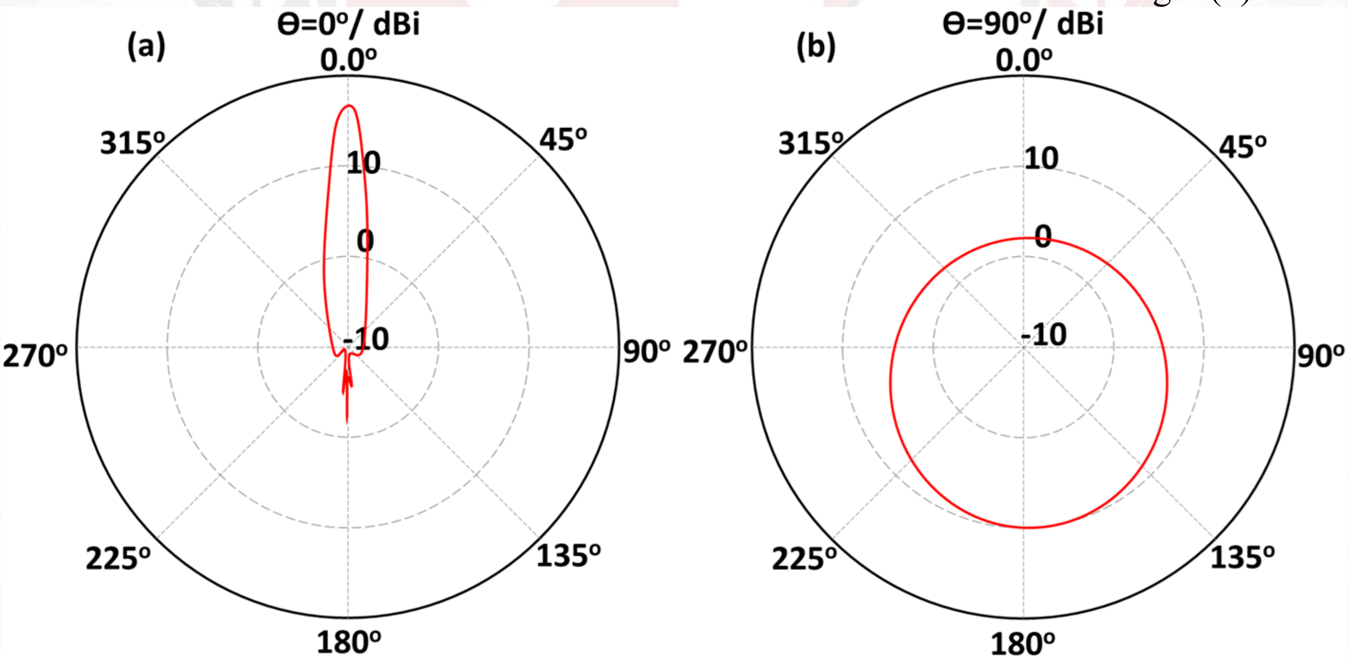


Fig. 8: Antenna array Farfield at f=26 GHz from CST MWS.

To arrive to the optimal antenna design, the obtained results are validated numerically using CST and HFSS. The performance of the proposed antenna in terms of S11 and gain spectra are compared to those obtained from both software packages. It is found that the results obtained from the software packages used to provide excellent agreements. The results obtained from the two software packages are presented in Fig. 9. The proposed antenna shows a gain of 22dBi over the frequency band between 18GHz to 40GHz with excellent matching below -10dB. It is found from the measurements that the effects of rain between

20GHz to30GHz can be reduced when the antenna terminal can change the frequency carrier smoothly during the operation; that will be discussed later. Such frequency bandwidth is achieved by introducing slot array on the antenna cone that matches the electro-magnetic radiation ultimately to the free space impedance with excellent suppressing to the surface waves that reduces the frequency bandwidth [18]. Nevertheless, the antenna directivity is increased rapidly with introducing the reflector that suppresses the side lobes significantly [29].

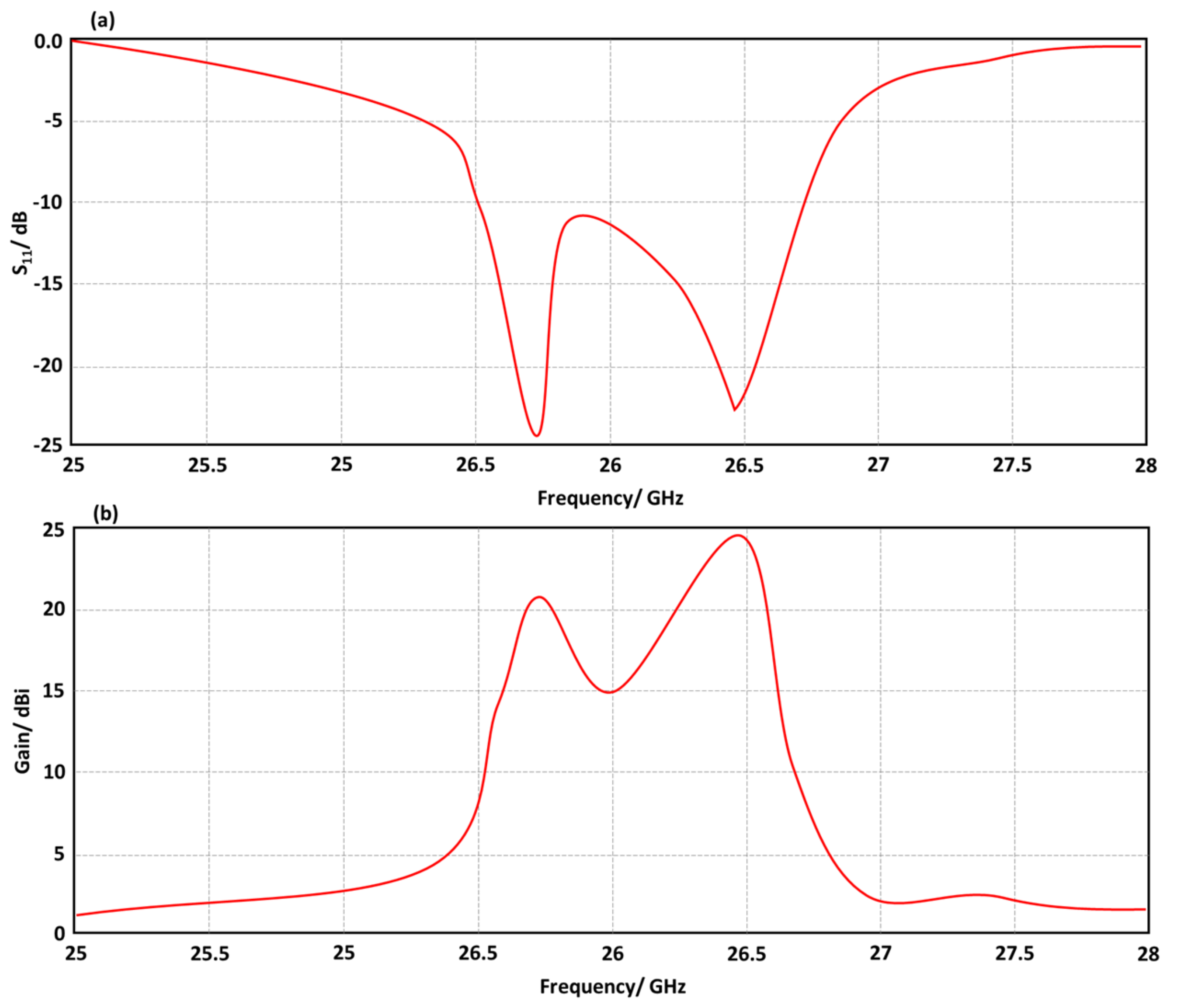


Fig. 9: The evaluated antenna performance based on S11 and gain spectra from CST MWS.

The proposed antenna provides an excellent gain bandwidth product due to the tangential traveling phenomena that was explained in [3]. The antenna radiation patterns and current distributions are presented in Fig. 10. The antenna radiation patterns at 26GHz and 28.5GHz are evaluated in 3D form. The antenna provides end fire radiation pattern due the effects of antenna IRS that realizes high normalization in the E-plane as explored in [1].

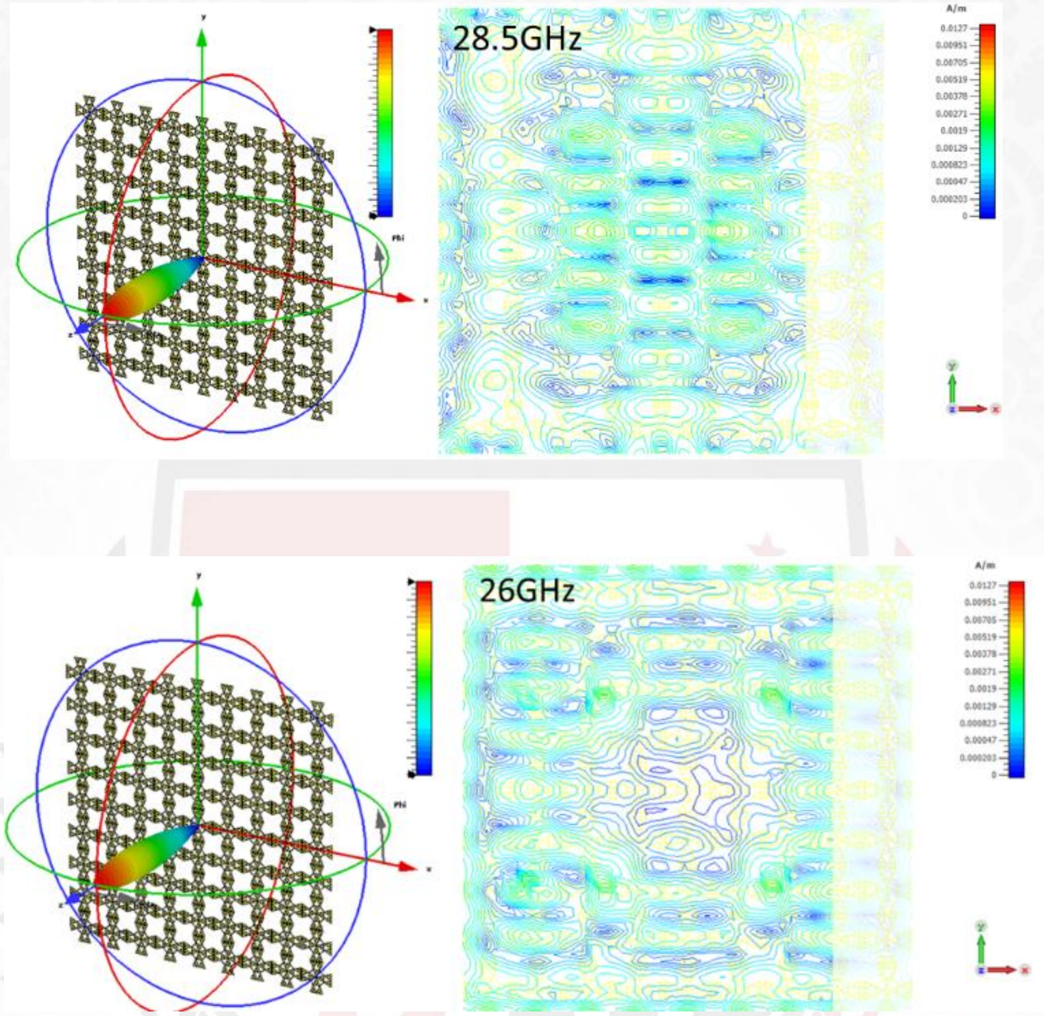


Fig. 10. Attenuation using 5G prediction models from CST MWS for (a) lower operating frequency of 26GHz (b) higher operating frequency of 28.5GHz.

V. Conclusion

This work presents a design for a fractal IRS unit cell element intended for 5G mm-wave communication systems. The proposed element is configured as a square patch with an area of 5 mm^2. The proposed unit cell encompasses a bandwidth of 2 GHz centered at 26 GHz, achieving a gain of 7 dBi. The singular design is subsequently transformed into a 10×10 array of identical elements along the x-y plane. The array enhances the gain to 26 dBi while maintaining high radiation efficiency. The results indicate that the proposed IRS array is a viable candidate for 5G, characterized by its straightforward design, compact size relative to alternative designs, and commendable performance. The design of IRS operating in the mm-wave frequency range has garnered significant interest among researchers. High frequencies necessitate small-sized antennas, which complicates the incorporation of slots and shapes, as well as the fabrication process. The short wavelength of millimeter waves facilitates signal penetration through walls, leading to attenuation in the absence of line-of-sight communication. Massive 5G transmitters and receivers are employed to address the challenges associated with mm-waves; however, the maintenance of IRS arrays operating within these frequency ranges presents additional difficulties.

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