Circularly Polarized Patch Antenna for Future 5G Mobile Phones

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ABSTRACT A circularly polarized patch antenna for future fifth-generation mobile phones is presented in this paper. Miniaturization and beamwidth enhancement of a patch antenna are the two main areas to be discussed. By folding the edge of the radiating patch with loading slots, the size of the patch antenna is 44.8% smaller than a conventional half wavelength patch, which allows it to be accommodated inside handsets easily. Wide beamwidth is obtained by surrounding the patch with a dielectric substrate and supporting the antenna by a metallic block. A measured half power beamwidth of 124° is achieved. The impedance bandwidth of the antenna is over 10%, and the 3-dB axial ratio bandwidth is 3.05%. The proposed antenna covers a wide elevation angle and complete azimuth range. A parametric study of the effect of the metallic block and the surrounding dielectric substrate on the gain at a low elevation angle and the axial ratio of the proposed antenna are presented.

INDEX TERMS Antenna radiation patterns, beamwidth enhancement, microstrip patch antennas, satellite antennas, size reduction.

I. INTRODUCTION

Since 4G has been deployed and becomes maturity, many interests are focusing on the future 5G communication system. Most of the research efforts are paying on the land communication and the polarization of the related antennas are linear. However, 5G mobile phones may include the function of satellite communication. Terrestrial cellular system has been well developed in urban area to provide good coverage and high quality of telecommunication service. Users are able to enjoy instantaneous two-way voice, message and even data communications for sharing photos or watching streaming video. However, the existing terrestrial network may not fully cover all remote areas in the world. In order to obtain ubiquitous wireless coverage on the earth, mobile satellite communication service [1] is the complement. It offers services including safety communications, broadcasting and accurate global positioning.

In the user terminals, the design of antennas for the handheld device is one of the most critical points for the mobile satellite communication system. To suit for portable handset application, specific requirements including operating frequency, bandwidth, polarization, antenna size, manufacturing cost, and the possible interaction effects with

handset have to be taken into consideration when designing the antenna.

The size of the antenna should not be too large as it is accommodated in the mobile handset. It was mentioned in [2] that the antenna designed for Satellite Personal Communication Network should have thickness about 10-12 cm (mainly described about helical antenna) and a width is smaller than 3 cm. Therefore the antenna is required to be compact for easy installation. The mobile satellite system requires the radiation patterns of antennas be able to cover the complete azimuth range and wide range of elevation angles, such that the communication channel can be established without paying effort to track the satellite. The field of view of the antenna can be accomplished with a directional, omni-directional or semi-directional pattern [3]. In general, directional antennas have beam tracking ability [3]–[5] in which a directive beam can automatically steer in the direction of the satellite. This type of antennas has relatively high gain due to its narrow beam, but larger size and extra circuitry for beam steering functionality is needed. Applying omni-directional antennas in the system is another approach, which cover very wide angles in both elevation and azimuth. However, low gain of only 0 to 4 dBic is achieved. Comparing with omni-directional

antennas, semi-directional antennas possess higher gain and cover most of the upper hemisphere region.

This paper aims at designing a handheld CP patch antenna with wide beamwidth and high gain at the low elevation angles for handset use in future 5G mobile satellite communication. A sequential feeding approach [6] for the proposed antenna is used, as wide axial ratio bandwidth can be obtained. A regular half wavelength patch is not small, thus some size reduction techniques are applied in our design. Most of the miniature patch antennas have been proposed. They include using dielectric substrate [7], [9], slot loaded patch [10]–[12], slit loaded patch [13], [14], folded patch [15], [16], defected ground [17], addition of shorted portions [18]. Generally, narrower operating bandwidth, asymmetric radiation pattern or high back lobe may be found as tradeoffs for smaller size. To fulfil the requirement of handset mobile satellite communication, we try to reduce the size of the antenna but retain the original features of broadside radiation pattern, acceptable gain and axial ratio bandwidth. Miniature methods including folding and cutting slot on a patch as well as surrounding the patch with a dielectric substrate have been employed. Besides compact size, the design of the CP antenna should accommodate the full sky coverage above the horizon.

In other words, the beamwidth of the radiation pattern should be as wide as possible. In our design, the beamwidth can be increased by surrounding the patch with a dielectric substrate and embedding a metallic block at the back of the ground plane. In fact, some wide beamwidth techniques have been proposed in [7] and [19]–[23], such as three dimensional ground structure [7], [19]–[21], folding conducting wall [22] and filling antenna with dielectric [19], [23]. However, no parametric study of antenna gain at low elevation angles can be found in [19]–[23]. In this paper, a related parametric study is carried out on this aspect to provide more useful information about the beamwidth enhancement techniques applied to the proposed antenna. The detailed design procedure of the proposed antenna will be demonstrated and the measurement results will be displayed to validate the idea.

II. ANTENNA CONFIGURATION

Fig. 1 shows the geometry of the proposed CP patch antenna. The antenna is composed of a slotted hat shape patch, a double sided printed-circuit-board (PCB), a metallic block and a dielectric substrate surround. The patch at the top and the double sided printed-circuit-board (PCB) are displayed separately for clarity in Fig. 1(b) and (c). The radiating element, a circular hat-shaped folded patch, of diameter $D_P = 22$ mm and thickness of 1 mm, is placed above the feed substrate of ph. Eight slots are loaded in the hat-shaped patch to reform its structure. All slots are identical with dimensions $ps_h = 3$ mm, $ps_L = 2.79$ mm and $ps_w = 1$ mm. Each slot is separated to adjacent slot at an angle of $45°$ with respect to the center of the patch. The feeding structure is fabricated on a square PCB with side length $G = 30$ mm, thickness $h = 1.5$ mm,

FIGURE 1. Geometry of the proposed antenna.
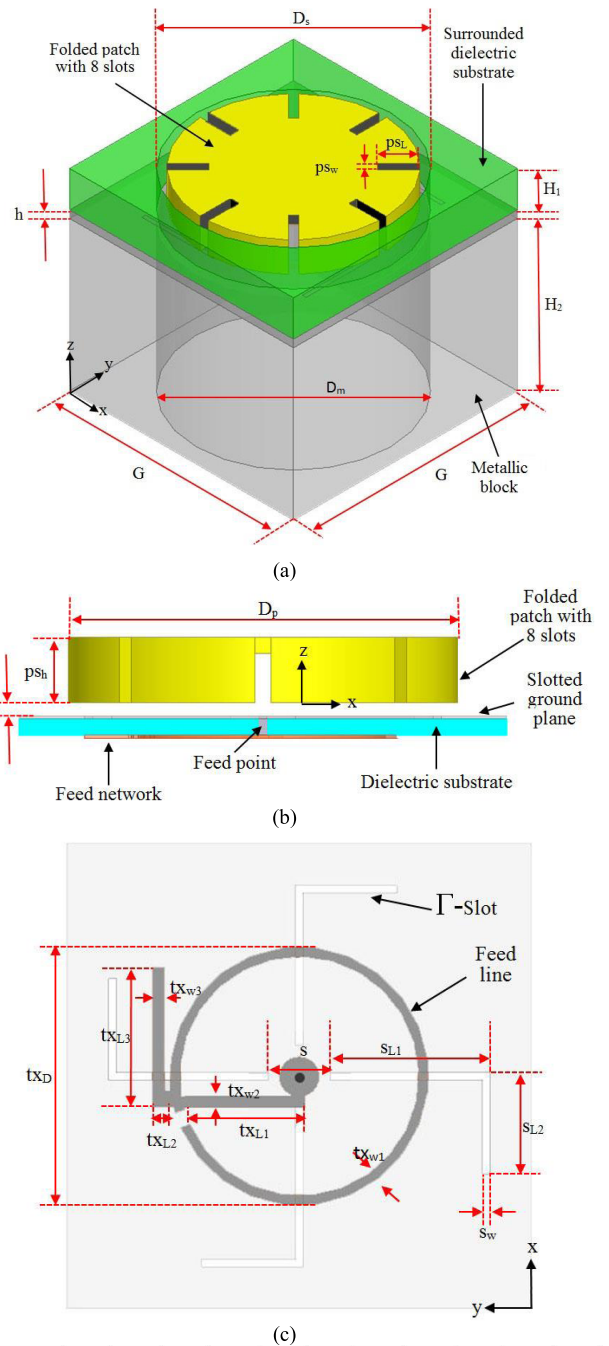
Parameters	tx_D	tx_{L1}	tx_{L2}	tx_{L3}	tx_{w1}	tx_{w2}	tx_{w3}	s	s_{L1}	s_{L2}	s_w
mm	16.7	7.8	1.39	8	0.65	0.8	0.8	4	10.3	6.55	0.5
λ_g	0.342	0.160	0.028	0.164	0.013	0.016	0.016	0.082	0.211	0.134	0.010

Parameters	D_p	p_h	ps_h	ps_w	ps_L	D_s	D_m	H_1	H_2	G
mm	22	4	3	1	2.79	24	26	4.5	20	30
λ_0	0.276	0.050	0.038	0.013	0.035	0.302	0.327	0.057	0.251	0.377

f_0=3.77GHz

dielectric constant $\varepsilon_r = 2.65$, and loss tangent $tan\tilde{o} = 0.002$. On the top side of the PCB, four identical Γ-shaped slots are etched on the ground plane, with their orientation sequentially rotated about the center of the antenna by $0°$, $90°$, $180°$,

and 270° respectively. The grounded slot has a width of $s_w = 0.5$ mm and a length of $s_{Lt} = s_{L1} + s_{L2}$. The separation between each opposite slot is s = 4 mm. At the bottom side of the PCB, a ring-shaped feeding microstrip line of outer diameter $tx_D = 16.7$ mm and width $tx_{w1} = 0.65$ mm is printed. It is noted that an extended potion of the microstrip line at -y direction to the center of the ring is shown. It allows the antenna to be center-fed with a connector. A bended potion of the microstrip line at the open end is an open stub for impedance matching.

Above the double-sided PCB, the circular hat-shaped patch is surrounded by a dielectric substrate with side length G = 30 mm, thickness $H_1 = 4.5$ mm, dielectric constant $\varepsilon_r = 2.65$. A cylindrical cavity with diameter $D_s = 24$ mm of the surrounded substrate is created. Below the PCB, a metallic block with height of $H_2 = 20$mm is attached. Similar to the surrounded dielectric substrate, a cylindrical hole with diameter of $D_m = 26$ mm is formed at the center of the metallic block. The detailed dimensions of the antenna are listed in Fig. 1.

III. ANTENNA PERFORMANCE

All the simulations on the proposed antenna are performed by using a commercial EM software namely HFSS (version 12). The proposed design was fabricated. The prototype is shown in Fig. 2. The VSWR of the antenna was measured by an Agilent E5071C Network Analyzer, while the gain, axial ratio and radiation pattern of the antenna were measured by a Satimo StarLab system.
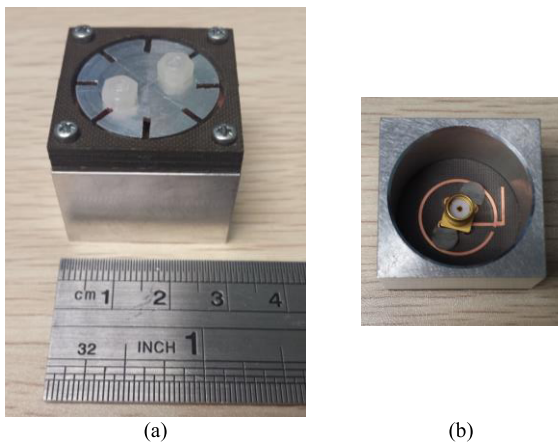

(a)   (b)

FIGURE 2. Prototype of the proposed antenna. (a) Top View. (b) Bottom View.

A. VSWR

Fig. 3 shows the simulated and measured VSWR of the proposed antenna. It can be observed that there are two resonances. They are the resonant modes from the patch and the slots on the ground plane and it has been discussed in [6]. The measured impedance bandwidth is 11.08% (VSWR <2), with a passband from 3.58 to 4.00 GHz. The simulated VSWR is below 2 from 3.53 to 4.01 GHz with an impedance bandwidth of 12.73%. The frequency range is within the S-band application.

B. AXIAL RATIO

The simulated and measured axial ratio is shown in Fig. 3. The simulated 3dB axial ratio bandwidth yields 3.44% ranging from 3.715 to 3.845 GHz. The corresponding measured 3 dB axial ratio bandwidth is 3.05% and the antenna operates between 3.715 and 3.83 GHz. The best value, 1.15 dB, can be found at 3.77 GHz.
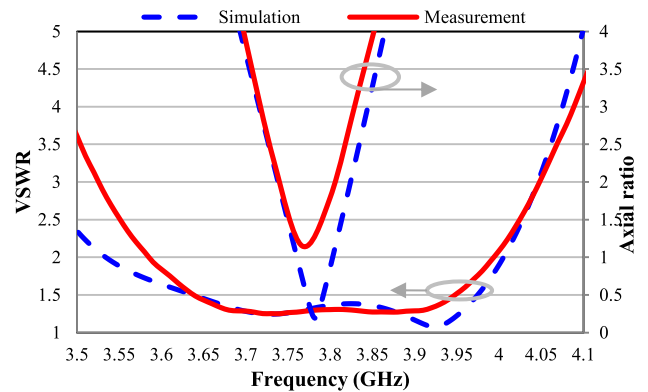

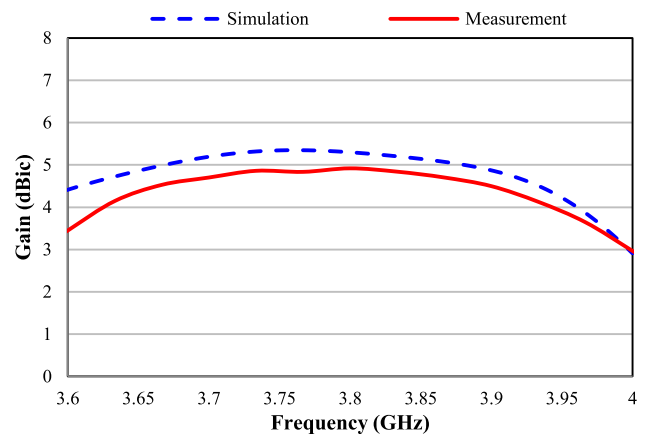**FIGURE 3.** Simulated and measured VSWR and axial ratio against frequency.

FIGURE 4. Simulated and measured gain against frequency.

C. RADIATION CHARACTERISTICS

Fig. 4 depicts the simulated and measured gain verse frequency of the proposed antenna. Within the frequency range of the 3 dB axial ratio bandwidth, the measured gain is 5 dBic with 0.2 dB variation, which is 0.5 dB lower than the simulation. The drop in antenna gain may be due to the cable and polarization loss.

The simulated and measured radiation patterns of the antenna at its resonance in the elevation-cut plane (phi = 0° and phi = 90°) have been illustrated in Fig. 5. Since the right hand circular polarization is less than the left hand circular polarization, the proposed antenna operates at left hand circular polarization. In the measurement, the half power beamwidth at 3.77 GHz is 124° in phi = 0° plane and 123° in phi = 90° plane. Symmetric radiation
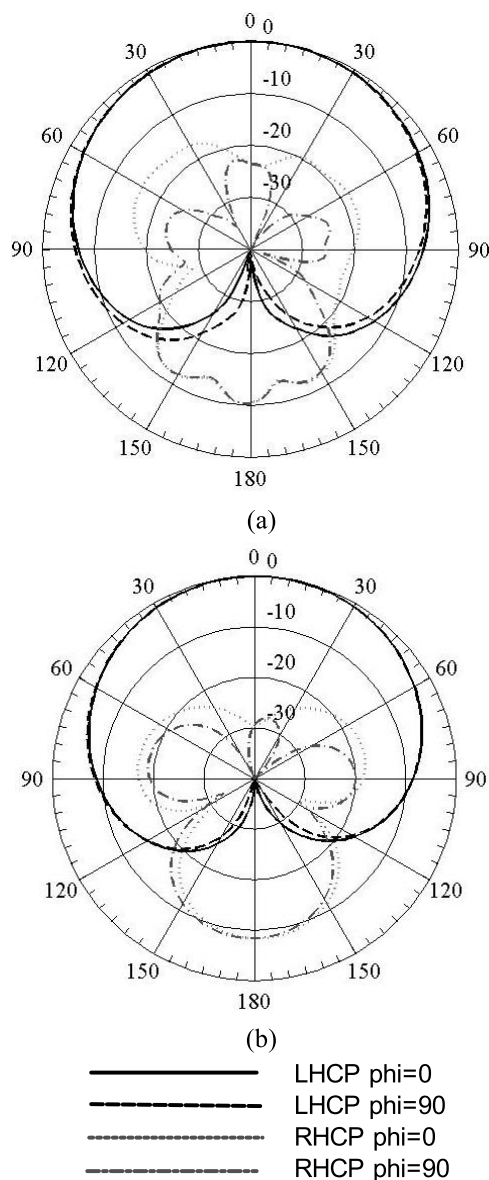
(a)

(b)

——— LHCP phi=0
– – – – LHCP phi=90
·········· RHCP phi=0
–·–·–·– RHCP phi=90

FIGURE 5. Normalized radiation pattern at 3.77GHz (a) measured (b) simulated.

——— E-Phi, theta = 30° –·–· E-Phi, theta = 50°
·········· E-Phi, theta = 70°

(a)

(b)

FIGURE 6. Measured results at 3.77 GHz (a) radiation pattern with different conic cut (b) axial ratio against theta in $\phi = 90°$ plane.

patterns can be seen in both principal planes. Apart from wide elevation coverage, the system of mobile satellite communication network also requires the antenna cover the complete azimuth range. Fig. 6(a) displays the measurement results of gain patterns in azimuth plane at theta = 30°, 50°, 70° (elevation angle = 60°, 40°, 20°). Small difference among the azimuth beam shape is observed. The gain variation is only 0.2 dB at theta = 30°, 0.47 dB at theta = 50° and 1 dB at theta = 70°. The 360° coverage in the azimuth plane is successfully demonstrated for the proposed CP patch antenna. Fig. 6(b) plots the axial ratio against theta at phi = 90° plane (yz-plane) at 3.77GHz. It is observed that the axial ratio is less than 3dB between theta = ± 90°. Hence, the proposed patch antenna possesses both wide half power and axial ratio beamwidth, which can cover much of the upper hemispherical area.
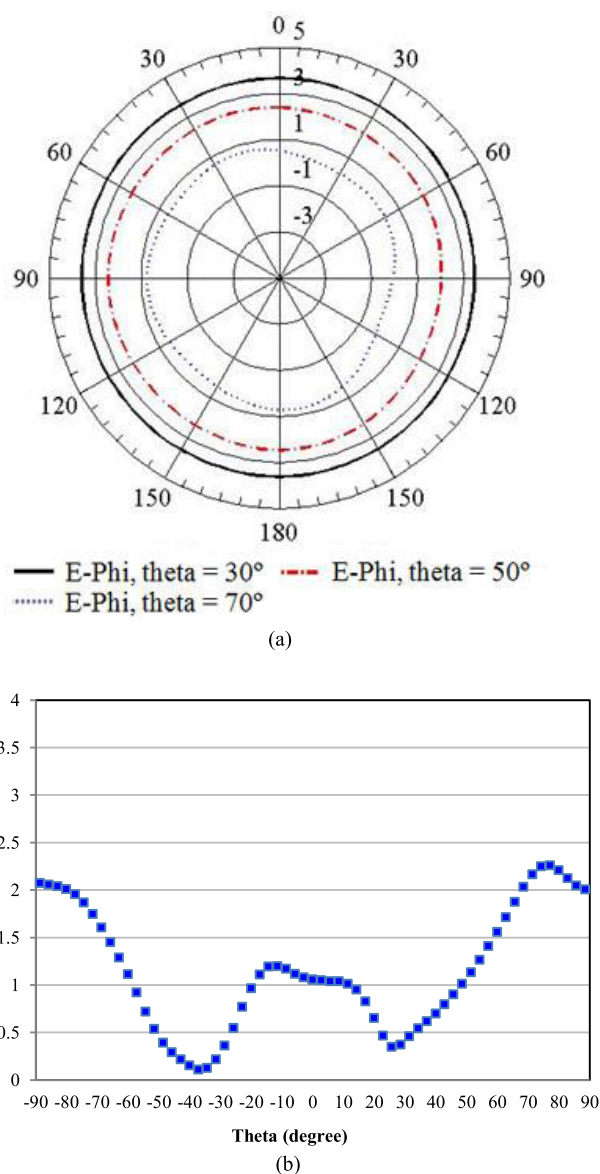
IV. PROCEDURE of ANTENNA DESIGN AND PARAMETRIC STUDIES

A. MINIMIZATION

The proposed antenna design begins with the simulation of a simple circular patch fed by a microstrip line coupling through four Γ−shaped slots. If a half wavelength circular patch is used, the size of the antenna is too large which is not applicable to handheld devices and thus miniature techniques are required. At the beginning, a circular patch with initial diameter of 24 mm is used, and is shown in Fig. 7(a). The patch is 4 mm above the ground plane. Folding the edge of patch with 3 mm downward as shown in Fig. 7(b) is the next step. A hat shape patch is formed. After that, four and eight slots are subsequently loaded on the patch. The structures are displayed in Fig. 7(c) and 7(d), respectively. Folding the radiating patch is a common way to reduce the size of
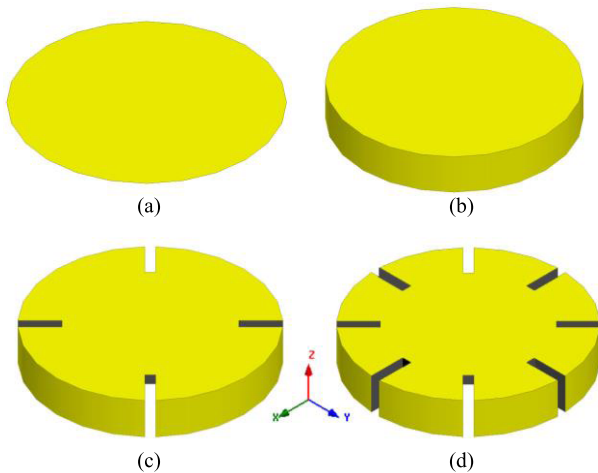
FIGURE 7. Different patch shape (a) circular patch (b) Folded patch (c) Folded patch with 4 slots and (d) Folded patch with 8 slots.
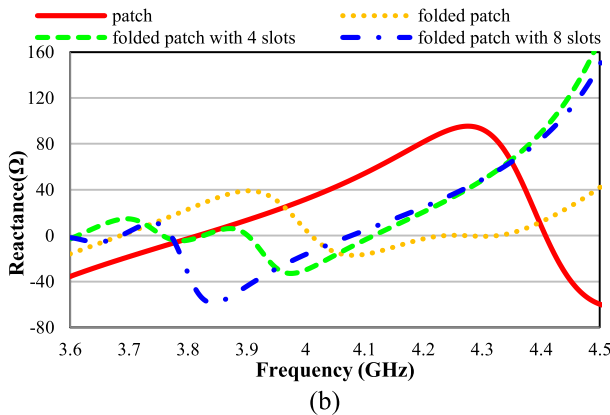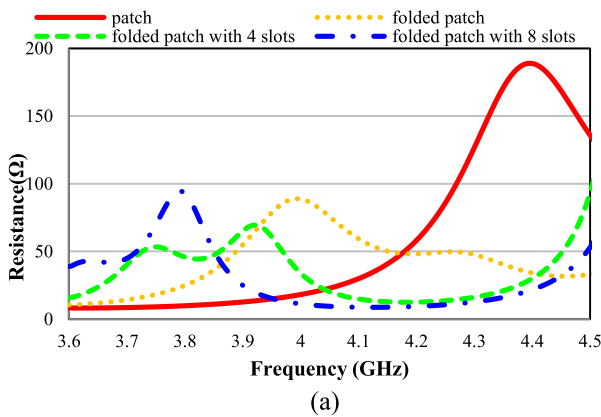

FIGURE 8. Impedance of the antenna with different patch shape (a) resistance (b) reactance.

FIGURE 9. The proposed antenna with different values of H_1 (a) axial ratio against frequency and (b) gain against theta.

an antenna. The principle of this method is that the effective current path of the antenna can be increased by folding the patch and hence the resonance of a patch antenna is able to be shifted down to a lower frequency. To further minimize the patch, four and eight slots are then loaded on the folded circular patch. The slot length is 4 mm for both cases. This approach can additionally increase the current path length on the folded patch. The simulated real part and imaginary part of the antenna impedance are plotted in Fig. 8. It is seen that the
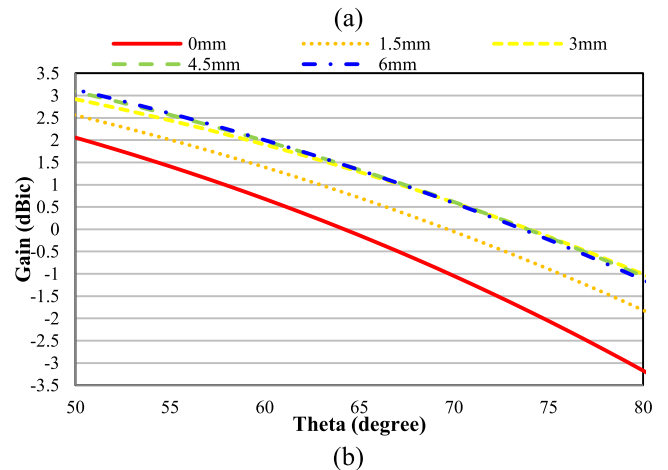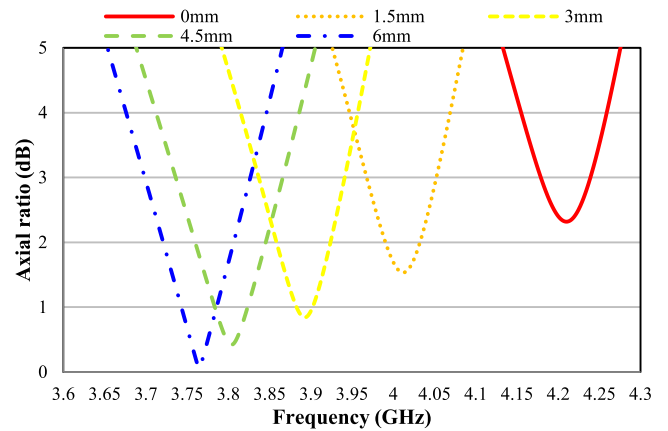
first resonant frequency is over 4.5 GHz for the initial circular patch. The resonance of the antenna shifts down to 4.15 GHz if the circular patch is folded. After cutting four slots on the folded patch, the resonance shifts down to 3.85 GHz. If four more slots are introduced, the resonance shifts to 3.7 GHz. After applying the above mentioned miniaturization techniques, the resonant frequency of the antenna can be shifted down effectively. It is noted that the slots implanted on the patch must be symmetric so as to retain symmetric radiation pattern of the antenna.

Another miniaturization technique is using a dielectric substrate. Generally, a dielectric substrate with high permittivity is loading under a patch to reduce the size of a patch antenna. High dielectric substrate placed below the patch will narrow the bandwidth, although the size of the antenna can be reduced. Instead of sandwiched between a patch and ground plane, a dielectric substrate is employed to surround the slot-loaded folded patch in the proposed antenna.

Fig. 9(a) shows the simulated axial ratio against frequency of the proposed antenna with different dielectric substrate thickness. It is noted that the best axial ratio is shifted from 4.22 GHz to 3.75 GHz when the thickness of the dielectric substrate increased from 0 mm to 6 mm. It demonstrates that surrounding the patch by dielectric substrate can also reduce the size of the antenna and the bandwidth can be retained.

B. BEAMWIDTH ENHANCEMENT

In our design, two beamwidth enhancement techniques are implemented. One is surrounding the radiating patch with a dielectric substrate and the other one is added a metallic block at the back of the antenna. For the former method, the concept is that the electromagnetic waves transmitted to and received from the patch can be refracted by the dielectric substrate and thus the half power beamwidth and the gain at low angles will be increased. As for the latter method, increasing the height of the metallic block changes the current flowing on the ground. This current is parallel to the z-direction and the gain at low elevation angles is improved finally. To deeply investigate the effect of the two proposed methods, the proposed antenna with different thicknesses of the surrounding dielectric substrate and different height of the metallic block are studied.

1) CHANGE THE THICKNESS OF THE SURROUNDED DIELECTRIC SUBSTRATE

In this part, all the parameters of the proposed antenna are fixed except the thickness of the surrounded dielectric substrate. 0 mm, 1.5 mm, 3 mm, 4.5 mm, and 6 mm are selected as the thickness of the dielectric substrate in the parametric study. Fig. 9(b) shows the simulated gain against theta (elevation angle from 10° to 40°) at $\phi = 0°$ plane with different heights of the dielectric substrate. The gain is taken at the frequency point with the best axial ratio of the corresponding substrate thickness. At theta = 50°, it is noted that the gain is 2 dBic with $H_1 = 0$ mm. The corresponding gain is 3.2 dBic with $H_1 = 4.5$ mm. The gain enhancement is about 1.2 dB. When H_1 is over 3 mm, the effect on gain enhancement is almost unchanged of 1.2 dB. The gain is −1 dBic at theta = 70° with $H_1 = 0$ mm. The corresponding gain is −0.2 dBic with $H_1 = 1.5$ mm. The gain enhancement is about 0.8 dB. The gain enhancement is saturated to 1.5 dB if H_1 is larger than 3 mm. The gain is achieved around 0.6 dBic. At theta = 80°, a significant improvement of the gain is observed when the thickness of substrate is only 1.5 mm. This low angle gain can be enhanced by 1.5 dB with $H_1 = 1.5$ mm. After that, the gain enhancement is saturated to 2.3 dB when H_1 is larger than 3 mm. It is observed that the optimized value of H_1 is 3.5 mm for enhancing the gain at low elevation angles.

Fig. 10 shows the half power beamwidth of the proposed antenna with different values of H_1. In this study, there is no metallic block. It shows that the half power beamwidth of the antenna is around 97.5° without the surrounded dielectric. The beamwidth is continuously increased with the increase of H_1. The beamwidth can be achieved a peak of 113.5° with $H_1 = 3$ mm. The beamwidth is then dropped to 109° with $H_1 = 6$ mm. Therefore, it can be concluded that the half power beamwidth does not continuously increase with the increase of H_1.

2) CHANGE The HEIGHT of The METALLIC BLOCK

In this part, a parametric study of the relationship between the height of the metallic block and the gain at low elevation angles as well as half power beamwidth is carried out.
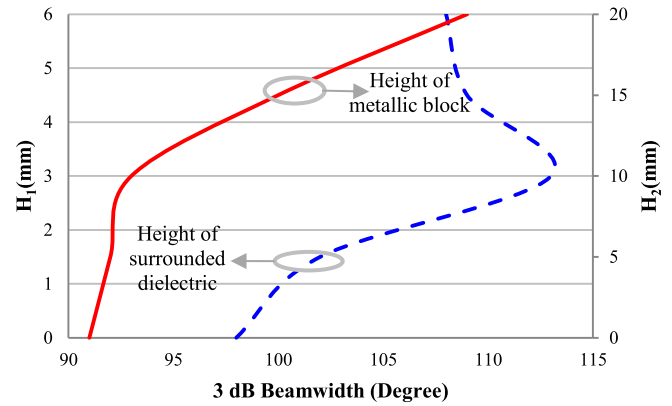

FIGURE 10. Half power beamwidth with different values of H_1 and H_2.
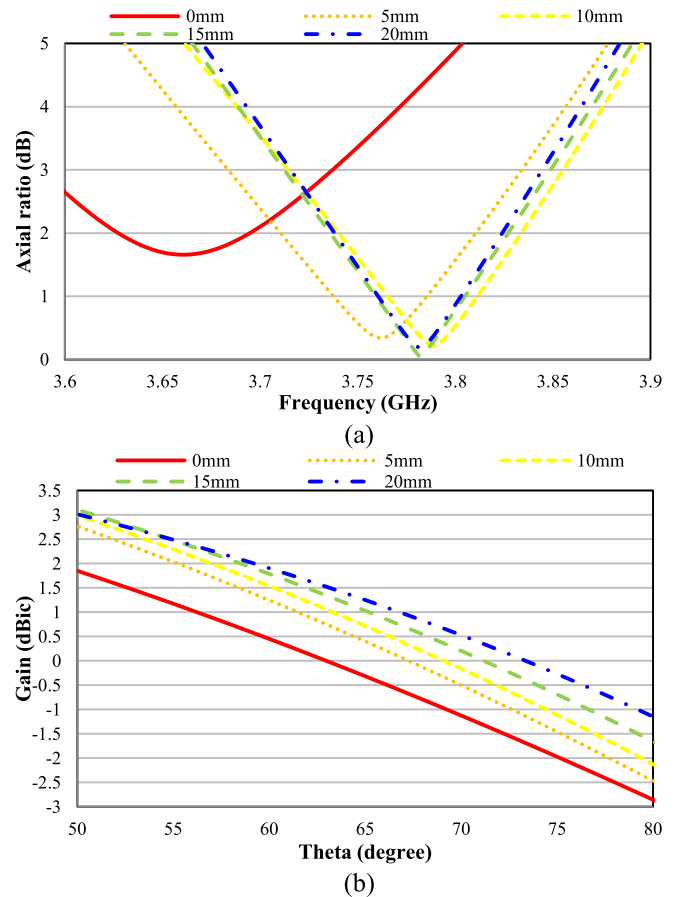
FIGURE 11. The proposed antenna with different values of H_2 (a) axial ratio against frequency and (b) gain against theta.

All the parameters of the proposed antenna are fixed except the height of the metallic block. The values of 0 mm, 5 mm, 10 mm, 15 mm and 20 mm are chosen as the height of the block. Fig. 11 shows the simulated axial ratio against frequency and the simulated gain against theta at $\phi = 0°$ plane with different heights of the metallic block. The gain is taken at the frequency point with the best axial ratio of the corresponding metallic block thickness. In Fig. 11(a), it is noted that the axial ratio is quite stable when H_2 is changed from 5 mm to 20 mm. In Fig. 11(b), the gain is increased around

TABLE 1. Performance of the proposed antenna and some exiting small-size antenna.

	Gain at (0, 0°)	Frequency	AR Bandwidth	3dB Beamwidth	Patch Length (Ground length)	
	dBic	GHz	%	°	mm	λ_0
Proposed antenna	5	3.77	3.05	124	22 (30)	0.276
Ref [7]	-0.6	1.575	0.76	132	46.5 (150)	0.25
Ref [8]	3.94	2.33	1.61	101	28 (28)	0.218
Ref [9]	6.5	2.33	1.07	<80	23 (30)	0.18
Ref [10]	6	1.525	0.65	83	66.62 (70)	0.34
Ref [11]	*	2.295	1.3	<90	33 (35)	0.25
Ref [12]	*	1.768	0.91	<90	48 (>50)	0.28
Ref [13]	*	2.306	0.41	80	40 (140)	0.31
Ref [14]	4.59	2.492	0.38	90	29 (45)	0.24
Ref [15]	4.7	1.114	1.53	100	30.5 (90)	0.11
Ref [16]	7.5	2.28	3.5	75	30 (90)	0.23
Ref [17]	2.5	1.07	1.6	96.4	19.6 (100)	0.18
Ref [18]	3.8	2.492	0.682	<85	11.35 (21)	0.1

*No information provided in the paper.

0.7 dB to 1.2 dB at theta $= 50°$ with $H_2 = 5$ mm, 10 mm, 15 mm and 20 mm. The variation is only 0.5 dB, which is quite stable. At theta $= 70°$, the gain is -1.1 dBic without the metallic block. When H_2 is increased to 5 mm, 10 mm, 15 mm and 20 mm, the gain is increased by 0.6 dB, 1 dB, 1.33 dB and 1.65 dB when compared with that of no block. At theta $= 80°$, the difference of the gain enhancement is 0.4 dB for every 5 mm increment of H_2 between 0 mm and 20 mm. Without the metallic block, the gain is -2.8 dBic. After mounting on the metallic block with a height of 20 mm, the gain is improved by 1.6 dB to -1.2 dBic.

Fig. 10 shows the half power beamwidth of the proposed antenna with different values of H_2. In this study, there is no surrounded dielectric. It is seen that the half power beamwidth of the antenna is around 92° without the metallic block. The half power beamwidth can be enhanced by 10° and achieved 110° by applying a metallic block with $H_2 = 20$ mm. The trend of the 3 dB beamwidth curve is increased continuously. It is found that the use of the metallic block can enhance the half power beamwidth effectively. From the studies, it is recommended that the metallic block and the dielectric substrate should be used together in order to optimize the beamwidth of the proposed antenna.

3) SUMMARY

In real application, the performance of the antenna is often deteriorated by the casing of handheld devices, especially metal casings. The study of the metallic block at the back of the antenna can not only investigate the influence of the beamwidth enhancement but also imitate the real casing

of handsets. From the parametric study, it is found that the axial ratio of the proposed antenna is very stable with different height (H_2) of the metallic block. In addition, the height of the metallic block can help improve the half power beamwidth and the gain at low elevation angles. The result implies that the performance of the antenna can be improved by the use of a metallic casing in product design. Even though it seems that the metallic block increases the height of the antenna, the enhanced height actually can be considered as a portion of the casing. In our design, a metal casing has contribution to the performance of the antenna, especially the low elevation gain and half power beamwidth.

The comparison of the antenna size, 3dB beamwidth, gain and axial ratio bandwidth between the proposed antenna and some small-size CP antennas [7]–[18] are summarized in Table I. It shows that the patch lengths of the antennas are ranging from 0.1 to 0.34 λ_0. Even though the patch sizes of the antennas are compact, it does not mean that the antenna size are small because of relatively large ground planes are used. The data in Table I also indicate that 3dB axial ratio bandwidths of most of the small CP patch antennas are less than 2%, except the antenna in [16]. However, the antenna reported in [16] has a large ground plane and the 3dB beamwidth is not sufficient wide. The proposed antenna possesses very wide 3 dB beamwidth and high gain in terms of its small size and wide 3dB axial ratio bandwidth, which is comparable to other compact patch antennas.

V. CONCLUSION

A compact circular polarized patch antenna with wide beamwidth for handheld device for future 5G application has been presented. In order to well-suit for the use in handset and fulfil the pattern requirement of the application, a procedure of miniaturization and beamwidth enhancement for the proposed CP antenna have been shown in details. The optimized design was fabricated and tested. The measurement results show that the CP antenna is able to cover wide elevation angles and the complete azimuth range (0°–360°). Medium gain of 5 dBic is obtained and the measured 3dB axial ratio bandwidth is 3.05%. The promising results allow the proposed CP patch antenna to be utilized in the future 5G mobile phones for satellite communication applications.

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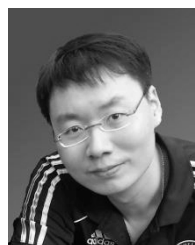
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