Design and Simulation of a High Performance 5G mm-Wave MIMO Antenna Array for Mobile Applications

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Abstract. *This paper presents the design and simulation of an efficient multiple input multiple output (MIMO) antenna array for 5G millimeter-wave (mm-wave) mobile applications. With a dielectric constant of 2.2 and a loss tangent of 0.0009, the substrate employed is a Rogers RT5880 that is 0.254 mm thick. The 37 GHz frequency spectrum, reserved for millimeter-wave mobile applications for 5G, is covered by the proposed MIMO antenna arrays. The single antenna element has a gain of 6.44 dBi, which is increased to 7.89 dBi with a two-element array configuration and 10.88 dBi with a four-element array configuration. The proposed MIMO antenna array performance metrics—including reflection coefficient, gain—are seen and discovered to be below the accepted threshold. A power divider is incorporated into the array structure and is designed to ensure that every antenna element receives the same amount of power in order to produce good radiation characteristics. In the desired operating frequency band, it is noticed that more than 85 % of the proposed MIMO antenna array's radiation efficiency is achieved. According to simulation findings, the proposed design may be potentially feasible for mobile applications using millimeter waves in the 5G network.*

Keywords: MIMO, mm-Wave, Patch Antenna, 5G, CST Software

1. Introduction

Since its inception, wireless communication has drawn people's interest because of its affordability, viability, mobility, flexibility, and numerous other alluring aspects. Research and development (R&D) in the field of communication systems has been expanding at an enormous rate, particularly in the previous three decades, because the advancement of communication systems is essential to the advancement of human civilization.

Wireless communication is impossible without the use of an antenna. The dipole, monopole, whip, and helix antennas were the first types of external antennas used in telephones. These antennas had detrimental impacts on the user's head and provided poor performance [1]. Due to superior performance, internal antenna systems like microstrip antenna found an enormous increase in use in mobile phones after being introduced when it comes to printed circuit board fabrication, size, and manufacturing costs. Therefore, the telecommunications sector as well as researchers in this field had been interested in microstrip antennas. This topic is hence strongly related to microstrip antenna. The need for increased telecommunication network capacity has been steadily growing in the meantime. In order to meet these demands, the telecommunications sector has developed new generations of wireless communication standards nearly every ten years. Wireless communication will enter a new era thanks to 5G, as will device-to-device (D2D) communication and, most excitingly, the Internet of Things. A number of enabling technologies, including mm-wave system, multiple radio access technology (Multi-RAT), advanced multiple input multiple output (MIMO), an advanced network, and advanced small cell, will be introduced by the telecommunications sector to solve these features [2]. There is no other option except to choose higher frequency bands in order to enable 5G to offer the features mentioned previously with higher antenna gain.The most common and effective method for creating high-gain antennas is to create an array of antennas where the gain grows according to the number of elements in the array. However because it would occupy more space, it is impossible to raise the array's element count intentionally. It increases interior space in areas of the phone when space is limited. As a result, there is a trade-off between the array antenna's gain and the number of elements. However, Using high-quality materials is crucial to achieving optimal functionality in any communication instrument, but it's much more crucial in one as demanding as 5G communications. As previously stated, 5G functions with the current 4G network giving exceptional data aptitudes, unrestricted call capabilities, and information dissemination that is influenced by the most pertinent materials for the particular request at higher frequencies and spectrums. A further obligation that needs to be taken into consideration in order to get good outcomes while safeguarding signal reliability and preventing signal losses is coming up with creative processing routes. Flexibility connected to implantable and wearable features can accelerate this evolution and provide further advantages [3].The selection and growth of the antenna is an important factor in communication, and it is regulated by the incidence range, transmission power, and/or atmosphere [4].

2. Related Works

For the Internet of Things, the 5G wireless network, and other advanced spectrum-based applications, the FCC has recommended using the 37 GHz MmWave spectrum [5]. At the operational frequency of 37 GHz for 5G technology, various researchers have been working. For 5G mobile applications, a H slot and inverted T slot antenna has been proposed for 37 GHz with minimal return loss -43.05 dB, gain 8.18 dB [6]. In [7] a single element modified Pharaonic Ankh-Key antenna, with a peak gain of 10.2 dBi, is designed to complement contemporary technologies and improve the use of 5G applications. Antenna specialists have demonstrated a heightened level of interest in developing antenna designs for fifth generation technology, particularly within the frequency range of 37-40 GHz [8]. The frequency range under consideration exhibits minimal atmospheric losses [9], hence facilitating the achievement of enhanced bandwidth provision and data speeds, a key objective of future 5G communication systems relying on millimeter-wave technology. In their study, the researchers introduce an antenna that operates inside the particular 5G frequency range of 38 GHz, as documented in reference [10]. One of the primary objectives of contemporary communication technology is to address the issue of atmospheric attenuations encountered during mm-wave transmission. To tackle this obstacle, a proposed solution involves employing a single feed antenna arrangement, without the use of an array or MIMO setup. The antenna's highest gain is stated to be 10 dB, as referenced in [11]. This paper introduces a multi-element array antenna working within the frequency band of 38 GHz, which consists of four individual elements. The capacity of the given design is limited due to its single feed, despite its gain exceeding 12 dB, which is deemed adequate for 5G mobile communications. The frequency range of 37-40 GHz, commonly referred to as the mm-wave band, has been designated for the implementation of 5G technology. In a previous study referenced as [12], an antenna design capable of operating within this frequency range was presented. The utilization of an array design enhances the gain by a maximum of 12 dB. Nevertheless, the absence of a MIMO setup in the single feed restricts the capacity for data processing. The antenna depicted in reference [13] possesses dimensions of 8 mm by 8 mm and is capable of operating throughout the frequency range of 37.1-38.1 GHz. However, it should be noted that this antenna does not incorporate any gain enhancement techniques or utilize a multiple-input multiple-output (MIMO) strategy to mitigate the effects of atmospheric attenuation.

This work presents an efficient MIMO antenna arrays with two and four slotted E-shaped elements for 5G communication systems. The antenna operates at the 37 GHz band and utilizes microstrip technology. The proposed antenna performance matrices such as reflection coefficient, antenna gain ensure that it will be a best fit for mm-wave mobile applications. Furthermore we also compare our results with existing MIMO antenna array which shows a significant improvement in terms of performacne.

3. Materials and Methods

3.1. Antenna Design

1) Single Element

A flow chart representing the entire design process is shown in Figure 1. First, a single element rectangular microstrip patch antenna (MPA) operating in the 37 GHz band is constructed using equation-based antenna design, which is based on the fundamental equations for creating MPA. After that, the construction is modelled to see if the results show that the antenna satisfies the requirements. Figure 1 depicts the front side of the suggested single element antenna. Figure 2 illustrates the antenna element design utilizing RT-5880 modeling, a 0.254 mm thick substrate, a relative permittivity of 2.2, a loss tangent of 0.0009, and operating in the desired 37 GHz frequency region. This substance is suited for high frequency applications due to its low dielectric constant and minimal dielectric loss. It isotropic and has a low moisture absorption rate. The suggested antenna element has the following dimensions: 10× 6× 0.254(mm×mm ×mm), respectively. On the substrate's top side, copper

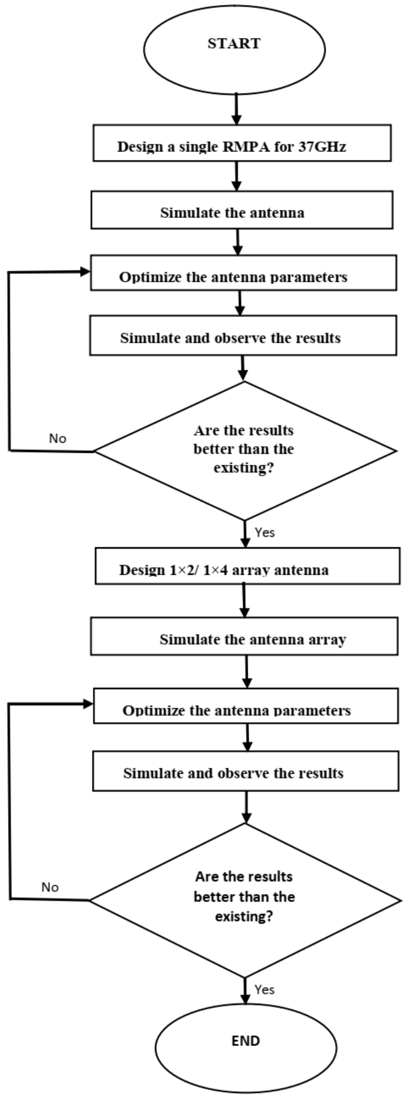


Fig. 1: Flowchart of the proposed antenna design

is employed and inserting E-shaped slots. The design parameters are listed in the Table 1. To compute the parameters, this study uses the equations shown below [14]. The width of the patch

$$W_p = \frac{c_0}{2f_r\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

The actual length of the patch

$$L_p = L_{eff} - 2\Delta L \tag{2}$$

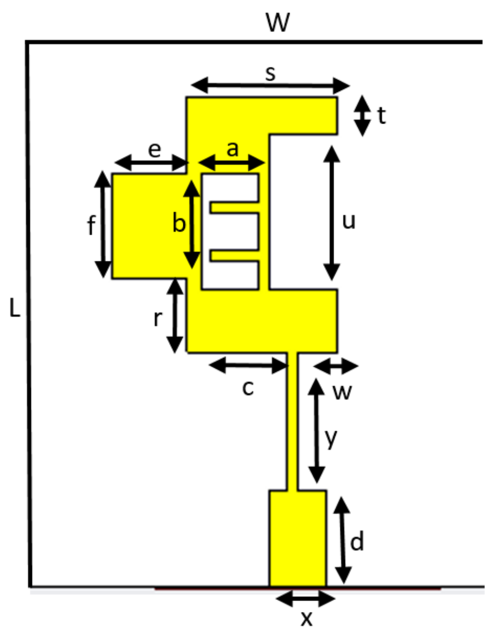


Fig. 2: Equation based Single element antenna

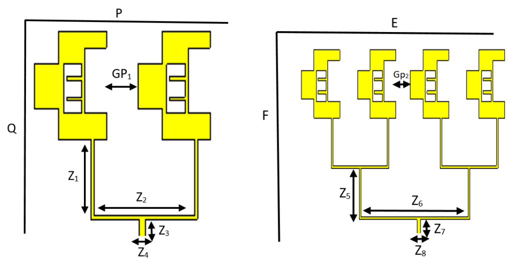


Fig. 3: (a) 1×2 array (b) 1×4 array.

Tab. 1: Dimensions of the Proposed Single Element Antenna

Parameter	L	W	e	f	r	s
Value (mm)	6	10	0.8	1	0.8	1.5
Parameter	t	u	v	w	x	y
Value (mm)	0.4	1.6	0.6	0.4	0.6	1.5
Parameter	a	b	c	d	-	-
Value (mm)	0.6	1.2	1.05	1	-	-

Calculation of Effective length

$$L_{eff} = \frac{c_0}{2f_r\sqrt{\varepsilon_{eff}}} \quad (3)$$

The Dielectric Constant of Effective Potential

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} - \frac{\varepsilon_r - 1}{2}\left(1 + 12\frac{h}{W}\right) - 0.5 \quad (4)$$

Calculation of the length extension

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)\,(W/h + 0.264)}{(\varepsilon_{eff} - 0.258)\,(W/h + 0.8)} \quad (5)$$

2) Single Element: Design of a Multiple Element Antenna Array

The single antenna element shown in Figure 1 that works at a frequency of 37 GHz. Although the progress made is significant, it is not enough to address some issues. In order to maximize the gain of a single antenna, an array technique is used, in which a single feed is used to supply power. The 1×2 and 1×4 arrays' geometry is depicted in Figure 3. The design parameters are listed in the Table 2.

Tab. 2: Dimensions of the 1×2 array and 1×4 array antenna.

Parameter (1×2 array)	P	Q	Gp_1	Z_1	Z_2	Z_3	Z_4
Value(mm)	10	6	3.4	2	3.5	0.5	0.2
Parameter (1×4 array)	E	F	Gp_2	Z_5	Z_6	Z_7	Z_8
Value(mm)	19	7.7	6.6	1.9	6.7	0.6	0.2

3.2. MIMO Configuration

The expanded array design architecture, which was made possible by applying the corporate feed technique to the two-port MIMO arrangement, is depicted in Figure 4. In order to provide pattern variety and excellent isolation among antenna arrays, the arrays are positioned side by side. This frequently causes problems when the arrays are extended to the MIMO. Similar to array structures, we already use several elements to increase the antenna's gain; but, because they only use one port, there are still serious issues with channel capacity, which must be effectively addressed by using multiple ports. Controlling the coupling between comparable arrays can be difficult in arrays, even though that technique is quite simple in single-element cases. Symmetry is preserved in the suggested MIMO structure, and the array structure below the position is left unchanged. The overall substrate dimensions employed in the MIMO arrangement are L = 7.70 mm × W = 32 mm.

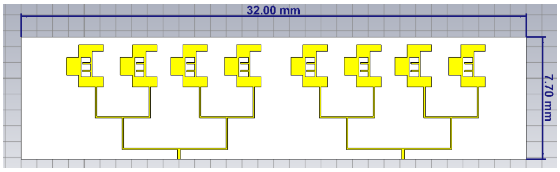


Fig. 4: MIMO arrangement of corporate feed array

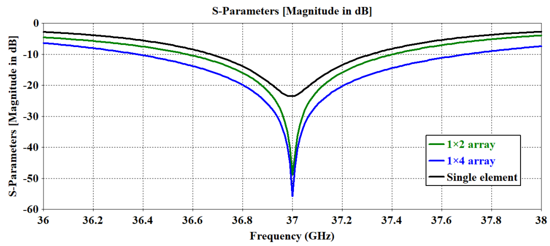


Fig. 5: S11 graph for proposed antenna array

3.3. Optimization through Optimizer in CST Software

The geometric design of the antenna should be optimized using an optimizer for improved impedance matching after it has been designed using the formula. In this study, the optimizer uses the "Trust Region Framework" technique since it yields better results.The operating frequency is changed once an antenna array has been created. Therefore, optimization is required for both antennas to operate at the intended frequency. Here, the S11 of the 1×2 array antenna is only slightly better than previously, whereas the S11 of the 1×4 array antenna is unchanged.

4. Results

The graph below compares the return loss of a single element antenna with that of an upgraded 1×2 array and 1×4 array. For a single element, a 1×2 array, and a 1×4 array, the coefficient of reflection and return loss are represented in Figure 5. As is generally accepted, the antenna is functioning well at the frequencies if the Return loss (S11) value through the frequency is less than -10 dB. In figure 5 when operating at 37 GHz, a single element antenna got a return loss of -23.477 dB, an optimized 1×2 array got a return loss of -48.771 dB, and a 1×4 array got a return loss of -55.658 dB. The return loss graphs are functioning effectively at the target band. Comparing three different antennas, it can be shown that a 1×4 array generated the best performance in terms of the 1×2 array and single element antenna. Analysis of the voltage standing wave ratio (VSWR), which is one of the major factors influencing an antenna's performance, is crucial. Less than two is the VSWR number that is optimum. As VSWR levels decrease, the antenna's performance improves. Figure 6 depicts a single element, a 1×2 array, and a 1×2 array with respective VSWR values of 1.1437, 1.0073, and 1.0033. In terms of the standard limit, which falls between standard 1 and 1.5. The 3D ra-

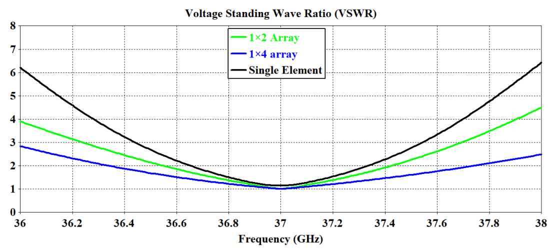


Fig. 6: Voltage Standing Wave Ratio of the proposed antenna array

diation pattern, which is measured in the far-field region, is a three-dimensional representation of the radiated power from the antenna in free space. In relation to an isotropic antenna, it is the measurement of the power radiated in a particular direction. It is quite simple to see the power provided in a certain direction from a 3D radiation pattern. Figure 7 below at 37 GHz depicts the 3D radiation patterns of the single element, 1×2 array, and 1×4 array antennas. This figure demonstrates that the maximum gain for a 1×4 array antenna is around 11 dBi at 37 GHz.

Figure 8 displays the single element, 1×2 array, and 1×2 array antennas' total efficiency and radiation efficiency vs. frequency curves.It has been noted that the overall efficiency and radiation efficiency of single element, 1×2 array, and 1×2 array antennas, respectively, are 86%, 81%, and 78%.This single element, 1×2 array, and 1×2 array antenna have total efficiency and radiation efficiency of more than 70%, making them suitable for mobile mm-Wave applica-

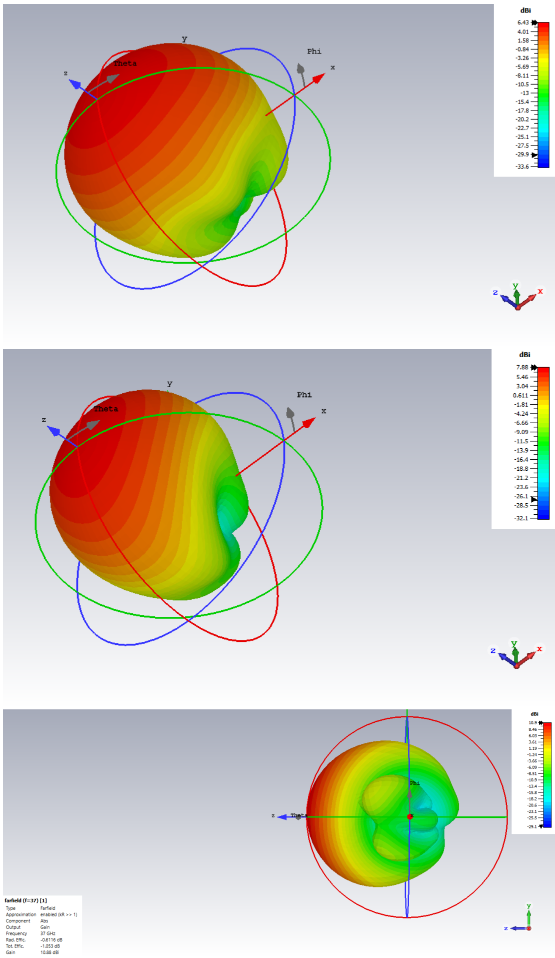


Fig. 7: 3D radiation pattern of (a) single element (b) 1×2 array (c) 1×4 array antenna at 37 GHz.

tions. Figure 9 displays the gain vs. frequency

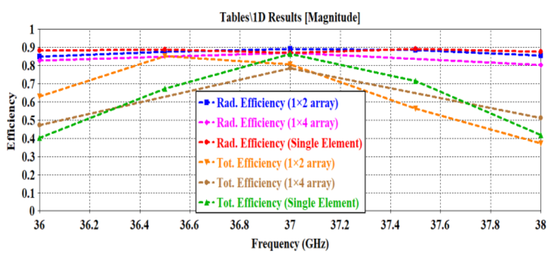


Fig. 8: Total and Radiation efficiencies of single element, 1×2 array and 1×4 array Antenna.

curve for a single element, a 1×2 array, and a 1×4 antenna. It demonstrates that the 14 array antenna's maximum gain is roughly 10.88 dBi. Figure 8 show that the single element and half-array antennas have gains of 6.44 and 7.89 dBi, respectively. Figure 10displays the reflec-

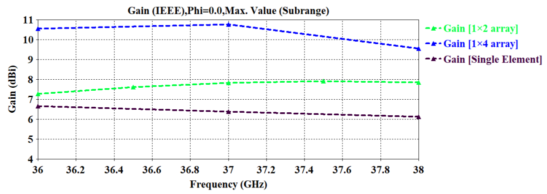


Fig. 9: Gain of single element, 1×2 array and 1×4 array Antenna.

tion coefficient for the suggested MIMO structure. The antenna for port-1 resonates at 37.01 GHz, which is the center frequency, providing a bandwidth of 36.4 to 37.8 GHz. In contrast, the magnitude reached was −46 dB. Similar to port 1, port $2's$ bandwidth spans from 36.4 to 37.8 GHz below the 10 dB band, and the antenna resonates at the central frequency of 37 GHz with a reflection coefficient magnitude of -58 dB. Figure 11a analyzes and displays the gain

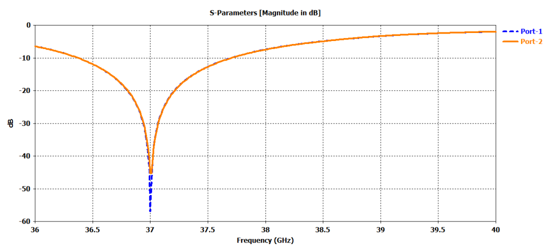
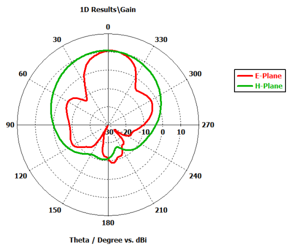
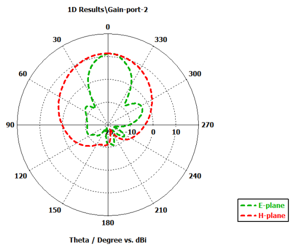


Fig. 10: S11 graph for proposed MIMO antenna array.

patterns for the port-1 in the 0- and 90-degree planes. The antenna array main lobe direction is initially found at 353.0 degrees in the 90-degree plane. Although an excellent side lobe level of -24.3 dB is attained having a 68.2 degree beam-width at 3 dB. The radiation pattern is very directed, with very few side and rear lobes. The major lobe is oriented toward the 359-degree angle, according to the 0-degree plane analysis, and the side lobe level is -11.7 dB. Moreover, the beam-width at 3 dB is 22 degrees. With a low degree of back lobes, the radiated beam likewise appears to be highly directional in this plane. The radiation pattern analysis for the two primary planes, E and H, in the instance of port-2 is similarly shown in Figure 11b. In the 0-degree plane, the side lobe level is -23.8 dB, and the



(a)



(b)

Fig. 11: Configuration gain pattern for corporate array MIMO (a) port 1 (b) port 2.

main lobe direction is along the 4.0-degree angle. In this plane, however, the angular width is 69.3 degrees. The major lobe's path in the 90-degree plane is also along a 359.0-degree angle, with an angular width of 20.6 degrees. In this plane, the side lobe level is -10.7 degree of its maximum.

The summary of the results of proposed antenna array represent in Table 3 and the comparison between the proposed antenna array and the existing works are presented in Table 4.

Tab. 3: Comparison between single element, 1×2 array and 1×4 array

Antenna	Resonant frequency (GHz)	Return loss (dB)	VSWR	Gain (dBi)	Directivity (dBi)
Single element	37	-23.477	1.1437	6.44	7.03
1×2 array	37	-48.771	1.0088	7.89	8.39
1×4 array	37	-55.658	1.0033	10.88	11.49

5. Conclusions

This paper proposes a design for an effective MIMO antenna array for 5G mm wave mobile communication systems. The proposed MIMO antenna array will cover the 37 GHz frequency range, which is reserved for 5G mm-wave mobile communication applications. The antenna element's gain is 6.44 dBi, however when two elements and a four-element array are used, the gains are 7.89 dBi and 10.88 dBi, respectively. The return loss, voltage standing wave ratio, directivity, and surface current distribution performance measures for MIMO antenna arrays are observed and found to be within the allowed threshold. The radiation efficiency of the proposed MIMO antenna array is determined to be efficient within the defined operational frequency range. The proposed antenna array is also a design that may be a competitor for 5G mm-wave communication systems when compared to existing antennas.

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Tab. 4: Dimensions of the 1×2 array and 1×4 array antenna.

Antenna reference	No. of elements	Year	Return Loss (dB)	Gain (dBi)	Bandwidth (GHz)	Size (mm^2/mm^3)	Wavelength
[15]	2	2022	-36.24	-	0.653	-	0.25 of 37 GHz
	4	2022	-33.23	12.8	0.677	40.64 mm^3	
[16]	1	2019	-25.8	5.5	5.5	28.332 mm^3	-
[17]	1	2017	-25.77	1.72	7.7	34.02 mm^2	-
[18]	7	2020	-17	7.71	1.107	224 mm^2	-
[6]	1	2021	-43.5	8.25	6	0.504 mm^3	-
[19]	4	2017	-12	5.75	0.3	287.375 mm^2	-
[20]	4	2016	-30	6.7	1.2	68.6 mm^2	0.66 of 37 GHz
[21]	2	2019	-23	7.49	4.56	25×30×0.8 mm^3	-
[22]	4	2019	-40	7.11	3.96	12×25.4×0.8 mm^3	-
[23]	4	2017	-24.07	-	0.64	3.025×3.2×1.6 mm^3	0.6 of 37 GHz
[24]	4	2021	-18	9.9	0.4	35×35×4.75 mm^3	-
Present work	2	2023	-48.771	7.89	0.82	15.24 mm^2	0.42 of 37 GHz
	4	2023	-55.658	10.88	1.31	37.2 mm^3	0.82 of 37 GHz

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