Design of a Wideband Dual-Feed Circularly Polarized Antenna for Different Axial Ratio Requirements

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***Abstract*—A novel method of designing a wideband dual-feed circularly polarized (CP) antenna is presented for different axial ratio (AR) requirements. The output characteristics of the feed network for the dual-feed CP antenna is first analyzed and illustrated that how to obtain the variance ranges of the output magnitude and phase of the feed network for a required AR. Based on the analysis, different branch-line couplers are used for achieving wide AR bandwidths of less than 3 dB, 2 dB, and 1 dB respectively. Compared to the traditionally used 3 dB coupler, the presented feed method can have an AR peak with the expected value at the center frequency and two AR valleys beside the peak, while the traditional 3 dB coupler can only get an AR valley with narrower bandwidth. Therefore, much wider AR bandwidths for different AR requirements are obtained by using the presented method. The wideband dual-feed antenna fed by these different couplers was also simulated, fabricated, and measured for the final performance verification.**

***Index Terms*—Axial ratio, circularly polarized antenna, dual-feed, wide bandwidth.**

I. Introduction

To increase the communication channel capacity and reduce the multi-path fading effect, and also because of the advantage of orientation flexibility between the transmitting and receiving antennas [1], circularly polarized (CP) antennas are widely applied in many wireless communication systems, such as satellite, navigation, radar, radio frequency identification, etc. With the increasingly wider communication bandwidth requirement, wide impedance and axial ratio (AR) bandwidths are commonly needed for these CP antennas.

A traditional and simple method to develop a CP antenna is using the quadrature feed networks to excite two orthogonal radiating modes on a single patch [2]-[4] or the crossed dipoles [5]-[8]. By using the orthogonal even-odd mode on the inverted-F patch [3], good CP radiation is realized by using a Wilkinson power divider. To obtain a wider bandwidth for CP radiation, a crossed bowtie-shaped dipole antenna using a wideband 90° phase shift line [8] is developed with the relative AR bandwidth of 51.8%. In addition, by using monopoles [9]-[10] and slots [11]-[13], much wider AR bandwidth is achieved. In [12], by using tapered slot and wideband Schiffman quadrature phase shifter, an overlapped bandwidth of 105.8% for both impedance and AR is obtained.

In these designs, the quadrature feed networks are the key components for the wideband CP radiation. However, it is not clear yet how the required output magnitude and phase variance ranges of these quadrature feed networks can actually affect the AR bandwidth of these CP antennas. In some high communication quality required systems, the radiated AR is required to be lower than 2 dB, or even lower than 1 dB. However, to meet these specified much lower AR bandwidth requirement, what the variance ranges of the output power and phase should the feed network have is not clear, all the designers need to do is trying to reduce the variance ranges as much as possible.

In this letter, the relation between the radiated AR and the output magnitude and phase of the feed network for the dual-feed CP antenna is first theoretically investigated. Then, variance ranges of the output magnitude and phase of the feed network for different specified AR requirements are obtained. Based on the analysis, 4.78 dB, 4.1 dB, and 3.53 dB branch-line couplers are used to obtain the wide AR bandwidth of less than 3 dB, 2 dB, and 1 dB, instead of using the traditional 3dB branch-line coupler. The presented method is also verified by the simulation and measurement, which show that this method can be effectively increase the AR bandwidth of the dual-feed CP antenna for different AR bandwidth requirements.

II. Feed Network Analysis

In this section, the output characteristics of the feed network for the dual-feed CP antenna is analyzed and discussed for the required variance ranges of magnitude and phase for the feed network to obtain the wide AR bandwidth. Fig. 1 (a) shows the equivalent circuit of a dual-feed CP antenna. In the figure, two crossed dipoles are used to realize x-axis polarized radiation and y-axis polarized radiation respectively. The input ports for the dual-feed CP antenna are designated as ports 4 and 5. A quadrature feed network is used to drive the crossed dipoles for CP radiation with the input port 1 and output ports 2 and 3.

Suppose that the connections between the power divider and the crossed dipoles are ideally matched, the crossed dipoles are highly isolated, and the radiated radiation patterns have high polarization purity (This is also common for the practical

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antenna design), then the following far-field radiation characteristic depending on the outputs of the feed network can be obtained.

$$\frac{E_x}{E_y} = \frac{S_{21}}{S_{31}} = Me^{j\phi} \tag{1}$$

where $M = |S_{21}/S_{31}|$ and $\phi = \angle(S_{21}/S_{31})$.

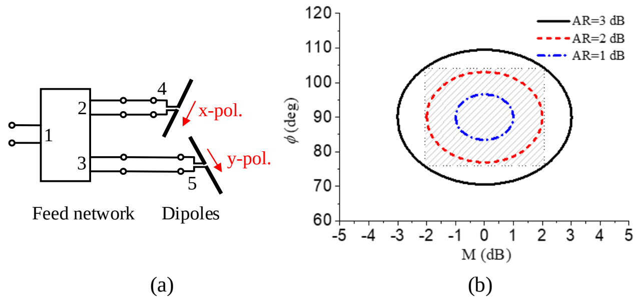


Fig. 1. (a) Equivalent circuit of a dual-feed CP antenna. (b) The calculated curves when AR=3 dB, 2 dB, and 1 dB using (4).

TABLE I. VARIANCE RANGE OF M AND ϕ FOR DIFFERENT AR REQUIREMENTS

AR (dB)	M (dB)	ϕ (°)	AR (dB)	M (dB)	ϕ (°)
< 3	0	(70.5, 109.5)	< 2	0	(76.9, 103.1)
	(-3, 3)	0		(-2, 2)	0
	(-2.13, 2.13)	(76.3, 103.7)		(-1.41, 1.41)	(80.8, 99.2)
< 1	0	(83.4, 96.6)			
	(-1, 1)	0			
	(-0.7, 0.7)	(85.3, 94.7)			

In addition, the AR of a radiated CP wave can be determined by its far-field components (E_x and E_y) [14]. Without loss of generality, the right-hand polarized wave is analyzed for illustration, and the resulted AR can be expressed as

$$\begin{aligned} AR &= cot\varepsilon \\ sin2\varepsilon &= sin2\gamma sin\phi \\ tan\gamma &= M \end{aligned} \tag{2}$$

After the simplification of (2), one can get the following relation between AR, M, and ϕ.

$$sin\phi = \frac{M + 1/M}{AR + 1/AR} \tag{3}$$

Therefore, the relation of the resulted AR between the output characteristics (M and ϕ) of the feed network is established. One can directly use the defined output parameters of the feed network (M and ϕ) to evaluate the AR performance of a dual-feed CP antenna.

It will be a little difficult to get an intuitive understanding for (3). Interestingly, when $(|\phi| - \pi/2) \to 0$, (3) can be approximated as an ellipse function, which is

$$\frac{(20logM)^2}{(20logAR)^2} + \frac{(\phi - \pi/2)^2}{(\pi/2 - arcsin\frac{2AR}{AR^2+1})^2} = 1 \tag{4}$$

By using this ellipse functions, it will be much easier to understand the constraint relation between M and ϕ for a given AR. Variance ranges of the output magnitude and phase of the feed network for a specified AR can be obtained by using (3) or approximated (4).

Fig. 1 (b) shows the calculated curves of AR=3 dB, 2 dB, and 1 dB using (4). The detailed calculated results are tabulated in Table I. It can be seen that, when the radiated AR is required to be within 3 dB, if the output power difference is exactly 0 dB, the output phase difference can be increased up to (70.5, 109.5)°. If the output phase difference is exactly 90°, the output power difference can be increased up to (-3, 3) dB. If both the output power and phase are varied within (-2.13, 2.13) dB and (76.3, 103.7)°, AR of less than 3 dB can be ensured. Variance ranges of other detailed AR requirements for the feed network can be obtained by calculating (4). Note that the above analysis is illustrated for the right-hand polarized wave. The difference of the variance ranges between the left-hand polarized wave and right-hand polarized wave is changing the values of the phase ranges to negative values or simply exchanging the output ports of the feed network.

III. DESIGN FOR DIFFERENT AR REQUIREMENTS

Based on the above analysis, one can get a clear understanding of how the output variance ranges of the feed network can affect the resulted AR. In this section, a dual-feed CP antenna with different required AR bandwidths is designed by designing the different output characteristics of the feed network. To get the wide AR bandwidth of less than 3 dB, 2 dB, and 1 dB, 4.78 dB branch-line coupler, 4.1 dB branch-line coupler, and 3.53 dB branch-line coupler are used as the feed network respectively, instead of using the traditional 3 dB branch-line coupler.

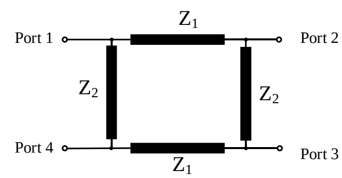


Fig. 2. Equivalent circuit of the branch-line coupler.

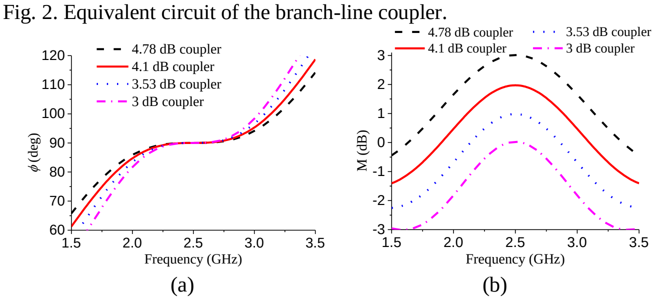


Fig. 3. (a) Phase differences and (b) power differences of the four different branch-line couplers.

Fig. 2 shows the equivalent of the branch-line coupler. By changing the characteristic impedances of the transmission lines [15], 4.78 dB coupler with output power difference of 3 dB (Z_1=40.8Ω, Z_2=70.7Ω), 4.1 dB coupler with output power difference of 2 dB (Z_1=39.2Ω, Z_2=62.9Ω), and 3.53 dB coupler with output power difference of 1 dB (Z_1=37.3Ω, Z_2=56Ω) are developed for the dual-feed CP antenna design.

Fig. 3 shows the calculated output characteristics of these four branch-line couplers. In Fig. 3 (a), all the four couplers can have the exact 90° phase shift at the center frequency, and keep almost unchanged phase shift across the wide bandwidth from 2.2 GHz to 2.8 GHz. However, as shown in the figure, 3 dB coupler has equal magnitude output at the center frequency, and gradually reduces to the negative power difference. Other couplers have the designed coupling magnitude at the center frequency, and gradually reduce to the negative values. According to the analysis in Section II, if the output phase of the feed network keeps stable at 90°, the maximum output power difference can be increased and up to 3dB for AR<3 dB, 2 dB for AR<2 dB, and 1 dB for AR<1 dB. Also observing from the figure, the phase difference becomes large as the frequency away from the center. If output power difference keeps small as the frequency away from the center, and the output power difference at the center frequency increased but still within the required variance range, then the AR bandwidth excited by the feed network can be broadened.

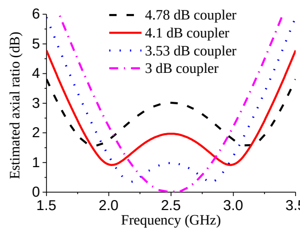


Fig. 4. Estimated AR performance by using (4).

TABLE II. ESTIMATED AR BANDWIDTH

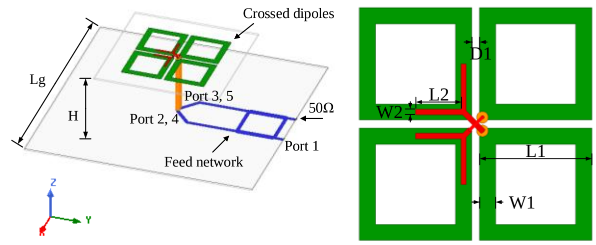
Estimated	BW (AR<3 dB)	BW (AR<2 dB)	BW (AR<1 dB)
4.78 dB coupler	72.8%		
4.1 dB coupler		56.0%	
3.53 dB coupler			37.6%
3 dB coupler	47.2%	37.6%	25.6%

The estimated AR performances of these four branch-line couplers by using (4) are shown in Fig. 4. It can be seen that the 3dB coupler has an estimated AR valley at the center frequency, but has the narrower AR bandwidth compared to other couplers. To broaden the required AR bandwidth, 4.78 dB branch-line coupler are used for the wide bandwidth of AR<3 dB, 4.1 dB branch-line coupler are used for the wide bandwidth of AR<2 dB, and 3.53 dB branch-line coupler are used for the wide bandwidth of AR<1 dB. The estimated AR responses of these three couplers all have a peak with the desired AR value at the center frequency and have two valleys beside the peak. The detailed AR bandwidths of these couplers for different AR requirements are shown in Table II. Compared to the traditionally used 3 dB coupler, the enhancement of required AR bandwidth is obvious and appealing.

IV. VERIFICATION

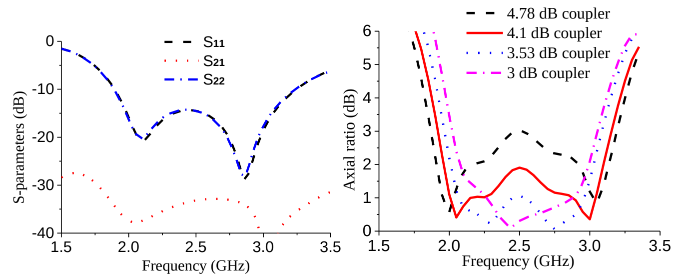
Based on the above analysis, a dual-feed CP antenna fed by these four different branch-line couplers is simulated, designed, and measured for the AR performance verification. Fig. 5 (a) shows the 3D view of the simulated dual-feed CP antenna, which is composed of a crossed-dipole radiator for dual orthogonal polarizations, a branch-line coupler as the feed network, and a square reflector for the unidirectional CP radiation. Two coaxial cables are used to connect the top radiator with the bottom feed network.

Fig. 5 (b) shows the detailed structure of the radiator. The crossed dipoles consist of four square-loops with the length of L1, width of W1, and coupling distance of D1. The dipoles are printed on the bottom layer of the substrate and shown in green color. Y-shaped stubs with the width of W2 and length of L2 are used as the top feed lines for the crossed dipoles and shown in red color. A substrate of Rogers 4003C with the relative permittivity of 3.55 and thickness of 0.813 mm is used for the radiator and feed network design. Note that the outer connector of the coaxial cable is soldered to one dipole arm, while the inner conductor is penetrated through this dipole arm without electrical connection and then soldered to the top feed line.



(a) (b)

Fig. 5. Configuration of the dual-feed CP antenna realized by using a branch-line coupler. (a) 3D view. (b) Top view of the crossed dipoles. (Detailed parameters. L1=31 mm, W1=3 mm, D1=1.5 mm, L2=9 mm, W2=1 mm. Lg=120 mm, H=30 mm.)



(a) (b)

Fig. 6. (a) Simulated S-parameters of the dual-feed CP antenna without the feed network. (b) Simulated AR performances of the dual-feed CP antenna fed by different branch-line couplers.

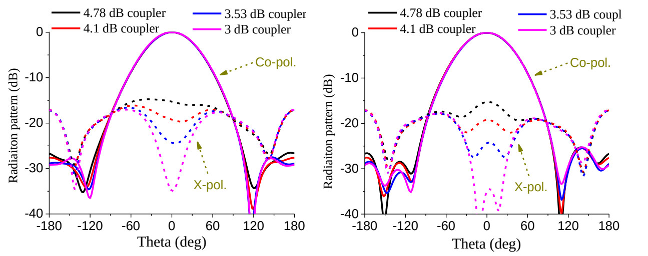
TABLE III. SIMULATED AR BANDWIDTHS FED BY DIFFERENT BRANCH-LINE COUPLERS

Simulated	BW (AR<3 dB)	BW (AR<2 dB)	BW (AR<1 dB)
4.78 dB coupler	52.2%		
4.1 dB coupler		45.1%	
3.53 dB coupler			35.4%
3 dB coupler	46.6%	35.8%	24.1%

The simulated S-parameters of the dual-feed crossed-dipole antenna without the feed network are shown in Fig. 6 (a). As can be seen in the figure, the simulated overlapped impedance bandwidth for reflection coefficients of lower than -10 dB is 1.89-3.25 GHz. The isolation between the two input ports is higher than 32.5 dB within the impedance bandwidth.

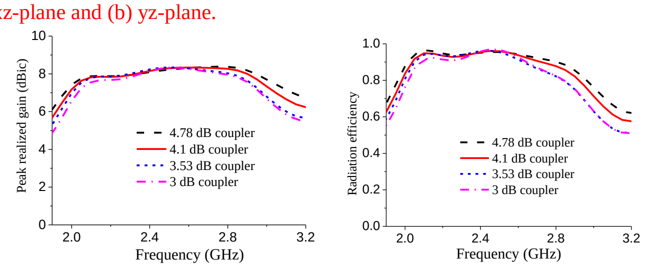
Fig. 6 (b) compares the simulated AR performances of the dual-feed CP antenna fed by difference branch-line couplers. As expected, the traditional 3 dB coupler can get the lowest AR at around the center frequency. However, it has the narrower AR bandwidth of AR<1 dB, 2 dB, and 3 dB compared to the using of 3.53 dB, 4.1 dB, and 4.78 dB couplers. By using these couplers, the simulated AR get a maximum expected value at the center frequency, which is close to the designed AR value. Then, the simulated AR gradually decreases to the minimum values beside the peaks. Therefore, the required AR bandwidths can be broadened.

The detailed simulated relative AR bandwidths are calculated and shown in Table III. The simulated related AR bandwidths are a little narrower than the estimated bandwidth shown in Table II, especially when the frequency is away from the impedance bandwidth of the dual-feed antenna. This is because that the mismatching between the input ports of the radiator and the output ports of the coupler and the isolation of the two polarized waves become seriously deteriorated at these out-of-band frequencies. The estimated AR will become inaccurate compared to the simulated AR as the frequency away from the bandwidth. However, the AR bandwidth improvement by using these three couplers is obvious, as compared to the traditional used 3 dB coupler.



(a) (b)

Fig. 7. Normalized radiation patterns in different planes at 2.5 GHz, (a) xz-plane and (b) yz-plane.



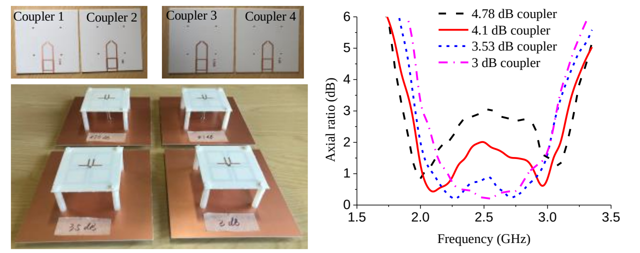
(a) (b)

Fig. 8. (a) Simulated peak realized gains and (b) radiation efficiencies of the dual-feed CP antenna fed by different couplers.

Fig. 7 shows the simulated radiation patterns in different planes at the center frequency of 2.5 GHz. It can be seen that, the co-polarized radiation patterns fed by different couplers are almost the same, and nearly no distortions can be observed for the co-polarized radiation patterns. The co-polarized radiation patterns are all symmetrical without tilt in the main beam. The obvious difference is existed in the cross-polarized radiation patterns. To broaden the AR bandwidth for different AR requirements, the cross-polarization levels are increased for the dual-feed CP antenna fed by different couplers, but they are well below the respective AR requirements.

Fig. 8 shows the simulated peak realized gains and radiation efficiencies of the antenna fed by different couplers. As shown in the figure, the antenna fed by 3 dB coupler has the narrowest gain and efficiency bandwidths due to the narrowest AR bandwidth. While the antenna fed by 4.78 dB coupler has the widest gain and efficiency bandwidths. Therefore, compared to the traditionally used 3 dB coupler, the presented method can effectively enhance the antenna gain and efficiency bandwidth.

The dual-feed CP antenna fed by these four different couplers were fabricated and measured for further verification. Fig. 9 (a) shows the photograph of the fabricated dual-feed CP antenna fed by different branch-line couplers. The measured AR performances of antenna fed by different branch-line couplers are shown in Fig. 9 (b). The antenna was measured in the far-field anechoic chamber at University of Kent. As shown in the figure, the measured AR responses agree well with the simulated results shown in Fig. 6 (b). The dual-feed CP antenna fed by the 3 dB coupler was measured with an AR valley as simulated. In addition, the antenna fed by other couplers was measured with corresponding two AR valleys and one AR peak. The detailed bandwidth enhancement for different AR requirements is shown in Table IV. The measured AR bandwidths agree well with the simulated results shown in Table III. Some minor discrepancies may be caused by the fabrication tolerance and measurement errors in the anechoic chamber.



(a) (b)

Fig. 9. (a) Photograph of the fabricated dual-feed CP antenna fed by different branch-line couplers. (b) Measured AR performances of the dual-feed CP antenna fed by four branch-line couplers.

TABLE IV. MEASURED AR BANDWIDTH FED BY DIFFERENT BRANCH-LINE COUPLERS

Measured	BW (AR<3 dB)	BW (AR<2 dB)	BW (AR<1 dB)
4.78 dB coupler	53.1%		
4.1 dB coupler		44.9%	
3.53 dB coupler			33.6%
3 dB coupler	42.2%	35.9%	24.4%

TABLE V. COMPARISON WITH OTHER DUAL-FEED CP ANTENNAS

Ref.	Height	AR Bandwidth	AR valley	Arm of the branch-line coupler
[2]	$0.068\lambda_0$	21.3% (AR<3 dB)	1	2
[4]	$0.06\lambda_0$	29% (AR<3 dB)	1	2
[6]	$0.29\lambda_0$	23.7% (AR<1.5 dB)	1	3
[7]	$0.26\lambda_0$	75% (AR<3 dB)	1	4
Presented	$0.25\lambda_0$	53.1% (AR<3 dB) 44.9% (AR<2 dB) 33.6% (AR<1 dB)	2	2

Table V compares the recently published dual-feed CP patch antennas [2], [4] and dipole antennas [6], [7] with the presented antenna, they are all using branch-line coupler as the feed network. As can be seen that, by using the simplest branch-line couple with 2 arms, the realized AR bandwidth is no more than 30% in [2] and [4]. By increasing the arms of the branch-line coupler from 2 to 4, the AR bandwidth can be further increased, as presented in [6] and [7]. However, the complexity of the feed network design is increased. In addition, all of these antenna are achieved with only one AR valley designed near the center frequency. In this work, only simple two-arm branch-line couplers are used in the CP antenna design, but wider AR bandwidth with two AR valleys are obtained utilizing the presented method.

V. CONCLUSION

This letter presents a method to design a wideband dual-feed CP antenna for different AR requirements. To meet the different AR requirements for the dual-feed CP antenna, the variance ranges of the output magnitude and phase of the feed network are first analyzed for detailed illustration. Based on the theoretical analysis, 4.78 dB, 4.1 dB, and 3.53 dB branch-line couplers are utilized for the wide AR bandwidth of less than 3 dB, 2 dB, and 1 dB, instead of using the traditional 3 dB coupler. Finally, the design method of the wideband dual-feed CP antenna fed by different branch-line couplers for different AR requirements is verified by both simulation and measurement.

REFERENCES

[1] S. Gao, Q. Luo, and F. Zhu, *Circularly Polarized Antennas*. Hoboken, NJ, USA: Wiley, 2013.

[2] M. He, X. Ye, P. Zhou, G. Zhao, C. Zhang and H. Sun, "A small-size dual-feed broadband circularly polarized U-slot patch antenna," IEEE Antennas Wireless Propag. Lett., vol. 14, pp. 898-901, 2015.

[3] L. Sun, Y. Li, Z. Zhang, and Z. Feng, "Low-profile compact circularly polarized slot-etched PIFA using even and odd modes," *IEEE Trans. Antennas Propag.*, vol. 67, no. 6, pp. 4189-4194, June 2019.

[4] W. Zhu, S. Xiao, R. Yuan, and M. Tang, "Broadband and dual circularly polarized patch antenna with H-shaped aperture," *2014 Intern. Symp. Antennas Propag. Conf. Proc., Kaohsiung,* 2014, pp. 549-550.

[5] R. Xu, J. Li, and W. Kun, "A broadband circularly polarized crossed-dipole antenna," *IEEE Trans. Antennas Propag.*, vol. 64, no. 10, pp. 4509-4513, Oct. 2016.

[6] Y. Luo, Q. Chu, and J. Bornemann, "Enhancing cross-polarisation discrimination or axial ratio beamwidth of diagonally dual or circularly polarised base station antennas by using vertical parasitic elements," *IET Microw. Antennas Propag.,* vol. 11, no. 9, pp. 1190-1196.

[7] H. Sun, H. Zhu, C. Ding, and Y. J. Guo, "Wideband planarized dual-linearly-polarized dipole antenna and its integration for dual-circularly-polarized radiation," *IEEE Antennas Wireless Propag. Lett.*, vol. 17, no. 12, pp. 2289-2293, Dec. 2018.

[8] Z. Zhang, N. Liu, J. Zhao, and G. Fu, "Wideband circularly polarized antenna with gain improvement," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 456-459, 2013.

[9] Y. Cai, K. Li, Y. Yin, and W. Hu, "Broadband circularly polarized printed antenna with branched microstrip feed," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 674-677, 2014.

[10] X. Yang, Y. Z. Yin, W. Hu, and S. L. Zuo, "Low-Profile, Small Circularly Polarized Inverted-L Antenna With Double-Folded Arms," *IEEE Antennas Wireless Propag. Lett.,* vol. 9, pp. 767-770, 2010.

[11] C. Lee and Y. Chang, "An improved design and implementation of a broadband circularly polarized antenna," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3343-3348, June 2014.

[12] R. Xu, J. Li, Y. Qi, Y. Guangwei, and J. Yang, "A design of triple-wideband triple-sense circularly polarized square slot antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1763-1766, 2017.

[13] X. Ding, Z. Zhao, Y. Yang, Z. Nie, and Q. H. Liu, "A compact unidirectional ultra-wideband circularly polarized antenna based on crossed tapered slot radiation elements," *IEEE Trans. Antennas Propag.*, vol. 66, no. 12, pp. 7353-7358, Dec. 2018.

[14] J. D. Kraus and R. J. Marhefka, *Antennas for All Applications,* 3rd ed. New York, NY, USA: McGraw-Hill, 2001.

[15] R. E. Collin, *Foundations for Microwave Engineering*, 2nd ed. New York, NY, USA: IEEE &Wiley, 2001.