Dwi Astuti Cahyasiwi - Orthogonal Resonators for Circularly Polarized Filtering Antenna Using A Single Feedline

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Orthogonal Resonators for Circularly Polarized Filtering Antenna Using A Single Feedline

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Abstract— **Polarization diversity is an antenna feature that has been widely researched to increase the capacity of a wireless communication system. The conceptual theory of polarization states that all polarization vectors can be decomposed into two orthogonal electric field vector modes. This study proposes a novel framework to bridge the gap between circular polarization technique and filtering antenna design using two orthogonal resonators with the ability to represent any polarization. The proposed method combines the techniques of antenna-filter and circular polarization design into a single integrated step. To achieve second-order antenna-filter integration and generate circular polarization, the two orthogonal resonators modeled as a rectangular radiator and a lambda/4 resonator combined. The circular polarization filtering antenna operates at a frequency of 4.65 GHz, with an impedance bandwidth of 4.7%, axial ratio bandwidth of 3.2%, and a gain of 6.2-dBi. To validate the circular polarization filter antenna, simulations and measurements were performed, and the results were found to be in good agreement.**

Index Terms— **Circular polarization, filtering antenna, interdigital, orthogonal resonator**

I. INTRODUCTION

CIRCULARLY polarized antennas have been developed using various methods. The main principle that distinguishes antennas with linear and circular polarization is the ± 90° phase difference between two orthogonal magnetic fields. Some techniques for generating circular polarization have been studied [1], [2]. A single feed technique intervenes the radiator to create two electromagnetic field modes with a 90° phase delay. This technique can be achieved using truncated and perturbation radiator elements [2]–[14]. The simplest method to achieve two orthogonal modes is to insert two orthogonal feeders [15]–[18]. However, as previously stated, two equal orthogonal fields will only generate circular polarization if there is a 90° phase difference, so this technique requires an additional phase delay circuit. The cancellation circuits to generate delay have been reported in [19]–[26], and some of the circuit has been applied to obtain circular polarization [18], [27].

The integration of a filter and antenna known as filtering antenna is advanced because of its controllable bandwidth

impedance. Furthermore, it performs a frequency selectivity with its bandpass-like response gain. The most common method to design a filtering antenna is to create a filter network using a radiator as a resonator. In a co-design technique, the antenna replaces the last stage resonator of the filter. Circular polarization (CP) filtering antennas have been studied using a single feedline [3], [4] and two orthogonal feedlines [17], [28], [29]. A truncated radiator generates CP, and a filtering circuit is added to provide selectivity features [3].

The filtering antennas create two orthogonal feedlines and 90° a phase delay circuit using a λ/4, λ/2 and two parallel λ/2 stub resonators [17], [28], [29]. Dispersive delay lines are added to one of the two orthogonal feedlines to obtain a circularly polarized filtering antenna [18]; their function is as filtering and delay circuits. All the extra components and two-step designs in the previous studies result in a bulky circuit.

In our previous studies, we developed 75°, 45° and; vertical polarization filtering antenna using the λ/4 resonator and a rectangular radiator [30]–[32]. In [31] the interaction between the radiator and resonator stimulates a second mode on the radiator and results in two orthogonal modes with a single feedline; additionally, with proper radiator size, 0° and 180° phase delay using a cancellation circuit in [22], the design generated 45° polarization. Based on the common characteristics of 45° polarization and CP, a circularly polarized antenna with a similar structure as in [31] can be designed by adding 90° phase delay. To the best of our knowledge, no technique on filtering antenna uses its integration process to generate CP, have been reported. Therefore, this study proposes a technique for designing a circularly polarized filtering antenna using single feedline that provides two orthogonal modes and 90° delay without an additional circuit or radiator perturbation. The proposed technique simplifies the design process of CP filtering antenna from two steps to one step. This method merges the antenna-filter integration and polarization generator technique. Furthermore, it applies to generate linear and CP. Characteristics of CP are proven with $|E_\theta|/|E_\Phi|$, phase difference (δ_L) and axial ratio (AR) parameters, within the bandwidth operational. Selectivity performance is represented with the gain over the operational bandwidth. This paper is organized as follows; Section II explains the proposed
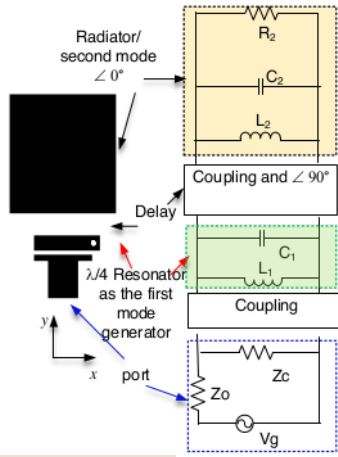
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Fig. 1. Concept of the proposed antenna and its equivalent circuit

Fig. 2. Impure vertical polarization filtering antenna based on (a) third-order and (b) second-order filter [32].

Fig. 3 (a) Impure 75° slant polarization [30] and (b) 45° polarization [31].

method for CP excitation using two orthogonal resonators based on the general polarization theory. Section III describes the antenna–filter integration. Section IV presents the result and discussion. Finally, the results are concluded in Section V.
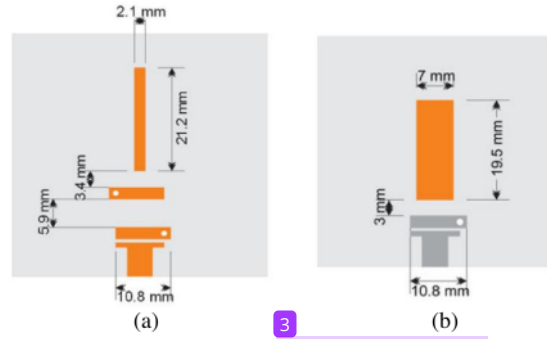
II. PROPOSED METHOD

Polarization is a relation of the electrical fields in θ and Φ in the spherical coordinate system, as expressed in (1),

$$\overline{E} = E_\theta cos(\omega t)\hat{\boldsymbol{\theta}} + E_\Phi cos(\omega t + \delta_L)\hat{\Phi},\qquad(1)$$
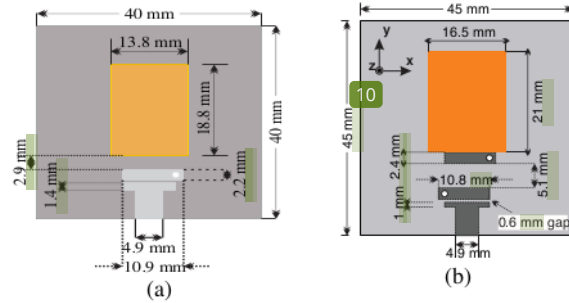
which explicates that total electrical field, $\overline{E}$, can be decomposed into two virtual orthogonal electrical field vectors in $\hat{\theta}$ (E_θ) and $\hat{\phi}$ (E_Φ) directions [33]. Any polarization can be represented by two orthogonal linear polarizations (E_θ and E_Φ). In general, the magnitudes of these fields can be different or equal, and they may be in-phase or out of phase by an angle δ_L. If δ_L is 0° or 180°, it is linear, whereas, if δ_L is + 90° or − 90°, it is circular. Hence, from the theoretical framework above, these two virtual orthogonal electrical fields can be realized, with two individual structures represented by vertical and horizontal surface currents.

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

The physical construction of the proposed method can be represented using the two orthogonal resonant structures as shown in Fig 1, where an $\lambda/4$ resonator (L_1, C_1) represents e-field in the $\hat{\theta}$ direction, with a horizontal surface current along the x−axis to excite second mode on the radiator, which is orthogonal to the radiator surface current. The gap between $\lambda/4$ resonator and radiator offers a 90° phase delay in addition to coupling between resonator and rectangular radiator. Using this gap, no additional delay circuit is required. The radiator (L_2, C_2, and R_2) represents e-field in the $\hat{\phi}$ direction, with vertical surface current along the y−axis. The gap between the $\lambda/4$

resonator and radiator, as well as the length and width of the radiator, balanced the magnitude of the orthogonal modes. Finally, these structures are integrated to realize a total electrical field that accomplishes linear polarization or CP using a single port.

In the case of CP, the magnitude of the two electrical fields must be equal, as in (2), and the phase difference, δ_L, is 90° and −90° for left-hand and right-hand circular polarization, respectively. The equivalence between the two-magnitude e-fields in this method is determined by the ratio of the radiator's length (L_p) and width (W_p). While in the conventional filtering antenna, the ratio between L_p and W_p determines the radiator's radiation quality (Q_{rad}), which should be equal to the external quality (Q_{ext}) of the resonator. In the proposed method, the antenna–filter integration is applied by steering the ratio of W_p and L_p near 1, implying that Q_{rad} is not always equal to Q_{ext}. Besides the equal magnitude between the orthogonal e-fields, we have to provide a 90° phase delay between E_θ and E_Φ by increasing the radiator and resonator gap (C_B), thereby weakening E_θ. To maintain an equal ratio between the two fields, E_θ is strengthened by nearly equalizing W_p and L_p size while maintaining the same resonance frequency.

Previous studies have validated that W_p and L_p size and the gap between the orthogonal resonators are the main variables. determining the polarization[30]–[32]. As shown in Fig. 2 (a) and (b), the two designs based on third- and second-order filter

(a)

(b)
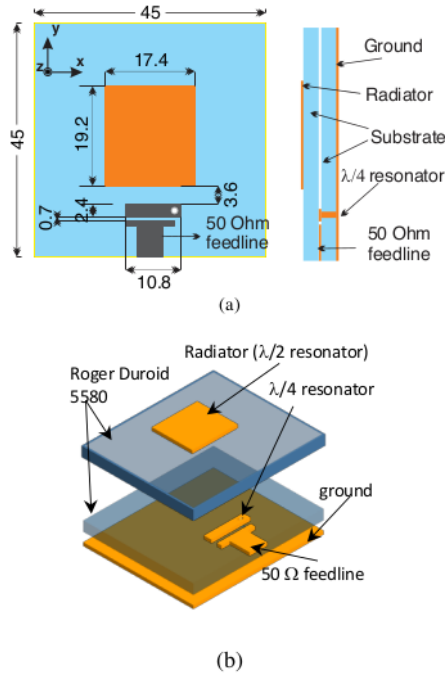
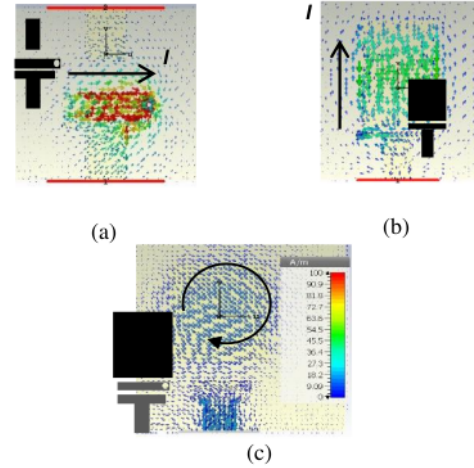Fig. 4 (a) Geometry and side view of Antenna I with unit dimension in mm and (b) 3D-view

Fig. 5. Two individual structures comprising (a) an interdigital with hole extracted using two ports with a horizontal surface current (I), (b) a rectangular radiator with coupled feed that has a vertical surface current, and (c) the integration of two previous structures for left-hand circularly polarized filtering antenna. All structures resonant at 4.65 GHz.

using a narrow rectangular radiator, resulted in impure vertical polarization [32]. Meanwhile, Fig. 3(a) shows using wider W_p than the two previous design introduces stronger magnitude e-field in $\hat{\theta}$ direction thus pulls the polarization to impure 75° slant. Furthermore, in Fig. 3(b), removing the gap between the radiator and interdigital resonator followed by equalizing the e-field in $\hat{\phi}$ and $\hat{\theta}$ with widening W_p, forms 45° polarization [31].

The following section presents an antenna–filter integration adaptation to excite circularly polarized filtering antenna using two orthogonal resonators to validate the proposed method.

III. ANTENNA–FILTER INTEGRATION

A. Antenna Geometry

This section presents a geometric structure of the optimized filtering antenna using a new method for CP excitation. The design uses second-order antenna–filter integration and focuses on CP excitation. The geometric structure of the filtering antenna, as shown in Fig. 4(a), comprises a 17.4 mm × 19.2 mm rectangular patch radiator proximity coupled with an $\lambda/4$ resonator. The gap between the rectangular radiator and resonator (C_B) is 3.6 mm. The width of the $\lambda/4$ resonator is 2.4 mm, and the approximated length of $\lambda_g/4$ is 10.8 mm; it is also coupled with 50-Ω transmission lines using a 0.7-mm gap. To generate a horizontal surface current, a through-hole of 1.2-mm diameter is attached on the left arm of the resonator. The antenna is printed on a 45 mm × 45-mm double layers Roger Duroid 5880 substrate with a thickness of 1.575 mm and

permittivity of 2.2. Fig. 4(b) shows the two-layers antenna (3D view), comprising of a radiator printed on the first substrate, resonator, and 50-Ω feedline on the second substrate, and ground at the bottom.

B. Design Process

First, we realize this design starting from the conventional filtering antenna extraction method to obtain the resonance frequency. The resonator and radiator as the first and second mode generator, respectively, are extracted using two ports and they must have a matching resonant. As shown in Fig. 5(a), the first mode generator is embodied by the resonator's surface current along the x–axis. This current flows from the open circuit resonator's arm to the short circuit resonator's arm. The rectangular radiator's surface current initially generates a vertical surface current along the y-axis as the second mode as shown in Fig. 5(b). These two modes are integrated adapting the antenna–filter integration, and using the appropriate rectangular radiator size to obtain circular polarization, as depicted in Fig. 5(c). The designs of the conventional filtering antenna (Ant I) and the proposed method (Ant II) are compared to prove the novelty of the new method. All design simulations and investigations are performed using CST tools.

The conventional filtering antenna is designed on the basis of a second-order Chebyshev filter with 4.65-GHz operational frequency, 0.1-dB ripple, 4.15 fractional bandwidth, as well as the low-pass parameters of $g_o = 1$, $g_1 = 0.843$, $g_2 = 0.622$, and $g_3 = 1.3544$. The quality external factor (Q_{ext}) and coupling ($M_{i,i+1}$) obtained using (3) and (4) are 17.8, and 0.051, respectively.

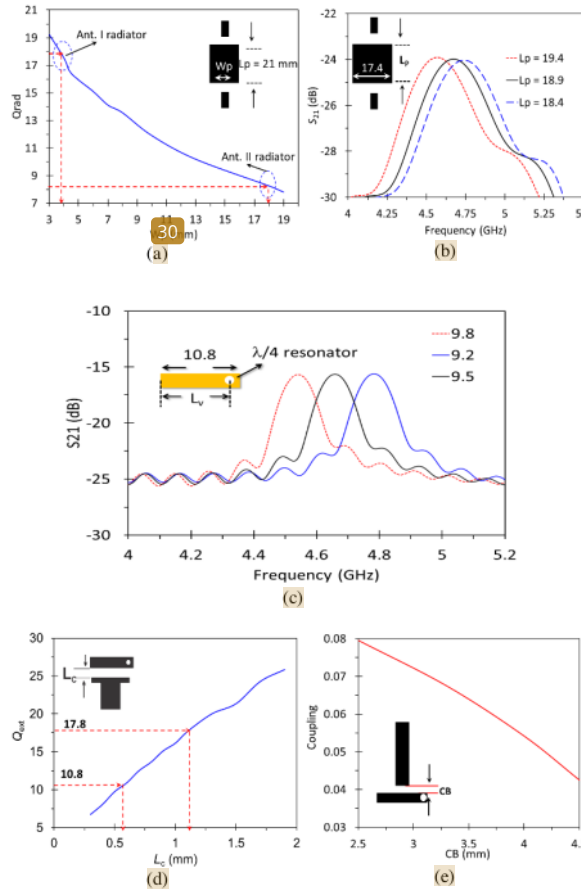$$Q_{ext} = \frac{g_n g_{n+1}}{FBW} \qquad (3)$$

Fig. 6 (a) Q_{rad} with the variation in W_p, (b) L_p variations with $W_p = 17.4$ under different resonance conditions, (c) $\lambda/4$ frequency resonant with various L_v, (d) Q_{ext} with variation in L_c [31] and (e) coupling with various in C_B (unit dimensions in mm)

$$M_{i,i+1} = \frac{FBW}{\sqrt{g_i g_{i+1}}} \tag{4}$$

$$Q_{rad} = \frac{f_o}{\Delta f} \tag{5}$$

The rectangular radiator are extracted using (5) to achieved Q_{rad}, where the Δf is 3-dB bandwidth and f_o is the center frequency.

The rectangular patch dimension described in Fig. 6(a) shows that 4.65-GHz resonance can be achieved using two $L_p \times W_p$ variations. The difference between these variations is the value of Q_{rad}. If the ratio of L_p to W_p is close to one, Q_{rad} will be decreased and reversed. Based on the extraction of conventional filtering antenna, Ant I's Q_{rad} should be 17.8, with $L_p \times W_p$ around 21 mm $\times$ 4 mm. However, the ratio between L_p and W_p is steered to be equal using the proposed method in Ant II, as shown in Section II. Then, we used an $L_p \times W_p$ of 19 mm $\times$ 18 mm, which resonates at 4.65 GHz with Q_{rad} of 8.3 to balance the E_θ and E_Φ strength. A parametric study of L_p variations to
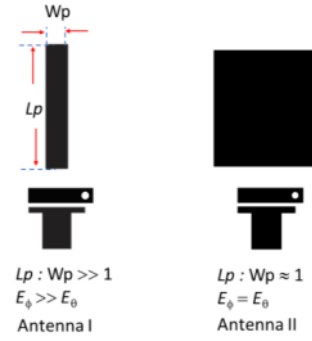

Fig. 7. Filtering antenna, Antenna I based on the second-order filter with vertical polarization, Antenna II adapting second-order filter with circular polarization
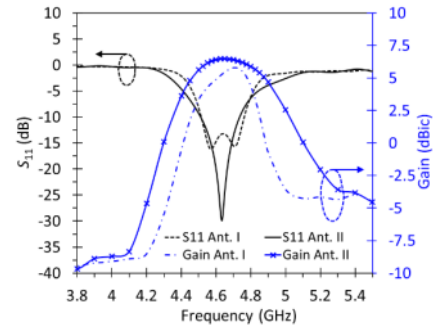

Fig. 8. Simulation of S_{11} and gain result for both designs

$$M_{n,n+1} = \frac{f_{n+1}{}^2 - f_n{}^2}{f_{n+1}{}^2 + f_n{}^2} \tag{6}$$

obtain 4.65-GHz resonance is shown in Fig. 6(b). The $\lambda/4$ resonance frequency extraction is performed similarly to [31], where the length of the resonator and through-hole position (L_v) are used to determine the resonant frequency. The $\lambda/4$ resonator obtains a 4.65-GHz resonant using a 10.8-mm arm's length with 9.5-mm L_v as shown in Fig.6(c).

The Q_{ext} of 17.8 is obtained when the gap between the $\lambda/4$ resonator and coupled feed (L_c) is near 1.1 mm using the conventional filtering antenna extraction method for Ant. I as shown in Fig. 6(d). The gap between the resonator and patch radiator (C_B) is ~4.3 mm to obtain a 0.051 coupling using (6), as described in Fig. 6(e). While for Ant. II, L_c is set to be minimum to strengthen E_θ, and C_B is set to provide a 90° phase difference between E_θ and E_Φ. Different from the conventional filtering antenna design in Ant I that performs external quality between the resonator and the coupled feed, in Ant II, we set L_c in a range of 0.5–0.8 mm because this distance does not significantly affect polarization. However, it affects S_{11} response; thus, we need this parameter to adjust the impedance.

IV. RESULTS AND DISCUSSION
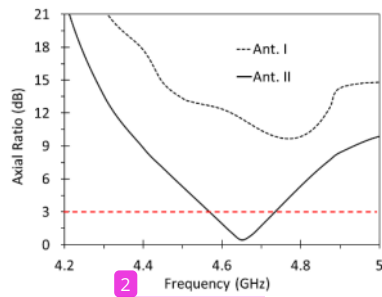
This section discusses the comparison results of the

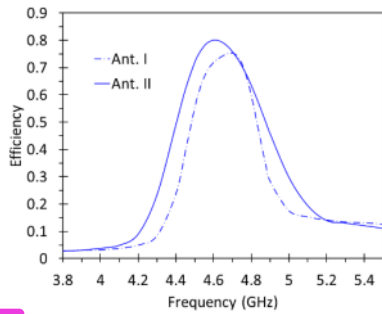Fig. 9 Axial ratio results of Ant. I and Ant. II

Fig. 10. Efficiency of Ant. I and Ant. II

conventional filtering antenna represented by Ant I and the newly proposed method represented by Ant II. The S_{11} and gain response of both designs are compared to the conventional antenna without filtering structure to understand the effect of the resonator addition and the new proposed method novelty. The parametric study and the measurement results of Ant II are presented to validate the proposed method.

C. Comparison Results of Ant I and Ant II

Applying the above procedure, we obtain an optimized design of the conventional and circularly polarized filtering antenna. Figure 7 shows the schematic design of the two filtering antennas. The conventional filtering antenna represented by Ant I has a narrower W_p than Ant II and a marginally longer L_p than Ant II. Fig. 8 shows the S_{11} and gain response of both designs. The S_{11} response in Ant I represents the second-order filter with two returns to zero and a single peak, whereas S_{11} of the proposed method in Ant II has a single resonant, as in a conventional antenna. This result is due to Ant II's omitted filtering antenna procedure, which should have a certain coupling value (0.051) between the radiator and resonator. The Q_{ext} and Q_{rad} equalization in Ant II were also excluded, resulting in the S_{11} filtering antenna with only a single minimal response.

Both antennas' center frequency is 4.65 GHz, and the −10 dB bandwidth impedance is 246 and 224 MHz for Ant I and Ant II, respectively. Ant I achieves its fractional bandwidth of 5.2% or 0.5% wider than the target value and two minimum S_{11} values of −16 dB at 4.57 GHz and −15.6 dB at 4.7 GHz. Ant II obtains
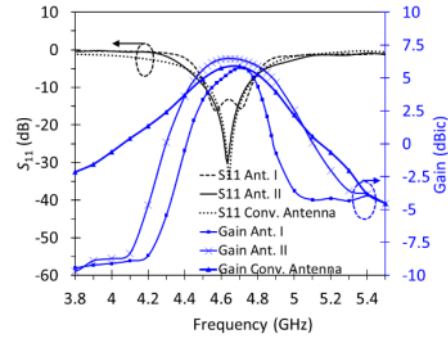
Fig. 11. S_{11} and gain parameter comparison of Ant I and Ant II to the conventional antenna
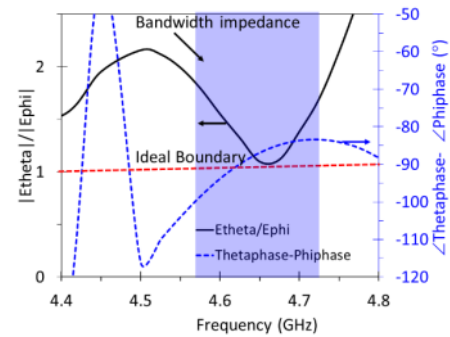
Fig. 12. Ratio magnitude E_θ to E_Φ and phase difference of Ant. II

4.8% fractional bandwidth with S_{11} minimum value of −24.4 dB at 4.634 GHz. The gain response of Ant I shows a lower peak value but sharper shape than that in Ant II, and this is because the conventional extraction mainly focuses on the antenna's selectivity. A maximum gain of 5.77 dBi is achieved at 4.7 GHz for Ant. I, whereas Ant II shows a maximum gain of 6.46 dBi at 4.65 GHz or 0.69 dBi higher than the previous design. Figure 9 shows that Ant. 1 does not generate circular polarization from its high AR; in contrast, Ant II shows a 3-dB AR bandwidth of 150 MHz in a range of 4.575–4.725 GHz and attain the lowest value of 0.45 dB at 4.65 GHz. The radiator's width affects the efficiency of both antennas, where Ant. I with the narrower rectangular patch has less efficiency than Ant. II. The Ant. I's and Ant's II maximum efficiency is ~75% and 80% respectively as shown in Fig.10 and both designs have a bandpass-filter-like response. The results of Ant I and Ant II compared to the conventional antenna without filter integration are shown in Fig. 11. Ant I shows the sharpest gain response and widest frequency compared to Ant II and the conventional antenna. Ant II has the highest gain response among the other two designs and a sharper shape than the conventional antenna. It is proven that the resonator affects selectivity in Ant II, although it is not mainly focused on gain selectivity but also on the CP characteristic. Ant II also has equal bandwidth to the conventional antenna. Other parameters to prove the CP
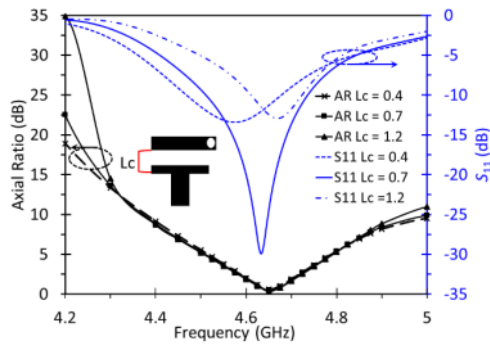
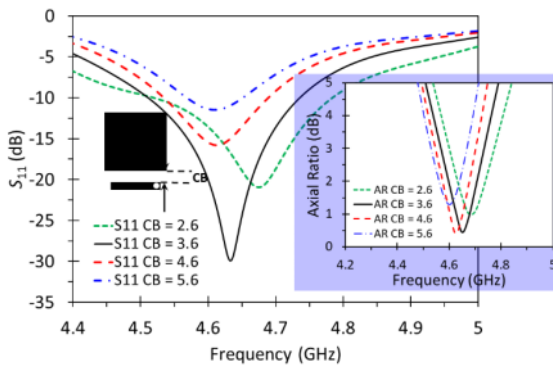Fig. 13 Axial ratio and S_{11} response vary under different L_C (all unit dimensions are in mm)

Fig. 14. Axial ratio and S_{11} response vary under different C_B with constant W_p and L_p (all unit dimensions in mm)

Fig. 15. Photograph of Ant II (a) integrated layers (b) radiator patch (c) feeding structure
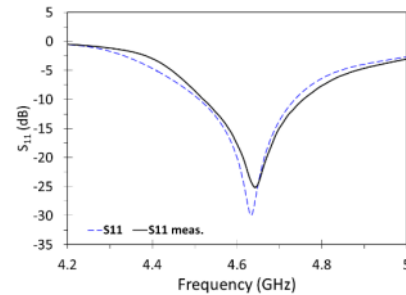
Fig. 16. S_{11} measurement result of Ant II

characteristic in Ant II, as explained in (1) and (2), are the magnitude ratio between E_θ excited from the $\lambda/4$ resonator and E_Φ excited from the rectangular radiator, as shown in Fig. 12. It shows that $|E_\theta|/|E_\Phi|$ along the bandwidth ranges between 1.7 and 1.09 or near the theoretical value of 1, whereas phase differences are between $-83°$ and $-98°$ or near the ideal value of $-90°$. Those values indicate that Ant II has a left-hand CP.

D. Parametric Study of Ant II

The response of AR under different Wp has been proven in Ant I and Ant II, which is heavily related to the magnitude of E_θ and E_Φ. Next, the effects of the gap spacing between the resonator and rectangular radiator (C_B) and the gap between the resonator and coupled feed are investigated in Ant II. Fig. 13 shows that in Ant II, the AR is unaffected by the gap between the resonator and coupled feed (L_c). It shows that S_{11} is optimum when L_c is 0.7 mm because, with less or more distance with an increment of 0.3 mm, its value increases; contrast to the AR, which is unaffected by L_c. In Ant II, the gap between the radiator and resonator (C_B) affects the axial ratio and S_{11}. Fig. 14 shows that with an increment of 1 mm, the S_{11} response and axial ratio are altered. The AR is minimum when C_B value is
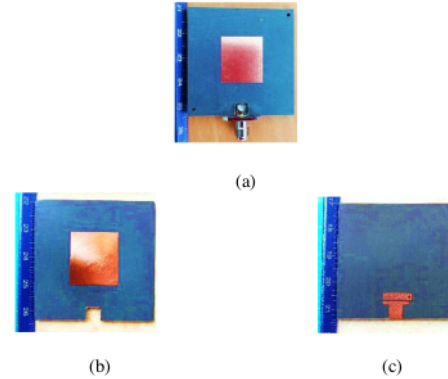
3.6 mm because if it is less or more, the AR and S_{11} increase. All parametric studies are conducted with constant W_p and L_p. C_B is an essential parameter for differentiating 45° linear polarization and CP in the proposed method because widening C_B will contribute 90° delay, whereas minimizing C_B to 0 mm will produce 0° or 180° delay between E_θ and E_Φ, as performed in [31].

E. Measurement Result

To validate the proposed method, Ant II is fabricated and measured. Fig. 15 shows the photograph consisting of the assembled antenna in Fig. 15(a), the radiator layer in Fig. 15(b), and the feeding network in Fig. 15(c). S_{11} result is depicted in Fig. 16, where the simulation and measurement results have a good agreement. The measured frequency range of the proposed circularly polarized filtering antenna with $S_{11} < -10$ dB is 4.520–4.756 GHz, which shifts to a higher frequency and 4.8% wider than the simulation result. Its S_{11} gets the lowest value of -25 dB at 4.61 GHz, which is 4 dB higher than the simulated results. The 3-dB AR bandwidth measurement results shown in Fig. 17 is 100 MHz in a range of 4.633–4.733 GHz, which is 30% narrower than the simulation result. The lowest axial ratio is better than the simulation by 0.33 dB but shifts to 4.68 GHz. The insignificant discrepancy between the measured and simulated results is attributed to the assembly and fabrication tolerance. The gain measurement result depicted in
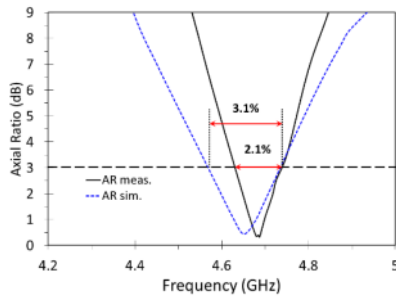
Fig. 17. Axial ratio measurement result of Ant II at φ= 0° and θ = 0°

Fig. 18. Gain measurement of Ant II

Fig. 19. Normalized radiation pattern Ant II at 4.68 GHz

in the main lobe is higher than 30 dB for φ= 0° and 90°, which agrees well with the simulation results.

Table 1 compares the proposed and previous methods, demonstrating that using a single feedline with an orthogonal resonator eliminates the need for an additional delay and filtering circuit. Reference [3] employs a single feedline with circular radiator perturbation, having the broadest AR bandwidth because it used a dipole antenna and a tradeoff with the lowest gain. The highest gain value was obtained in [12]–[14] using truncated radiator or radiator perturbation but with compensation for the size of the antennas. Some previous studies used two orthogonal feedlines to produce a broader AR bandwidth than the proposed method [16]–[18]. Although the proposed method had the narrowest AR bandwidth, it had the highest gain without extra circuit to produce CP and selectivity. Furthermore, we are optimistic that we can improve the AR bandwidth in the future research using antenna–filter integration that can control a bandwidth.

V. CONCLUSION

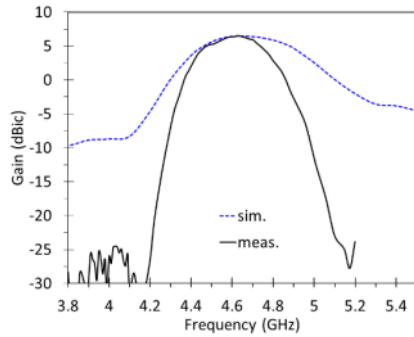A new method for developing a circularly polarized antenna adapting a second-order filtering antenna has been demonstrated. The integration of orthogonal surface current in

Fig. 18 shows a bandpass response along the bandwidth with a maximum value of 6.7 dBi at 4.65 GHz or 0.3 dB higher than the simulation result. The selectivity at the lower frequency is better than the upper frequency.

The measurement gain shows a sharper response than the simulation due to the simulation gain samples did not capture the dips that always arises in the filtering antenna measurement. The normalized radiation pattern measurement at 4.68 GHz is shown in Fig. 19. It shows a unidirectional pattern with the main lobe direction at 0° and −3 dB beamwidth of 80.5° and 81.5° at φ = 0° and 90° respectively. The cross-polarization discriminant
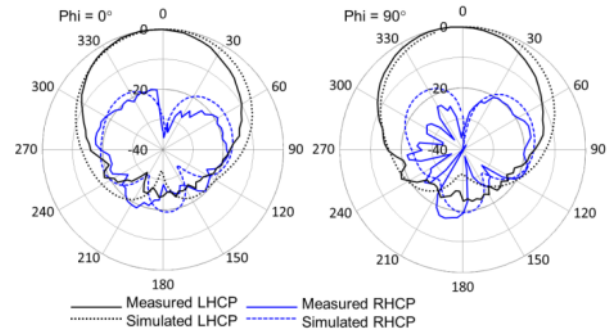
TABLE I
COMPARISON WITH PREVIOUS CP FILTERING ANTENNA

Ref.	Profile	CP Method	Delay/filtering circuit	Gain (dBic)	ARBW (%)
[3]	0.57λ×0.6125λ×0.006λ	Single feed line with truncated radiator	Extra circuit	2.1–2.8	20.5
[12]	0.77λ×0.77λ×0.03λ	Single feed line with truncated radiator	Extra circuit	8	8.5
[13]	0.91λ×0.91λ×0.022λ	Single feed line with radiator perturbation	Extra circuit	8.3	5.3
[14]	1λ×1λ×0.036λ	Single feed line with radiator perturbation	Extra circuit	8	3.9
[16]	0.53λ×0.53λ×0.07λ	Orthogonal feedlines	Extra circuit	5.2	12.5
[17]	1.06λ×1.06λ×0.027λ	Orthogonal feedlines	Extra circuit	5.8	8.8
[18]	0.72λ×0.72λ×0.018λ	Orthogonal feedlines	Extra circuit	6.1	3.8
This work	0.69λ×0.69λ×0.048λ	Single feedline with orthogonal resonators	No extra circuit	6.72	3.2

the rectangular radiator and λ/4 resonator resulted in a left-hand CP filtering antenna. The radiator's length and width significantly affected the electric field magnitude in θ and Φ directions. The gap spacing between the rectangular radiator and λ/4 resonator determined the phase delay. The performance of the conventional filtering antenna and the antenna based on the new method was compared. The proposed method was validated by the agreement between the simulation and measurement results.

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