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A Circular-Shaped Antenna Array for Wide-Band Millimeter-Wave Application

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

This paper presents a proposed $1x2$ Circular-shaped Antenna array for millimeter-wave application. The proposed antenna is designed to operate at mm-wave frequency of 17 GHz. Circular antennas give good return loss, and better gain and directivity. The main aim of using the array is to improve the gain of the antenna. Inset feed technique is used to design the antenna. The size and feed technique are determined by design formulas. The simulation results show a good return loss (reflection coefficient) of -55.297 dB which is way below the benchmark of 10dB and a bandwidth of 1.79 GHz (16.42 – 18.21 GHz). The gain and VSWR results are 8.684 dB and 1.0034 respectively at 17.29 GHz frequency. The CST software is used for the simulation.

Keywords: Antenna array; millimeter-wave; circular-shaped; ROGERS substrate.

1. INTRODUCTION

This paper presents a design and performance analysis of a proposed Circular-shaped $1x2$ array antenna wide-band millimeter wave application.

Antennas are important components in many wireless communication systems. The IEEE definition of an antenna as given by Stutzman et al. [1] is, the component of a transmitting or receiving system designed to radiate or receive

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electromagnetic waves. Microstrip antennas are one of the most useful types of antennas. According to Shimu et al. [2], microstrip patch antennas have wide range of applications in medical, military, mobile, and satellite communication. Wideband antennas operating at higher frequencies are becoming increasingly important as wireless applications require more and more bandwidth. Such characteristics are inherent in microstrip patch antennas. The patch can be rectangular, square, circular, annular ring, elliptical, or triangular in shape. However, circular and rectangular shapes are the most commonly used due to their ease of analysis and fabrication, as well as their low cross polarization. The patch is constructed in such a way that its pattern is natural to it. Microstrip antennas have several advantages, including their light weight, ease of fabrication, low profile, and ease of integration with circuits. Various methods for increasing bandwidth have been reported in the literature, including shorting pins [2,3], semi-elliptic slots [3,4]. Shapes such as octagonal, tapered-slot [5,6]. Dikmen et al. [7] describes a circular slot feed with a trident shape. Ghosh and Kim et al. [8,9] mention inverted-L-shaped and hexagonal shapes.

Circular antenna arrays are widely used in various wireless communication applications such as satellite communication, radar systems, and mobile communication. The circular antenna array offers several advantages over other antenna arrays, such as omnidirectional radiation pattern, high gain, and low sidelobe level. Due to these advantages, circular antenna arrays are becoming increasingly popular in various communication systems [10]. Circular-shaped antenna arrays are a type of antenna system that consist of a circular arrangement of individual antenna elements. These elements are designed to work together to form a directional radiation pattern, which can be steered electronically to achieve a specific beam direction. The circular shape of the array allows for omnidirectional coverage, which is particularly useful in applications such as radar, wireless communication, and satellite communication. Circular-shaped antenna arrays are commonly used in millimeter-wave frequency bands due to their ability to provide high gain and directivity. They are also compact and lightweight, making them suitable for use in applications where space and weight constraints are critical. The design of a circular-shaped antenna array involves several key considerations, such as the frequency range, antenna type, number of elements, and beamwidth. The optimization of these parameters can lead to high-performance and efficient antenna systems.

Circular antenna arrays have become increasingly popular in recent years due to their numerous advantages over linear arrays, including improved pattern symmetry and circular polarization [11,12]. One of the key advantages of circular antenna arrays is their ability to generate circularly polarized electromagnetic waves, which have a number of important applications in fields such as satellite communications, radar systems, and navigation [13,14]. In addition to circular polarization, circular antenna arrays also offer improved directional properties compared to linear arrays, making them well-suited for applications such as wireless communication and direction finding [15,16].

2. LITERATURE REVIEW

Several studies have been carried out on the design of circular-shaped antenna array to achieve gain high gain suitable for a range of applications. The authors in [17] designed and analysed a low-profile circular antenna array with six elements for WLAN applications. The proposed antenna array is made up of six circular patch elements arranged in a circle and fed by a central network. To achieve beam steering capability, the authors use a corporate feed network with a 180-degree phase shifter. The array is designed to operate in the 5.8 GHz WLAN band with a 280 MHz bandwidth. The antenna array's performance results from simulations and measurements show that it has a low profile and a peak gain of 6.1 dB, making it suitable for WLAN applications. A comparison with other existing antenna arrays reveals that the proposed circular array outperforms them in terms of gain and bandwidth. The authors of [18] proposed an antenna array made up of four circular patch elements connected by a microstrip line feeding network. To achieve circular polarization, the authors employ a microstrip line-based feeding network with a balun. The array is intended to operate in the UHF RFID band. The antenna array's performance results from simulations and measurements show that it has a low profile and a peak gain of 5.3 dB and a bandwidth of 100 MHz (2.3-2.4 GHz), making it suitable for RFID applications. A parameter optimization study was conducted to improve the performance of the antenna array even further. The optimization is carried out with the help of a genetic algorithm, and the results show that the optimized antenna array performs better in terms of gain and axial ratio. In [19], an antenna array consisting of four circular patch elements arranged in a circular configuration with a microstrip line feeding network was proposed. The authors use a compact feeding network to achieve circular polarization, which is suitable for WLAN applications. The array is designed to operate at the WLAN frequency of 2.4 GHz. As shown by simulation and measurement results, the array has a compact size of $33mm\ x\ 36mm\ x\ 6.8mm$ and a peak gain of 6.1 dB and a bandwidth of 130 MHz (2.3-2.43 GHz), making it suitable for indoor WLAN applications. The authors also conduct a parametric study to investigate the effect of various parameters on the performance of the antenna array. The research looks at how substrate thickness, feeding position, and element spacing affect the performance of an antenna array.

To form a single antenna array, several antennas are arranged and connected in a regular structure. [20] classified antenna array into four types: log periodic dipole arrays, planar arrays, collinear arrays, and phased arrays. A phased array antenna is made up of multiple antenna systems that allow the radiation pattern to be reinforced in desired directions while suppressed in undesirable directions. Phased array antennas are now widely used and are finding their way into civilian applications. Many AM broadcast radio stations use phased arrays to boost signal strength and thus reduce interference to other areas.

Antenna arrays are widely used because they increase radiated power and provide a highly directional beam, preventing power loss in other directions [21]. Arrays are primarily used to improve the radiation pattern. Phase arrays improve antenna directivity and provide electronic steering, which eliminates the need for mechanical steering via servo motor. As a result, the beam can be moved in less than a millisecond.

The basic information about the circular antenna and the arrays has been described in the introduction. The next section shows the design of the proposed circular-shaped array antenna which consists of the design method and design equations and the design parameters.

3. DESIGN OF AN ANTENNA

In the designing of the proposed antenna, several steps were involved. We first specify the design requirements which include the desired operating frequency, the design substrate material, thickness, and dielectric constant. Using the design equations, we determined the patch antenna geometry, including the physical radius and effective radius of the circular patch, feed location, and ground plane size and gradually adjusted the parameters so as to get the desired resonant frequency. We also designed the feeding network which is responsible for distributing the input signal to each element of the array. The proposed antenna is a circular antenna array microstrip patch antenna designed for millimetter-wave applications operating at 17.3GHz. The antenna was designed using Computer Simulation Technology (CST) Microwave Studio software, which is widely used in the industry for electromagnetic simulation and design.

The proposed antenna geometry is designed on a ROGERS RT5880 substrate with a thickness of 1.2mm and a relative permittivity of 2.2 and tangent loss of 0.02. The circular patch has a radius of 5.387 mm and $1x2$ array circular element created. The simulation setup entailed creating a 3D model of the antenna geometry using CST software to optimize its performance parameters such as bandwidth, gain, and radiation pattern.

3.1 Design Equations

The radius of the circular patch can be calculated using the formulas (1), (2), (3):

$$a = \frac{F}{\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{\frac{1}{2}}} \quad (1)$$

Where;

$$F = \frac{8.791x10^9}{f_r\sqrt{\varepsilon_r}}; \text{ (h in cm)} \quad (2)$$

$$a_e = a\left\{1+\frac{2h}{\pi\varepsilon_r F}\left[ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{\frac{1}{2}} \quad (3)$$

Where;

a_e = Effective Radius of circular patch
a = Physical radius of circular patch
ε_r = Dielectric constant of substrate

h = Height of substrate
f_r = Frequency of operation

Equation (1) is the physical radius of circular patch antenna which is the distance from the center of the circular patch to the edge of the patch. his parameter plays a critical role in determining the operating frequency of the antenna, as well as its radiation pattern and impedance characteristics. Equation (2) is the effective radius of a circular patch antenna is the radius of a hypothetical circle that has the same radiation characteristics as the actual patch antenna. It is a key parameter in the design of a circular patch antenna, as it determines the resonant frequency, impedance, and radiation pattern of the antenna. This antenna was designed using the inset feed technique. The line feed has dimensions of 2mm width and 4.4665mm length, which are calculated using the necessary formulas.

The width of the microstrip patch antenna is given by

$$W_1 = \frac{c_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (4)$$

Calculation for the effective dielectric constant ε_{reff}

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12h}{W}\right)^{\frac{-1}{2}} \quad (5)$$

$$\frac{\Delta L}{h} = 0.142\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.259)\left(\frac{W}{h}+0.9\right)} \quad (6)$$

Calculation for the Length of the Patch

$$L = \frac{c_o}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \quad (7)$$

Calculation for the Ground Dimensions

$$L_g = 6h + L \quad (8)$$

$$W_g = 6h + W \quad (9)$$

The CST Microwave Studio software is used to evaluate the return loss, VSWR, and gain for 1x2 circular patch microstrip antenna arrays [22].

The 1x2 array is made up of two circular patch antennas that are microstrip-fed on a 1.2 mm thick ROGERS RT5880 substrate (r =2.2). Table 1 shows the dimensions of the antenna array. The antenna array is simulated in CST Microwave Studio using these dimensions to see how it performs.

4. RESULTS AND DISCUSSION

4.1 Return Loss

Fig. 3 depicts the antenna's reflection coefficient S-parameter characteristic. The antenna performs well, resonating at 17.3 GHz. The reflection loss coefficient value at the resonance frequency is -55.3dB, indicating a good impedance match condition. The proposed antenna has a bandwidth of 1.79GHz (nearly 2GHz), making it suitable for wideband applications.

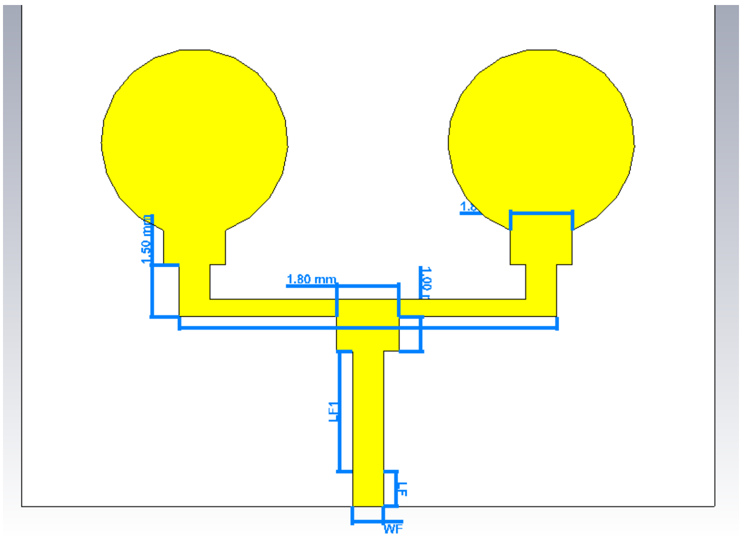

Fig. 1. 1x2 Circular array antenna dimensions

Table 1. Simulation parameters

S/N	Parameters	Description	Values
1	WS	Width of Substrate	20 mm
2	LS	Length of Substrate	15 mm
3	HS	Height of Substrate	1.2 mm
4	WG	Width of Ground	20 mm
5	LG	Length of Ground	15 mm
6	WF	Width of Feed	2 mm
7	LF	Length of Feed	4.4665 mm
8	a	Radius of Patch	5.387 mm

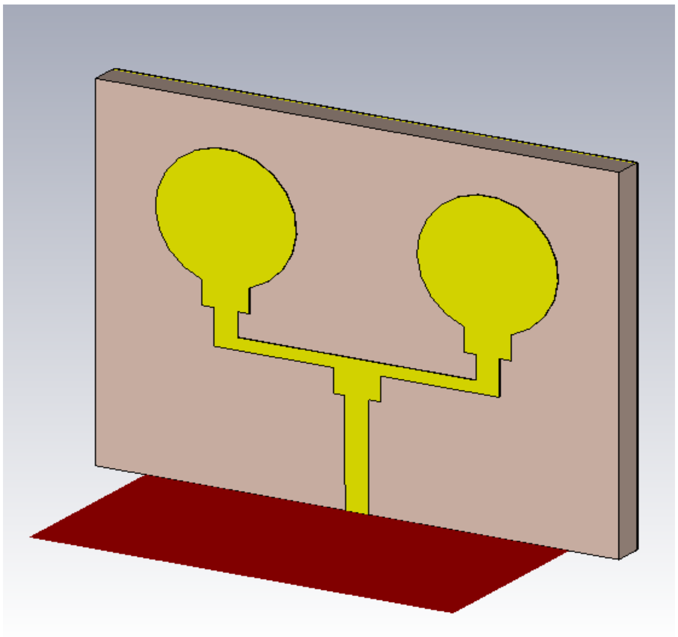

Fig. 2. 1x2 Circular array antenna perspective view

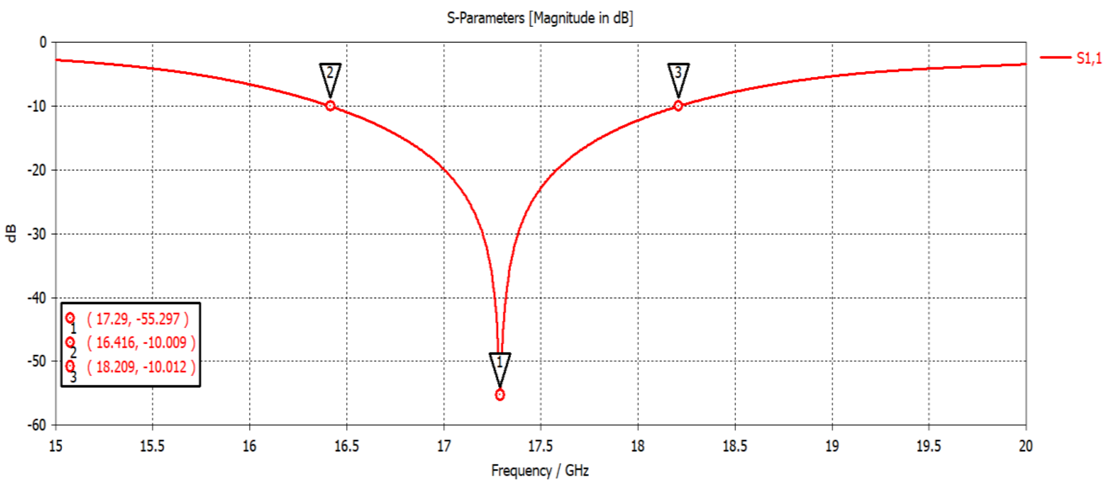

Fig. 3. Return Loss (S11-parameters)

4.2 VSWR

The VSWR is an impedance mismatch measurement between the feed line and the antenna. The mismatch raises the VSWR value. For perfect impedance matching, the minimum VSWR is one and the maximum VSWR is two. Figure depicts the proposed antenna's simulated VSWR v/s frequency plot. The proposed antenna has a VSWR value of 1.0034 at 17.3GHz and a VSWR less than 2 for the frequency range of 16.37 to 18.17GHz.

4.3 Gain and Radiation Pattern

The gain of an antenna describes its efficiency and directional capabilities. For the antenna to function properly, the gain value should be greater than 3dB. At 17.3GHz, the proposed antenna has a gain of 8.684dB. Also, the proposed antenna shows a directivity of 9.08dB. Fig. 5 and Fig. 6 depicts the gain and directivity plot of the proposed antenna.

4.4 Comparison of Antennas

The proposed antenna has been compared with recently designed Circular Antenna Array antennas. From Table 2, the simulation result for the proposed antenna is presented and it can be seen that the proposed antenna has a higher gain compared to the previous designed antennas. Also, it can be seen from the S11 parameter, the proposed antenna showed a large bandwidth compared to the previous designed antennas.

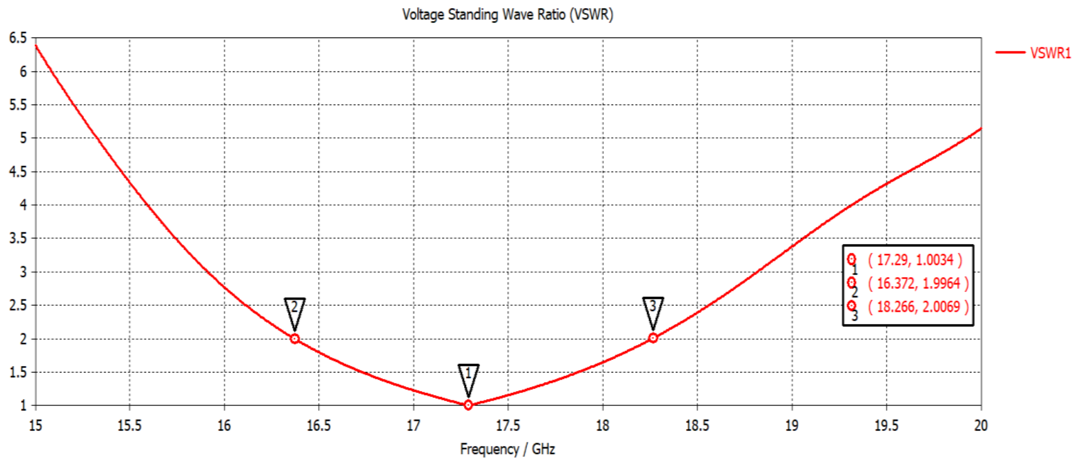

Fig. 4. VSWR

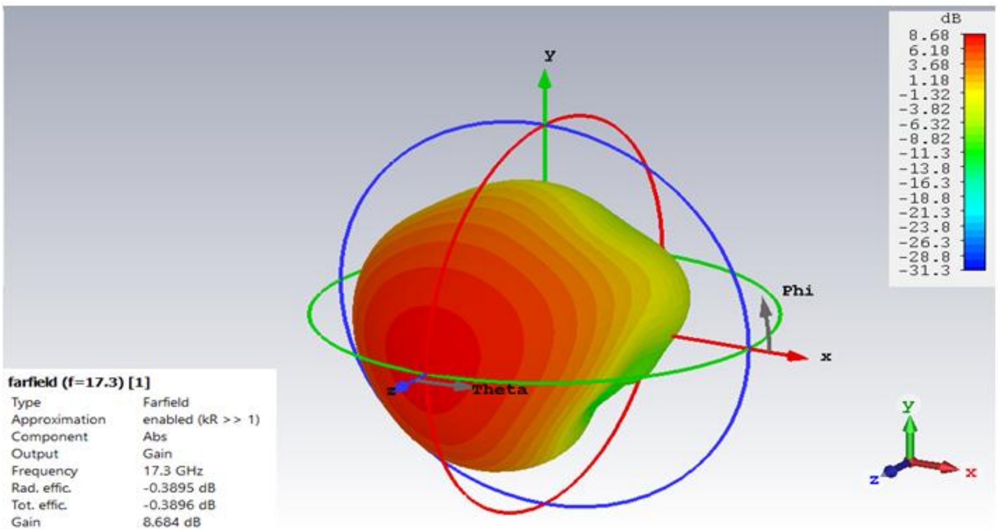

Fig. 5. Antenna gain

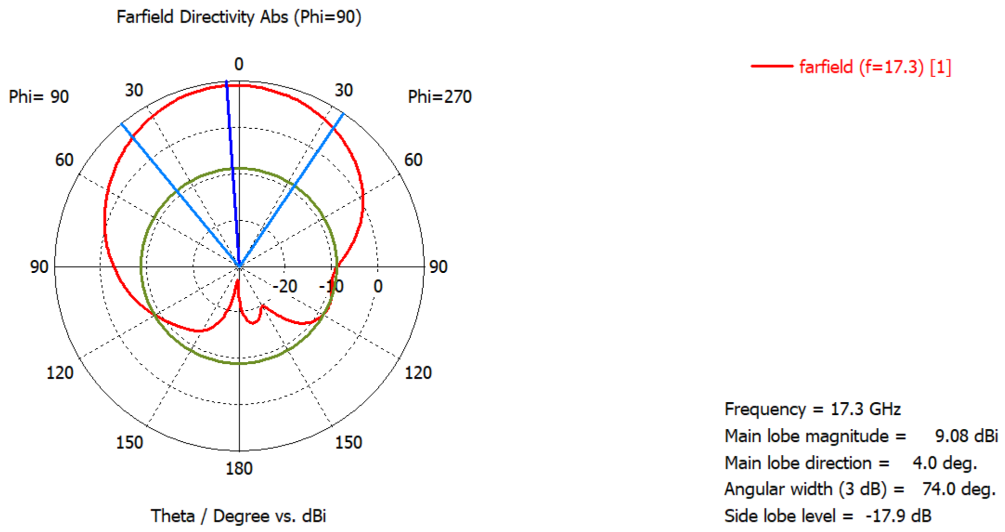

Fig. 6. Antenna gain in planar view

Table 2. Comparison of the proposed antenna with others

S/N	Description	Gain	Bandwidth	Ref
1.	6-Element Circular Antenna Array	6.1 dB	280 MHz	[16]
2.	Circularly Polarized Antenna Array (RFID)	5.3 dB	100 MHz (2.3 – 2.4 GHz)	[17]
3.	Circularly Polarized Antenna Array (Indoor WLAN)	6.1 dB	130 MHz (2.3 – 2.43 GHz)	[18]
4	Proposed Antenna	8.684 dB	1.79GHz (16.42 – 18.21 GHz)	
	1x2 Circular Array Antenna			

5. CONCLUSION

The design of a $1x2$ antenna array for millimetre wave applications is presented in this paper. The array is made up of two inset-fed circular patches that are mounted on a ROGERS RT5880 substrate. At the resonant frequency of 17.3 GHz, the antenna has good impedance match characteristics and a high gain of 8.7 dB and a bandwidth of 1.79 GHz. The results show that the antenna is suitable for use in the 17 GHz frequency band. However, for further research, the antenna's resonance frequency can be increased from 17.3 GHz with careful observation from the parametric study to determine which specific parameter can help achieve the increment.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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