Bulletin of Electrical Engineering and Informatics
Vol. 10, No. 3, June 2021, pp. 1446~1454
ISSN: 2302-9285, DOI: 10.11591/eei.v10i3.3017

Circularly polarized antenna array based on hybrid couplers for 5G devices

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Article Info

Article history:

Received Nov 13, 2020
Revised Mar 21, 2021
Accepted Apr 9, 2021

Keywords:

5G
Antenna array
Beam steering antenna
Butler matrix
Circularly polarized
Hybrid coupler
Printed dipole

ABSTRACT

This paper depicts a wideband circularly polarized (CP) antenna for 5G devices. The antenna array has a 3D structure including four simple printed dipole elements with directional radiations, high gain, and high efficiency. It achieves a CP by using the sequential rotation (SR) feeding based on 90°-3dB hybrid couplers in the proposed feeding network. The antenna array bandwidth is wide, 26.7%, with an operating frequency band from 3.35 GHz to 4.35 GHz. The antenna achieves a high peak gain of 10.73 dBi and high efficiency of 93.75%. Besides, the antenna gain is stable over the operating bandwidth (BW). At the centre operating frequency of 3.75 GHz, the angle of circular polarization is 51°. The antenna is designed and fabricated on the Rogers 4003 C substrate. The measured S11 is well matching with the simulation results. With the above characteristics, the proposed antenna can be a suitable candidate for 5G devices.

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1. INTRODUCTION

Circularly polarized (CP) microstrip antennas have been used widely in many communication systems, including 5G mobile communication, because of their advantages over linearly-polarized antennas in reducing energy loss, multipath effect, and Faraday rotation effect [1]. Also, 5G operating in both spectrums, including lower frequencies, frequency range (FR1) (4.1 GHz-7.125 GHz), and higher frequencies, FR2 (24.25 GHz-52.6 GHz), have attracted much attention [1]. There have been several researches about CP antennas working at FR1 using several structures such as single-feed [2]-[12] or multiple-feeds [13]-[17]. Using single-feed structures to achieve a CP antenna is the simplest technique, but it has a limitation of narrow bandwidth. Meanwhile, multiple-feeds structures such as antenna arrays can give not only wide bandwidth but also high gain. These CP antenna arrays have obtained significant achievements. Still, higher gain, wider bandwidth, simpler structure requirements for FR1 bands have been a challenge in designing CP antenna arrays.

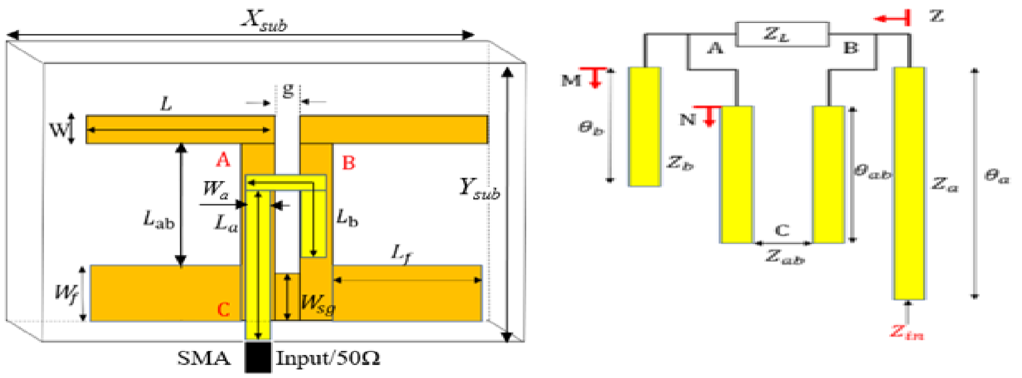
This paper proposes a CP antenna array that consists of four dipole elements. Rogers 4003 C substrate is chosen to design the antenna because of low weight, low loss, and high hardness. The SR technique is applied for feeding network design using 90° phase-shifters and quasi-equal-amplitude to obtain the wideband CP antenna. Two CP modes of the antenna are obtained by changing the feeding point PIN-diodes element to avoid the loss and non-linear effect. The antenna achieves a CP with a degree of 51°, a high gain of 10.73 dBi, and a wide bandwidth of 26.7%. The rest of this paper is organized is being as. Section 2 presents the design of the 5G CP antenna as well as its simulated and measured results. The conclusion of the paper is in section 3.

2. 5G CIRCULARLY POLARIZED ANTENNA DESIGN

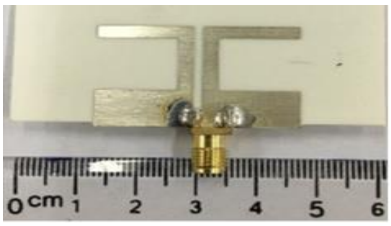
This section presents the design of the 5G CP antenna including the antenna element, the antenna array, and the feeding network in subsection 2.1, 2.2, and 2.3 respectively. The latest describes the simulated and measured results of the proposed antenna as well as the discussion and the comparison between the archived results and the publications.

2.1. Printed dipole antenna element

The 5G printed dipole element with "J"-Balun is proposed in Figure 1(a) according to the theory in [17]-[22] but high gain and directional pattern. Thanks to achieving high efficiency, the dipole antennas are often chosen to design CP antennas. The antenna element is designed on Rogers 4003 C substrate with a dielectric constant of 3.55 and a height of 0.813 mm. On the one side of the substrate, the antenna includes a radiator with two arms and a ground for obtaining directional radiation and high antenna gain. On the other side, a "J" Balun is integrated into the feeding to ensure electricity balancing for two arms. Figure 1(b) illustrates the equivalent circuit of J-Balun for impedance studying. The radiator and Balun's detail dimensions are calculated similarly to the steps in [8]. The perfect matching is achieved when $L_b = L_{ab} = \lambda/4$. The antenna is designed for the center frequency of 3.75 GHz. The parameters of the proposed antenna are calculated, optimized by CST software, and shown in Table 1. The antenna element prototype is presented in Figure 1(c).



(a) (b)



(c)

Figure 1. The printed dipole element with "J"-Balun propose, (a) The structure of printed dipole antenna, (b) The equivalent of the "J" Balun, (c) Prototyped

Table 1. Parameters of the printed dipole with integrated "J" Balun

Parameters	Values (mm)	Parameters	Values (mm)	Parameters	Values(mm)
L	15.5	L_b	12	W_{sg}	2.5
L_f	14.5	W	2.5	W_a	1.85
L_{ab}	20-8	W_f	8	X_{sub}	40
L_a	12.92	g	0.9	Y_{sub}	60

Figure 2 shows the S11 simulation results of the dipole antenna. The Figure shows that the antenna bandwidth is from 3.6 GHz to 4 GHz (at S_{11} < -10 dB), and the simulation reflection coefficient S_{11} is -45 dB at 3.75 GHz. Figure 3(a) presents the 3D radiation pattern of the antenna element and Figure 3(b) plots E-plane and H-plane of the radiation pattern. The printed dipole antenna achieves a peak gain of 6.478 dBi, an angular width (-3dB) of 129.30°, and total radiation efficiency of 96.63%.

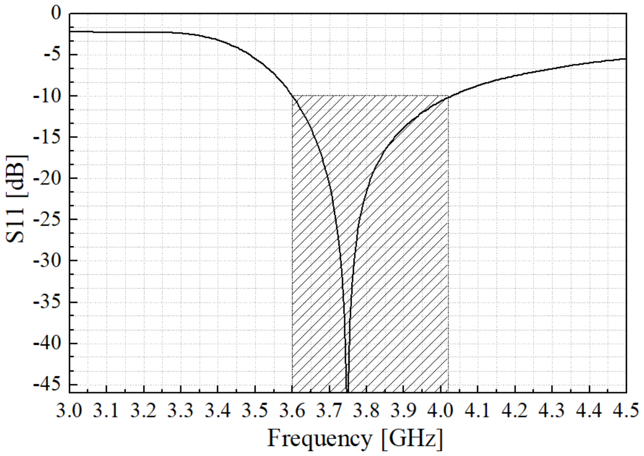
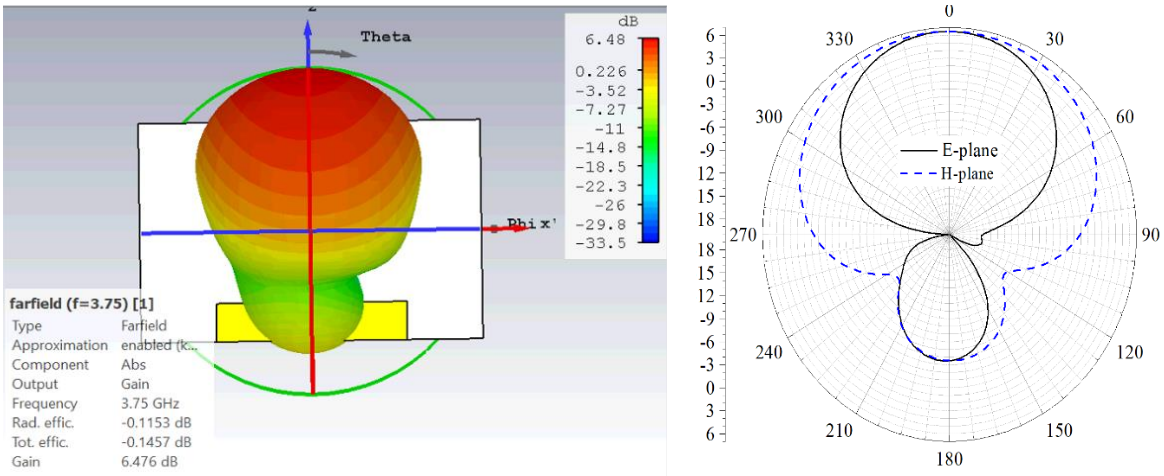


Figure 2. The simulated reflection coefficients of printed dipole antenna



(a) (b)

Figure 3. These figures are, (a) 3D radiation pattern of the proposed dipole element at 3.75 GHz, (b) Radiation pattern of the proposed dipole element at 3.75 GHz in E-plane and H-plane

2.2. Dipole antenna array

CP antennas can be achieved by using single-feed or multiple-feeds structures as mentioned in section 1. Several techniques have been reported in recent decades such as dual-feed, mutual coupling and reactive loading, stacked, aperture coupled, and sequentially rotated [23]. The CP antenna arrays that use sequentially rotated feed network generate wideband, high gain, and CP radiation from a linear polarization [5], [14], [16], [24]-[25].

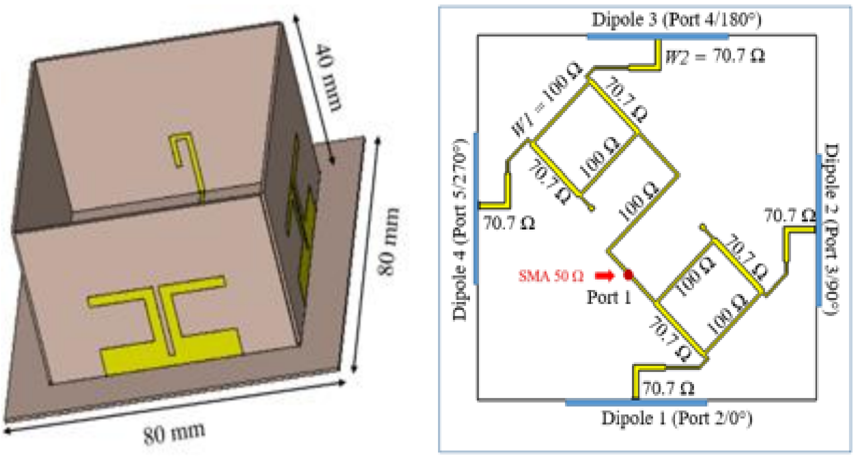
Figure 4(a) shows the structure of the CP antenna array with a total dimension of 80×80×40 mm^3. The antenna array consists of four above antenna elements, and the proposed feeding network presented in the next section (subsection 2.3). Two neighboring dipole elements are perpendicular, and all four elements are perpendicular to the feeding network. This configuration has the advantage of low mutual coupling between these elements in the antenna array. The antenna obtains a wideband CP by applying the SR feeding technique thanks to the feeding network. The excited phases feeding ports 2, 3, 4, 5 correspondings to four dipoles 2, 3, 4, 5 are arranged 0°, 90°, 180°, and 270° as shown in Table 2.

Table 2. Excited phases of antenna elements

Dipole 1 (Port 2)	Dipole 2 (Port 3)	Dipole 3 (Port 4)	Dipole 4 (Port 5)
0^0	90^0	180^0	270^0

2.3. Feeding network design

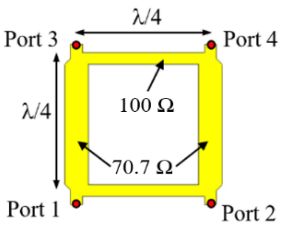
The feeding network is illustrated in Figure 4(b), and the desired phase difference between adjacent feeding ports presented in Table 2. It utilizes two 90°-3dB hybrid couplers and a 100 Ω quarter-wavelength transmission lines to create 90° and 180° phase shifts, respectively, and 70.7 Ω quarter-wavelength transmission lines for feeding and matching impedance between the elements.



(a) (b)

Figure 4. These figures are, (a) Structure of the CP antenna array, (b) The proposed feeding network

The 90° -3 dB hybrid coupler (HC) in the proposed feeding network is used for spliting power and changing phases [11]. The HC is designed form on a conventional microstrip hybrid with four ports, as depicted in Figure 5. The operation principle of the HC in Figure 5 is depicted is being as. The input power at port 1 is divided into two equal parts to port 3 and port 4 with a 90-degree phase change between two outputs, and it is not transmitted to port 5. S parameter of the HC is presented in (1).

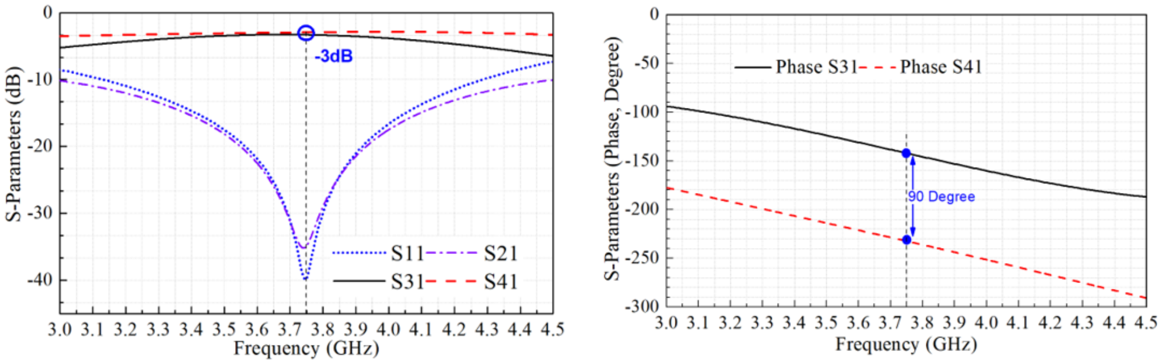


$$[S]_{HC} = -\frac{1}{\sqrt{2}}\begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix} \quad (1)$$

Figure 5. Structure of hybrid coupler

Figure 6 presents the S parameters and the phase changes between the two output ports of the HC in Figure 5. Figure 6(a) shows that the power at port 1 is divided into port 3 and port 4 while it is not transmitted to port 2 in operating bandwidth. It can be seen in Figure 6(b) that the phase difference tween port 3 and port 4 is 90^o at the center frequency of 3.75 GHz. The 3dB BW of the HC at -10 dB is from 3 GHz to 4.5 GHz. These two HCs are integrated into the feeding network.

The input power with 50-ohm impedance at port 1as shown in Figure 4(b) is splited to feed to four elements of the array. The dipole element feed impedance must be matched with feeding lines. The length of the microstrip line from the feeding point (port 1) to port 3 (dipole 2) longer than to port 2 (dipole 1) a quarter-wavelength for obtaining a 90-degree phase delay tween port 2 and port 3. This is similar to the pair of dipole 3 (port 4)/dipole 2 (port 3) and dipole 4 (port 5)/dipole 3 (port 4). The width of the quarter-wave lines is calculated to ensure impedance matching between 50 Ω inputs of the dipole elements and 100 Ω lines (width of *W1)* as well as between the input of subminiature version A (SMA) connector and 100 Ω lines. The impedance of the lines to match 50 Ω input dipoles and 100 Ω lines are 70.7 Ω with the width of *W2*. The value of *W1* and *W2* are calculated, then optimized by central standard time (CST) and presented in Table 3.



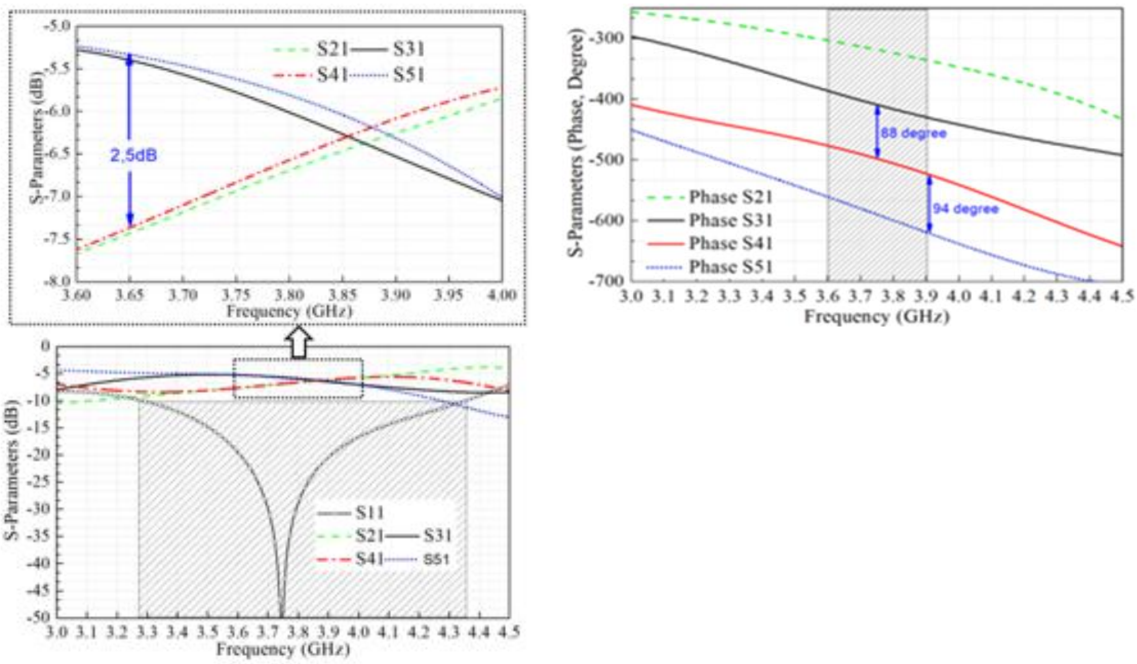
(a) (b)

Figure 6. These figures are, (a) The phase change of the output ports, (b) The simulated S parameter

Table 3. Dimension parameters of the lines in the feeding network

Parameters	Values(mm)	Parameters	Values(mm)
W1	0.423	*W2*	0.95

Figure 7 depicts the simulated S-parameters of the feeding network, including amplitude and phase when exciting port 1. The Figure 7(a) that antenna bandwidth is about 1 GHz (3.27 GHz-4.36 GHz). The arguments of S21, S31, S41, S51 are approximately -6 dB at 3.6 GHz-4.0 GHz band. It means that the power entering port 1 is equally divided into the rest four ports with low loss. Therefore, the antenna array obtains the CP at the band of 3.65 GHz-3.93 GHz. The minimum Axial ratio (AR) of the antenna is below 2.5 dB at 3.6 GHz-4.0 GHz. It can be enhanced when the amplitude of excitation at all antenna element ports are the same. According to Figure 7(b), the phase delay between two inputs of dipole 2/dipole 1, dipole 3/dipole 2, and dipole 4/dipole3 is approximately 90^0. This phase-difference is maintained at the band of 3.6 GHz-3.93 GHz. It explains why the CP antenna array has the CP at this band.



(a) (b)

Figure 7. Simulation results of array feeding network (FN), (a) Amplitude delivery created by the FN,

(b) Phase delivery created by the FN

2.4. Results and discussion

The CP antenna array is designed and fabricated on the Rogers 4003 C substrate with the feeding network and four dipole elements as presented above. Figure 8 shows the CP antenna array prototype with a total dimension of 80×80×40 mm^3. Figure 9 shows the antenna reflection coefficient. The antenna array bandwidth is increased by 16 % compared to single dipole antenna bandwidth. The CP antenna array has CP from 3.65 GHz to 3.93 GHz. The measured S11 reflection coefficient is well matching with the simulation results.

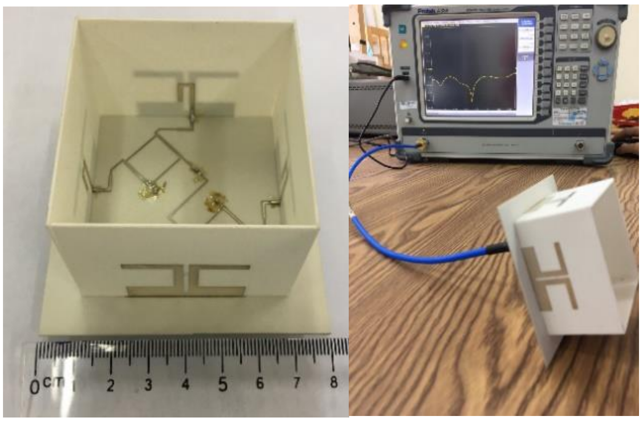


Figure 8. CP antenna prototype

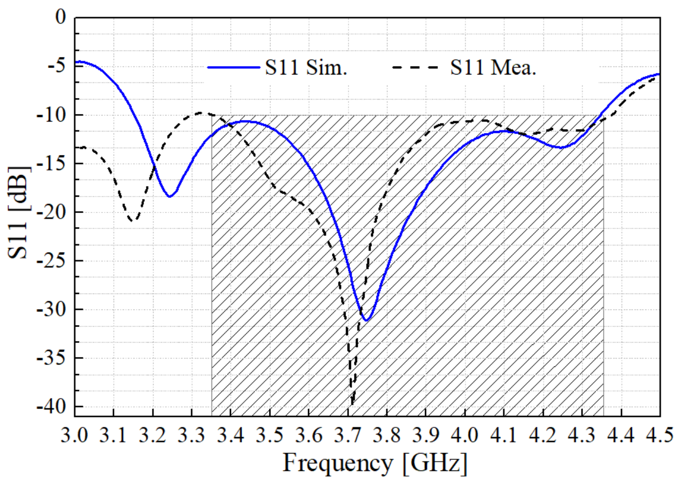
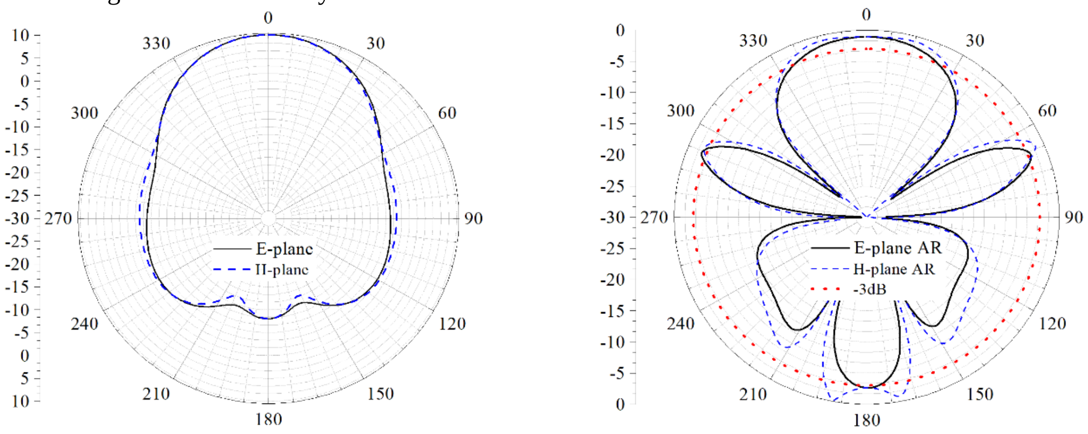


Figure 9. Simulated and measured S11

Figure 10 plots the simulated radiation pattern of our CP antenna and AR in H-plane and E-plane of the CP antenna array at 3.75 GHz. The Figure shows the antenna has a wide CP angle of 51° at 3.75 GHz. Figure 11 depicts the simulated AR and gain of the CP antenna array vias frequency. The array (AR) is less than 3 dB in the band of 3.6 GHz - 3.9 GHz (7.5%). It means that the proposed CP antenna array has high CP bandwidth of 250 MHz. This band's peak gain is more than 10.66 dBi with a maximum value of 10.73 dBi at 3.75 GHz. The total radiation efficiency is up to 93.75%. At 3.75 GHz, the beam-width of circular polarization is 51°. Table 4 summarizes the results of several circular polarization antennas [5], [6], [16], [17] which have a wide bandwidth, a circular polarization, and a 3D structure. Our proposed design has a higher gain at the microwave frequency ranges than in [5], [6], [16], [17]. The proposed design has wider bandwidth and wider bandwidth of CP compared to [6], [16]. However, the total dimension of antennas in [16], is smaller than our antenna dimension. The smallest bandwidth antenna in [6] (BW=100 MHz) has the smallest size (0.32×0.32×0.12). It is depict that the more broadband antenna is, the bigger the antenna dimension is. The very high gain, CP, wideband, and low-profile are advantages of our proposed antenna. This antenna is easy to be integrated into the 5G system.



(a) (b)

Figure 10. These figures are, (a) Radiation arrangement of CP antenna at 3.75 GHz in E-plane and H-plane, (b) Simulated AR in H-plane, E-plane of the CP antenna array at 3.75 GHz

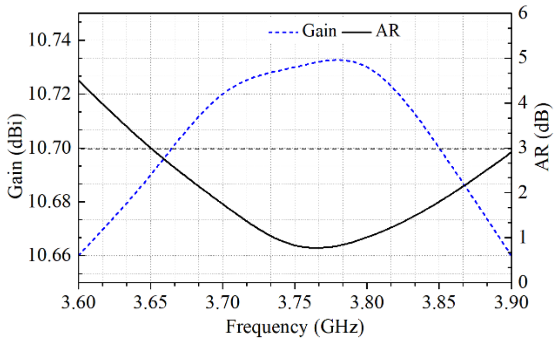


Figure 11. Simulated antenna array gain and axial ratio

Table 4. Comparison with related works

Ref	Freq (GHz)	Gain peak (dBi)	BW (MHz)	BW of CP (GHz)	Antenna size (λ)*
[5]	2.5	8.24	1200	1.4÷2.0 2.1÷2.35 2.4÷2.6	1×1×0.39
[6]	1.56	~ 4.8	100	1.52÷1.56	0.32×0.32 ×0.12
[16]	1.6	~ 5.5	500	1.52÷1.65	0.53×0.53
[17]	5.8	9.8	2800	5.5÷6.2 6.35÷6.8	0.9×0.9×0.38
This work	3.75	10.73	1000	3.6÷4.93	1.0×1.0×0.5

3. CONCLUSION

The wideband CP antenna array with four printed dipole antenna elements is depicted in this paper. Our antenna array obtains the CP by applying the SR feeding approach based on the HC feeding network. The antenna bandwidth is 26.7% (at -10 dB), and the beam-width of circular polarization is 51°. The antenna achieves a peak gain up to 10.73 dBi. The centre frequency of 3.75 GHz, the antenna can be applied for 5G devices that prefer high gain and wideband CP antenna characteristics.

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Thao Hoang Thi Phuong received the Dipl. of Engineer (2004), Master of Science (2007), and PhD degree (2019) in Electronics and Telecommunications from Hanoi University of Science and Technology, Vietnam. Currently, she is a lecturer at Electronics and Telecommunications Faculty, Electric Power University, Vietnam. Her research interests are antenna design, high-frequency circuits, metamaterials, wireless communication, and localization systems. She has had serveral publicattions in the ISI, Scopus jounals and international conferences in antenna and wireless communication field. She has a total experience of 15 years teaching and researching experience.

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