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A Wide Axial Ratio Bandwidth Circularly Polarized Filtering Antenna Using Two Quarter Wavelength Resonators

D.A. Cahyasiwi, Ali Musyafak, Teguh Firmansyah, Yus Natali, Dian Widi Astuti *Member, IEEE*, and E. T. Rahardjo

***Abstract*— This study proposes a single feedline technique result a wide axial ratio bandwidth circularly polarized filtering antenna. The antenna is designed to operate at 4.65 GHz. The design employed a rectangular radiator and two quarter wavelength resonators. The two components are integrated using single feedline and proximity coupling. The quarter wavelength resonators excited the second modes polarization on the coupled rectangular radiator. The combination of width and length of the radiator as well as the gap between the second resonator and radiator equalized the two modes e-fields' magnitude. The design requires no additional delay circuit, for the gap between the second resonator and radiator provides both selectivity and a 90° phase shift delay. The proposed design has an axial ratio bandwidth of 8.2% and an impedance bandwidth of 11.2%. The use of two resonators results in a gain curve resembling a bandpass filter response, with a maximum gain of 6.5 dBic. The antenna is fabricated and measured to validate the proposed method, and the measurement results align well with the simulation results.**

***Index Terms*— circular polarization, 5G, two quarter wavelength resonator, single feedline, second-order filter, wide axial ratio**

I. INTRODUCTION

A CIRCULARLY polarized (CP) antenna has the benefit of combating the multipath propagation [1], accommodating the object movement [2] and increasing the channel capacity rather than the linear polarization [3]. Many methods were proposed to obtain a circularly polarized patch antenna such as using single feed line with radiator perturbation [4]–[6], helical shape antenna [7], [8] and two orthogonal elements [9], [10]. In the two orthogonal feedlines method, a 90° delay circuit is essential to ensure the generation of circular polarization. Conversely, in the single feedline approach, a perturbation radiator is employed to manipulate the surface current flow on the radiator, achieving circular polarization. It is known that two orthogonal feedlines techniques can provide wider axial ratio bandwidth than the single feedline because with the right composition the two feedlines can create two oscillations on axial ratio thus widening the axial ratio bandwidth [2], [11]. However, many single feedline techniques have been conducted to obtained a wide axial ratio bandwidth using parasitic elements [12]–[15].

Recently, a new method of combining integrated antenna and filter has resulted in filtering antenna with linear or circular polarization [16]–[18]. This approach enables the simultaneous achievement of selectivity and polarization features through an integrated step design. In most cases, integrating an antenna and filter is primarily performed to add the selectivity function to an antenna [19]–[22]. However, some studies have proposed filtering antennas with an added circular polarization feature, achieved through two orthogonal feedlines [2], [11], [23], circular disk radiator [24], truncated radiators, and cross slots [5], [25], [26]. These methods typically involve a two-step design process, with the first step focusing on the filtering structure design and the second step on the circular polarization stimulation design.

The prevalent approach in designing a filtering antenna involves substituting the final stage resonator of the filter with a radiator [24], [27]. Several studies have explored these types of filtering antennas with circular polarization using two orthogonal feedlines [2], [11], [23], [28]. However, all CP filtering antennas that employ two feedlines were designed with both a filtering structure and an added delay circuit, making the design process more complicated due to the requirement of a two-step design approach. Our previous studies revealed that the integration of antenna and filter can be combined with the polarization generator to provide linear and circular polarization [16]–[18], [29]. This method simplifies the design process of filtering antenna with specific polarizations. By applying this method, a second-order CP filtering antenna is designed using a single feedline[16]. However, its axial ratio bandwidth remains narrow even when designed with double-layer substrates. The design employed a single resonator and even the selectivity response was acceptable for filtering antenna characteristics, it did not convey the second order filtering antenna.

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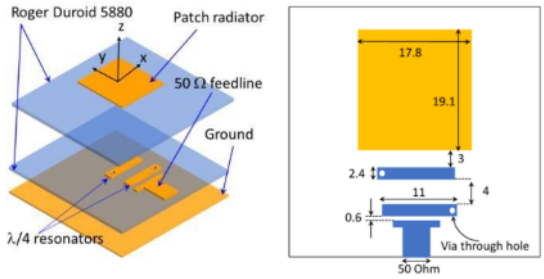


Fig. 1 The configuration of the proposed CP filtering antenna (a) 3-dimension view with transparent substrates and (b) Top view with transparent substrates and dimension (all units in mm)

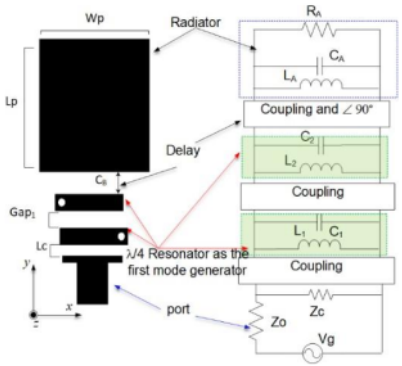


Fig. 2 Equivalent circuit and design concept

The selectivity of a cascade filtering antenna is affected by the order used. Therefore, this study strives to improve the selectivity, impedance and axial ratio bandwidth by implementing a higher-order filter circuit than the previous design in [16]. The design adopts the third order of filtering antenna to generate circular polarization, resulting in improved selectivity, wider axial ratio and impedance bandwidth using only a single feedline. The filtering circuit and polarization generator were designed simultaneously, eliminating the need for an additional delay circuit The antenna is designed to operate at 4.65 Ghz.

II. Antenna Design

A. Antenna Configuration

As shown in Fig. 1(a) and Fig. 1(b), the antenna consists of a rectangular radiator measuring 17.8 mm × 19.10 mm printed on the upper substrate, coupled with two λ/4 resonators with thickness of 2.4 mm and 11 mm length lay on the below substrate. There is a 3 mm space between the second λ/4 resonator and the radiator, which not only provides coupling between them but also a 90° phase delay. There is 4 mm gap between the quarter wavelength resonators. The first resonator is coupled to a 50-ohm feed lines with a space of 0.6 mm. The extraction of the radiator and the resonator are conducted as in [16] where the length of radiator (L_p) determined its resonance frequency. The length (P_k) and width of resonator as well as the position of a via through hole determined its resonance frequency [16], [17], [29]. The via through hole not only function as λ/4 resonator but also as an instrument to induce the second mode polarization on the radiator. All the structures are printed on 50 mm × 50 mm two double layers substrate of Roger Duroid 5880.

B. Equivalent Circuit and Design Procedure

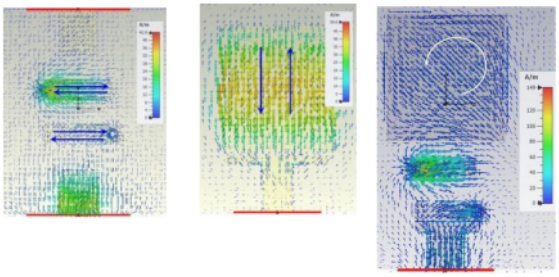
The equivalent circuit network of the CP filtering antenna is shown in Fig. 2, where two series of the resonator are described as L_1, C_1 and L_2, C_2 for the first and second resonators respectively. The short circuit holes on the left and right arms of the first and second resonators lead to a horizontal current flow along the transmission line. Upon reaching the rectangular radiator (L_A, C_A and R_A), there arises an interaction between two electric field vectors that are orthogonal to each other. The CP filtering antenna is obtained when the two vectors magnitude are balanced, and the phase delay is 90°. The space between the second resonators and radiator (*CB*) functions both as the delay circuit and coupling. The radiator's dimension is not square, dissimilar to the orthogonal feedline methods. *Wp* should be marginally shorter than L_p to balance the magnitudes of the orthogonal vectors. The space between the resonator (Gap_1) affects the bandwidth impedance, selectivity response and axial ratio on the center and lower frequency.

The concept of the orthogonal resonators refers to the fundamental equation of the electromagnetic wave polarization vector in (1). This equation explicates that the polarization vector is the resultant of the superposition of two distinct polarization vectors, each oriented orthogonally in the θ and φ directions. The production of circular polarization is subject to the equal magnitude of the θ and φ vectors as in (2) and a phase difference (δ_L) of approximately ±90° between these vectors. Consequently, orthogonality of these vectors can be established through the integration of two resonators featuring orthogonal current orientations. In the context of this study, this is exemplified by the utilization of the two quarter-wavelength resonators in the θ direction as the first resonator, and a rectangular radiator in the φ direction as the second resonator.

$$\bar{E} = E_\theta cos(\omega t)\hat{\theta} + E_\Phi cos(\omega t + \delta_L)\hat{\Phi} \quad (1)$$

$$|E_\theta| = |E_\Phi| \quad (2)$$

The orthogonality can be observed from the surface currents of both resonators, as seen in Fig. 3(a), where the horizontal surface current of two λ/4 resonators flows reversely along the *x*-direction from the open circuit to short circuit (via through hole). On contrary, Fig. 3(b) depicted the radiator surface current that flows along the vertical position or *y* direction when fed from the lower side of its length. Both circuits must operate at identic frequency. The integration result of the two vector directions is shown on the radiator, forming the right–hand



(a) (b) (c)

Fig. 3 Concept of orthogonal resonators from the surface current of the (a) λ/4 resonator as the first resonator, (b) radiator as the second resonator and (c) the interaction of the two vectors on the filtering antenna's radiator.

circular polarization as depicted in Fig. 3(c).

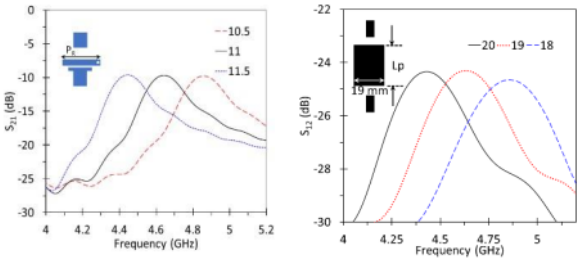
The length of the λ/4 resonator (P_R) and the position of the via through-hole determine its resonant frequency as shown in Fig. 4(a). Two λ/4 resonators are used to create the two minimal axial ratio and multiple resonant in S_{11}. The addition of the resonator in filter design also aims to increase its selectivity. The resonant frequency of the rectangular radiator shown in Fig. 4(b), affected essentially by its length (L_p) while its width (W_p) can be adjusted for balancing the magnitude of the two orthogonal vectors.

After obtaining the frequencies of both resonators, the integration is carried out using a single port. The determination of the space between the port (L_c) and the quarter wavelength resonator is made with the consideration of being sufficiently close to provide strong current to the feedline, thus setting the distance at 0.6 mm. So, there are 4 variables left to obtain the CP characteristic which are the size of the radiator, the space between the quarter wavelength resonators and the space between the quarter wavelength resonator and radiator. From the previous study, the space between the radiator and resonator function both as the delay and matching circuit [16], then in this design we start with 3.6 mm to optimize the response. The optimization goal was to achieve axial ratio less than 3 dB and impedance bandwidth of −10 dB over the bandwidth using the variations of W_p, L_p, *CB* and *Gap*1.

III. Results and Discussion

A. Parametric Study

The optimized results obtained from the iterative process, along with the corresponding responses of S_{11} and axial ratio under varying *CB*, are shown in Fig. 5. It is observed that *CB* exerts a notable impact on both bandwidth impedance and axial ratio (AR) values in the middle and lower band. Specifically, deviations from the 4 mm leads to a reduction in AR bandwidth, indicating a sensitivity to *CB* alterations. Moreover, variations in S_{11} are degrade with decreases or increases in CB from the 4 mm. The variation of Gap_1 to the S_{11} and AR is depicted in Fig. 6. The −10 dB bandwidth impedance and S_{11} is significantly affected by the variation of Gap_1. A wider Gap_1 improves S_{11}



(a) (b)

Fig. 4 The resonance frequency simulation of (a) the radiator as a function of the variation in its length (L_p) with a fixed width (W_p = 19 mm) and (b) the resonator as a function of the variation in its length (P_R). All dimensional units are in millimeters.

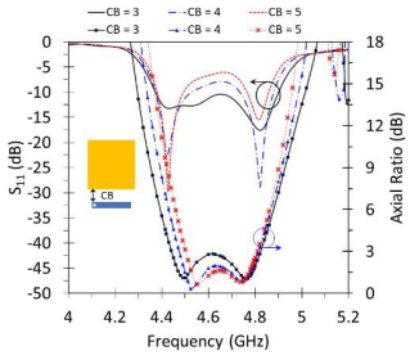


Fig. 5 S_{11} and axial ratio response in different *CB* (unit in mm)

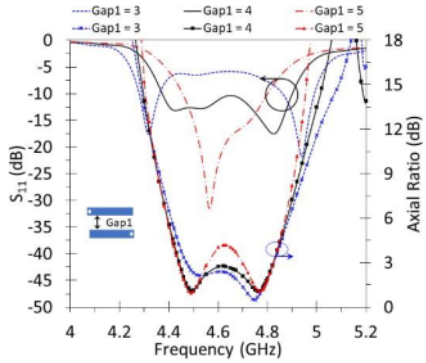


Fig. 6 The response of S_{11} and AR using different Gap_1 (all units in mm)

but degrades the bandwidth, and vice versa. AR is also considered in this optimization within the same parametric study, Gap_1 influences the AR in the middle and lower bands. Two minimum optimized ARs occur at 4.49 and 4.76 GHz results in 380 MHz axial ratio bandwidth (ARBw) or 8.2%. The characteristic of the right-hand circular polarization can be presented by the magnitude ratio of the orthogonal electrical field and its phase difference as shown in Fig. 7. The ratio of E_θ

and E_Φ magnitude over the bandwidth 4.5–4.8 GHz are varied between range 1.04 to 1.4 while the phase differences are

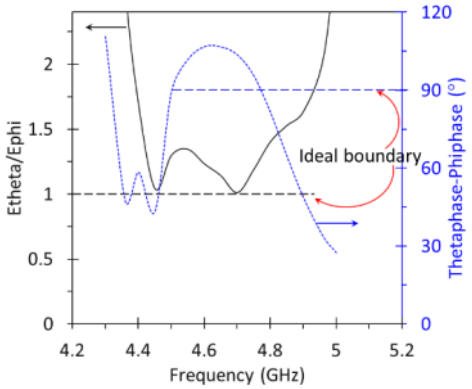


Fig. 7 Magnitudes and phases of the E_θ and E_Φ

between 43° to 106°. These values are near to the ideal value of 1 and 90°.

B. Measurement

To enhance the confirmation of both the proposed method and the simulation outcomes, we construct and assess a prototype of the CP patch antenna. The antenna is fabricated on two layers of RT5880, each with 1.575 mm thickness and 2.2 permittivity, as shown in Fig. 8. In this study, the fabricated antenna is measured using the Roger Schwarz ZNB-40 vector network analyzer. The measured of ARBw is depicted in Fig. 9, where the two minimum axial ratios are observed at 4.55 and 4.73 GHz. The presence of two distinct minimum ARs indicate the achievement of a wider-band AR characteristic than the second-order filter based in [16]. However, there is a slight discrepancy in the AR bandwidth measurement of 1.2 % from the simulation result.

The gains and reflection coefficients obtained through simulation and measurement are plotted in Fig. 10. The gain simulation and measurement response remain flat within a frequency band centered around 4.65 and 4.72 GHz, respectively and gradually decreases on both sides of this band, demonstrating favorable filtering characteristics. The centre frequency measurement result shows a shift from simulation of 1.5% to the higher frequency. The maximum gain of simulation and measurement are 6.3 and 6.33 dBic respectively. The measured frequency range with a 3 dB gain variation spans from 4.46 to 4.98 GHz, with a fractional bandwidth (FBW) of 11.01%. The reflection coefficient result shows that the measured antenna covers a wide impedance bandwidth from 4.499 GHz to 4.925 GHz, equivalent to a 9.04% fractional bandwidth. This result is 2.16% narrower than the simulation result, which is 11.2%. Both the gain and reflection coefficient measurements have slightly shifted, specifically at the lower frequency.

The far-field patterns were measured at two frequency points (4.55 and 4.73 GHz), corresponding to two minimum in the AR response. The normalized gain patterns for right-hand circular

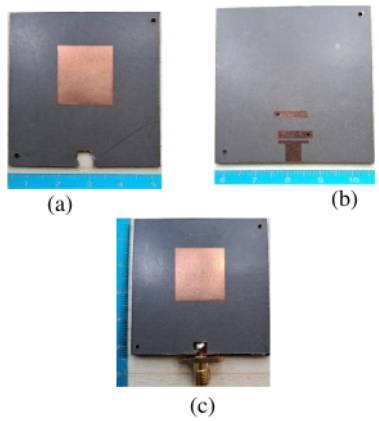


Fig. 8 The fabricated antenna (a) radiator, (b) feedline and (c) assembled prototype.

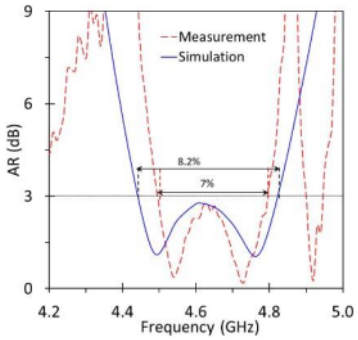


Fig. 9 Axial ratio simulation of the proposed design

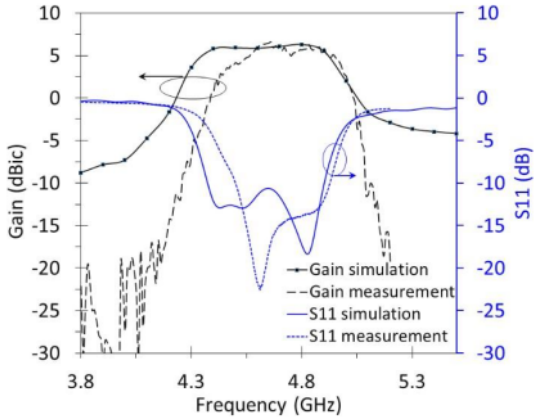


Fig. 10 S_{11} and gain of measurement and simulation results.

polarization (RHCP) and left-hand circular polarization (LHCP) are depicted in Fig. 11. The cross-polarization gain is roughly 20 dB less than the co-polarization gain in the direction of the main beam. The radiation patterns reveal a coherent beam

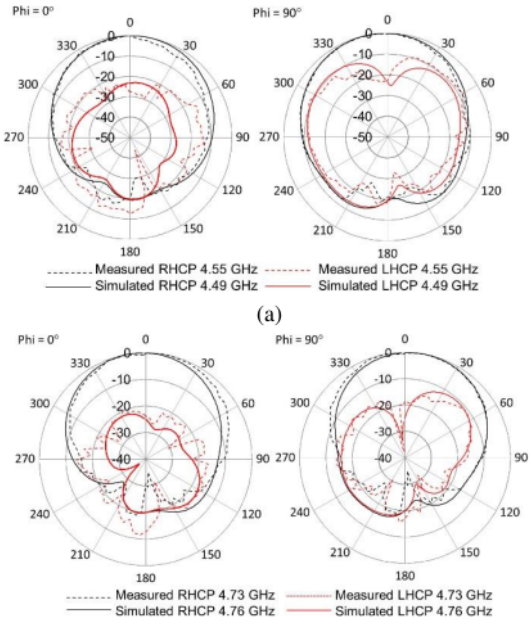


Fig. 11 Normalized radiation pattern at (a) 4.49 (simulation)/4.55 (measurement) GHz and (b) 4.76(simulation)/4.73 (measurement) GHz

shape in co-polarization, underlining the stable performance of the radiation. The 3 dB beamwidths measured in the phi = 0° at two different frequencies are 76.5°, and 78.6°, respectively. Similarly, in the phi = 90°, the measured 3 dB beamwidths are 84.2° and 77.5° at the corresponding frequencies.

Table 1 shows the comparison of the proposed design with the previous studies in the term of the method and the ARBW results. It is known that orthogonal feedlines can achieve a wider ARBW than the single feedline filtering antenna. The two orthogonal feedlines were implemented in [11], [23] using two substrate layers, while our proposed design, utilizing a single feedline, achieves a wider ARBw and IBw compared to [23] and and comes close to the ARBw and IBw reported in [11]. Reference [24] employs an omnidirectional antenna, which should theoretically have a wider bandwidth. However, despite emphasizing its dual-band performance, the ARBW, IBw, and gain results fall below those of our design. Our proposed design demonstrates an ARBw and IBw more than 250% wider than the previous study in [16], which using a single λ/4 resonator.

Table 1. Comparison of the proposed design with previous published CP filtering antenna

Ref.	Dimension (L×W×T) in λ	Integrated CP and filtering method	IBW/ ARBW (%)	Gain (dBic)
[5]	0.52 × 0.52 × 0.067	No	15.2/8.2	7
[11]	1.06 × 1.06 ×0.027	No	10.3/8.8	5.8
[16]	0.69 × 0.69 × 0.048	Yes	4.7/3.2	6.2
[23]	0.944 × 0.944 × 0.041	No	9.3/6.2	7
[24]	0.2 × 0.2 × 0.042	No	1.8/6 and 2.3/2.5	0/1.5
[28]	0.726 × 0.726 × 0.34	No	58.3/46.9	7.6
This work	**0.775 × 0.775 × 0.048**	**Yes**	**11.2/8.2**	**6.3**

IV. Conclusion

In this communication, a wide axial ratio bandwidth filtering antenna using orthogonal resonators has been designed and measured. The orthogonal resonators are modeled with two quarter-wavelength resonators and a rectangular radiator integrated through a third-order filter design. The circularly polarized filtering antenna is determined by three key factors: the ratio of length to width of the rectangular radiator, the gap between the resonator and radiator, and the gap between the two resonators. The realized model results in an 8.2% ARBW and 11% IBW, complemented by gain exhibiting filtering characteristics. The proposed method verifies that the integration of a filter and an antenna can function to generate a wide ARBW circular polarization filtering antenna using only a single feed line.

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