Low-profile circularly-polarized filtering antenna with improved bandwidth and gain

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Low-Profile Circularly-Polarized Filtering Antenna with Improved Bandwidth and Gain

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***Abstract*—A novel circularly-polarized (CP) microstrip antenna with a low profile, broad bandwidth, high gain and filtering characteristics is presented. The antenna has a resonator-based vertically coupled structure, which consists of a patch, an embedded slot resonator and a hairpin resonator. Such a structure can effectively broaden the impedance bandwidth without increasing the profile of the antenna. The CP characteristics are achieved by employing a single-fed dual-coupled feeding technique that an intrinsic and broadband 90° phase difference can be realized between the two coupling paths. This CP technique effectively excites the TM_{10} and TM_{01}-mode of the patch without using any power dividers and phase delay lines, resulting in the reduction of circuit complexity and insertion loss, and therefore the improved gain response. In addition, owing to the coupled resonant structures, the antenna exhibits the 3rd-order filtering features with improved impedance and axial ratio (AR) bandwidths, flat in-band gain and out-of-band rejection. The measured results verify the design, showing an impedance bandwidth of 29.6%, and 3-dB AR bandwidth of 17.6%. The antenna also exhibits a high gain of over 9.5 dBic.**

***Index Terms*—antenna, broadband, circularly polarized, filtering, high gain, microstrip antenna.**

I. Introduction

Microstrip circularly-polarized (CP) antenna has been widely applied in various modern wireless systems due to its advantages of light weight, low cost, low profile and ease of integration. However, microstrip CP antennas often suffer from limited impedance bandwidth and 3-dB axial ratio (AR) bandwidth [1]. Traditionally, the impedance bandwidth can be improved by increasing the thickness of the antenna, while the 3-dB AR bandwidth is usually enhanced by employing the dual-feed or triple-feed techniques [2]-[3]. However, these techniques require a large area to accommodate the feeding networks and the phase delay lines. The bandwidths of single-feed microstrip CP antennas can be increased by using artificial ground structures [4], reactive impedance substrates [5], asymmetric E-shaped patches [6] or stacked patches [7]. But these antennas suffer from complicated structures, thick profile and low gain. So, it is worthwhile to investigate new microstrip CP antennas with compact size, low profile, broad impedance/AR bandwidths and high gain.

The co-design concept where different functions are integrated into a single device in the radio frequency (RF) frontend has attracted intensive research interest in the past few years [8]-[18]. A variety of antennas with integrated filtering characteristics have been reported. Compared with traditional antennas, filtering antennas can significantly improve the bandwidths while reducing the out-of-band interferences. However, most of these works are focusing on linearly polarized antennas. Very little has been done in CP filtering antennas.

In this paper, a novel method of achieving the circular polarization on a microstrip antenna is demonstrated by employing a resonator-based stacked structure with all resonators vertically coupled. Broadband CP characteristics are achieved by employing a compact single-fed dual-coupled method where two transmission paths with intrinsic 90° phase difference are conceived to excite the TM_{10} and TM_{01} modes of the patch. Compared with traditional dual-feed antennas, no power dividers and phase shifters are used, leading to a compact size. At the same time, the gain of the antenna is significantly improved due to the reduction of the insertion losses from the power dividers and phase delay lines. It is also worth noting that the stacked structure can improve the impedance bandwidth of the antenna without increasing the thickness.

II. Antenna Design

A. *Configuration*

Fig. 1 shows the configuration of the proposed broadband CP filtering microstrip antenna. The antenna is composed of an F-shaped microstrip, a straight and a U-shaped slot in the ground and a square patch as the radiator. The patch is printed on the top layer of the upper substrate, while the microstrip feed is printed on the bottom layer of the lower substrate. The patch, microstrip and hairpin share a common ground in the middle placed on the top layer of the lower substrate. In the ground, a U-shaped slot is inserted to form a half-wavelength resonator. The straight slot, however, is used to couple the electromagnetic energy from the feed. Between the two substrates, a 2 mm thick foam is inserted. RO 5880 with a permittivity of 2.2 and loss tangent of 0.0009 is used as the upper substrate while RO 4003C with a permittivity of 3.55 and loss tangent of 0.0027 is the lower substrate. The optimization was performed using the high frequency structural simulator (HFSS 15) and the optimized dimensional parameters are given in the caption of Fig. 1.

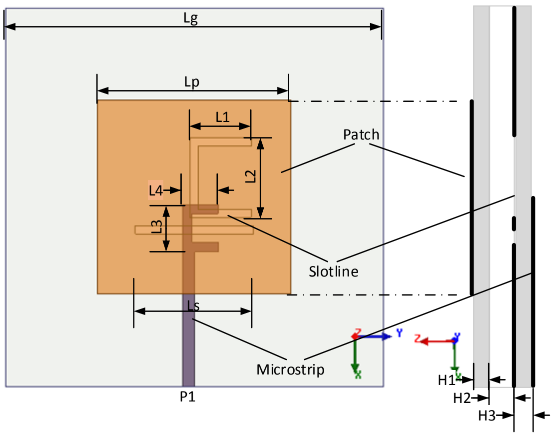


Fig. 1. Configuration of the proposed broadband CP microstrip antenna. *Lg* = 20 mm, *Lp* = 8.2 mm, *L1* = 3.4 mm, *L2* = 3 mm, *L3* = 2.5 mm, *L4* = 2.2 mm, *Ls* = 5.3 mm, *H1* = 0.254 mm, *H2* = 2 mm, *H3* = 0.2 mm.

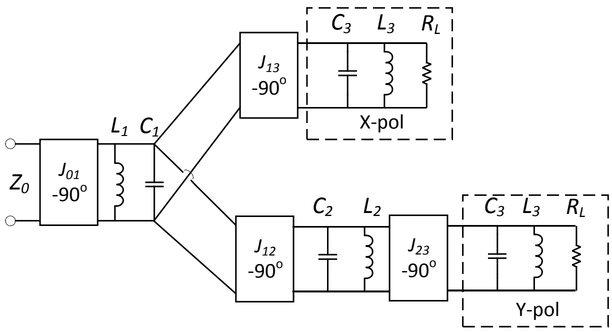


Fig. 2. Equivalent circuit of the proposed filtering CP microstrip antenna.

B. Generation of CP

In Fig. 1, the straight slot couples the electromagnetic energy from the feed to the patch directly, exciting the TM_{10}-mode of the patch. The U-slot, however, works as a resonator, exciting the TM_{01}-mode of the patch. The patch then combines the two components with 90° phase difference and produces the circularly-polarized radiation. To illustrate the mechanism of the 90° phase difference, the equivalent circuit of the antenna is given in Fig. 2. The U-shaped microstrip at the end of the feed can be viewed as a hairpin resonator, which has the same resonance as the patch. Both the hairpin and U-slot resonators can be modelled by shunt *LC* resonators, while the radiating patch resonator is modelled by a shunt *RLC* resonator, where *R* is the radiation resistance. The mutual couplings between the resonators can be modelled by the admittance inverters *J* with -90° phase delay [19].

It should be noted that since the straight slot does not resonate, the signal path of the X-polarization undergoes a 2nd-order resonant circuit. In contrast, since the U-slot is a half-wavelength resonator, the signal path in the Y-polarization undergoes a 3rd-order resonant circuit. As a result, a 90° phase difference between the two orthogonal components is produced without requiring extra phase delay lines. This single-feed dual-coupled structure significantly simplifies the feeding networks as compared with traditional dual-feed CP antennas. The power of the two orthogonal components can be balanced by adjusting the coupling between the feed and the straight coupling slot.

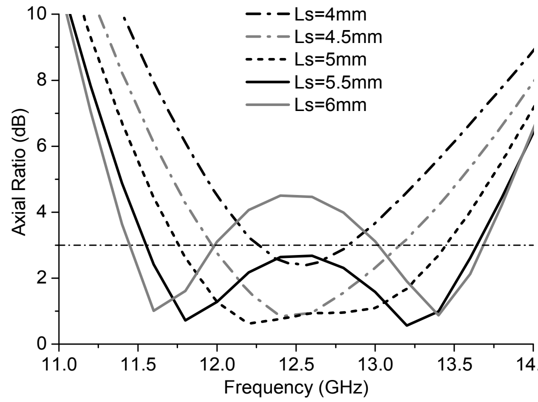
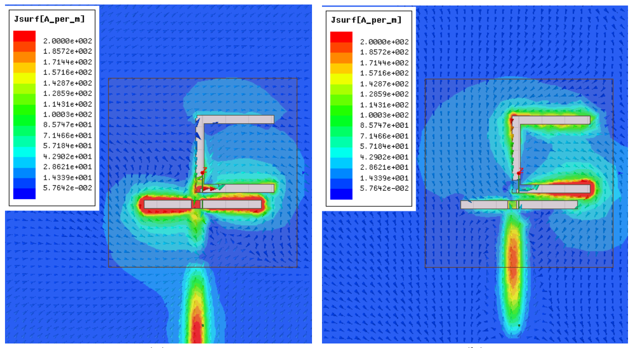


Fig. 3. Simulated AR of the proposed CP microstrip antenna as a function of the length of the straight slot, *Ls*.



(a) (b)

Fig. 4. Simulated current distribution on the ground (with the slots) of the proposed CP microstrip antenna: (a) *t* = 0°, (b) *t* = 90°.

Fig. 3 shows the simulated AR of the proposed CP antenna as a function of the length of the straight slot, denoted as *Ls*. As can be observed, when *Ls* is shorter than 4 mm, the coupling from the straight slot is inadequate, resulting in a weak component in the X-polarization. Correspondingly, the AR is high and the 3-dB AR bandwidth is limited. As the *Ls* increases, the two components in the X- and Y-polarization become more balanced, resulting in an improved AR performance with the 3-dB AR bandwidth over 2 GHz. When the *Ls* further increases to above 5.5 mm, the signal via the straight slot is over-coupled, again leading to unbalanced power between the X- and Y-components. As a result, the AR performance is deteriorated. As a trade-off between the AR and bandwidth, in this design, *Ls* = 5.3 mm was chosen.

The phase difference between the two components can be verified by the current characteristics on the ground. Fig. 4 shows the simulated current distribution of the antenna at different time *t*. When *t* = 0°, the straight slot is excited and the U-slot is inactive. When *t* = 90°, in contrast, the U-slot is active and the straight slot becomes inactive. This current distribution demonstrates that the component in the Y-pol is

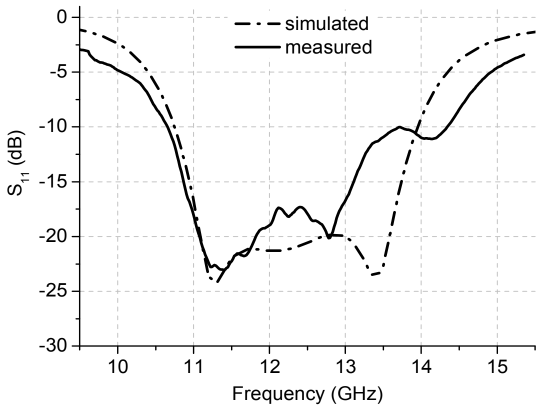


Fig. 5. Simulated and measured S_{11} of the proposed CP antenna.

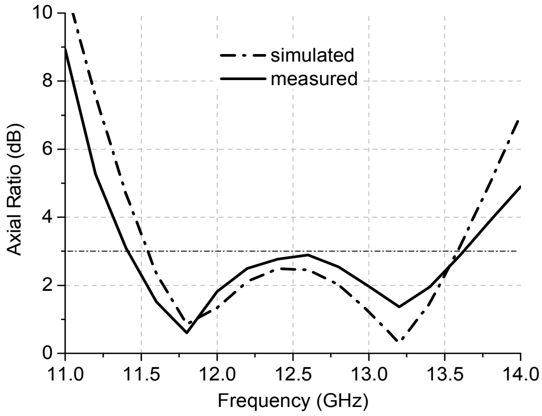


Fig. 6. Simulated and measured AR of the proposed CP antenna.

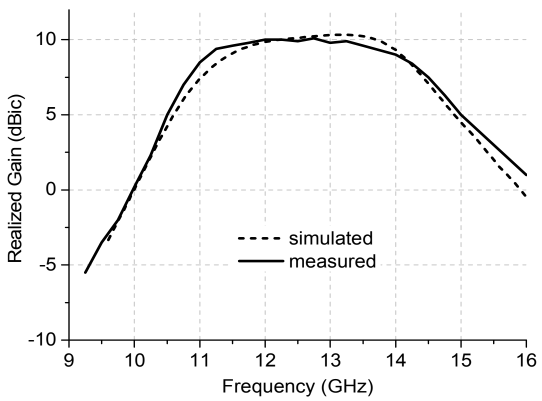


Fig. 7. Simulated and measured realized gains of the proposed CP antenna.

90° behind the X-pol, resulting in the left-hand circular polarization (LHCP).

III. RESULTS AND DISCUSSION

Fig. 5 shows the simulated and measured S_{11} of the proposed CP microstrip antenna. The antenna exhibits a broad impedance bandwidth from 10.7 to 14.4 GHz. The measured result is slightly wider than the simulation, which may be caused by the assembly tolerance that makes some couplings stronger than expected. Fig. 6 shows the measured and simulated AR of the proposed CP antenna. The measured AR bandwidth is shown from 11.45 to 13.65 GHz (17.6%), slightly broader than the simulated one (16.4%). This difference is associated with the fact of wider measured impedance bandwidth in Fig. 5. Fig. 7 presents the simulated and measured realized gains of the proposed CP microstrip antenna in the boresight direction. Both the simulation and measurement exhibit the gain of over 9.5 dBic over a broadband (from 11.5 to 14 GHz). Two factors contribute to this gain improvement: 1) The removal of traditional power dividers and phase delay lines reduces the insertion losses; 2) The radiation from the U-slot combines with the radiation of the patch, leading to an enhanced gain. Moreover, the proposed antenna exhibits the filtering performance with the gain rapidly reduced out of the band.

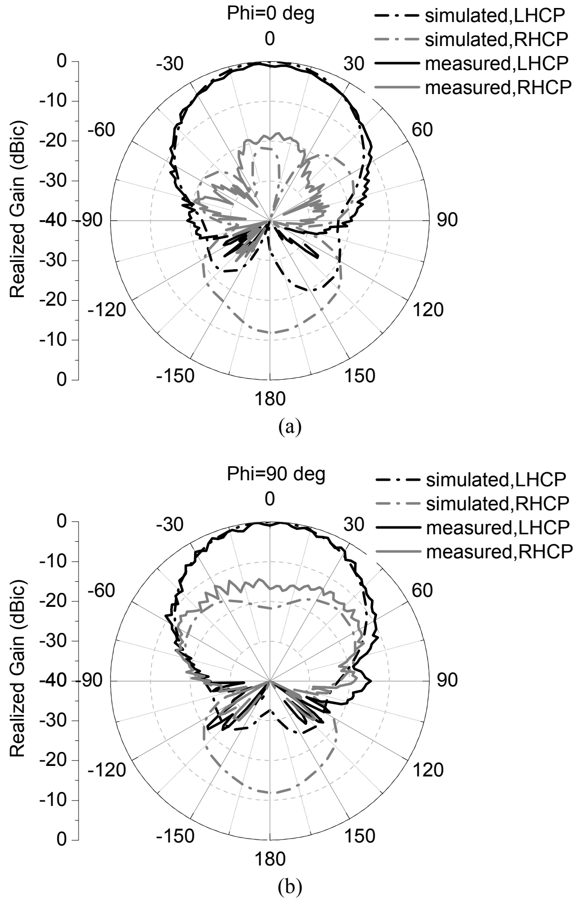


Fig. 8. Measured and simulated normalized radiation patterns of the proposed broadband CP microstrip antenna at 12.5 GHz: (a) E-plane, (b) H-plane.

Fig. 8 shows the simulated and measured normalized radiation patterns of the proposed CP microstrip antenna at 12.5 GHz. The measured results agree well with the simulations in the front side, exhibiting the LHCP radiation. The measured cross polarizations (right-hand circularly-polarized, RHCP) in the two orthogonal planes are lower than -18 dBic, which is slightly higher than the simulation result of -21 dBic. The backward radiation is largely

TABLE I
COMPARISON WITH OTHER CP MICROSTRIP ANTENNAS

Antennas	Thickness	Impedance bandwidth	AR bandwidth	Gain (dBic)
[4]	0.14λ	48.6%	25.2%	6.5
[5]	0.19λ	19.0%	14.9%	5.7
[6]	0.12λ	9.3%	16.0%	8.3
This work	0.09λ	25.6%	17.6%	9.5

suppressed in the measurement. This is due to the blockage of the metallic mounting structure in the anechoic chamber.

Table I compares the proposed CP microstrip antenna with the other three reported CP microstrip antennas in [4]-[6]. The comparison focuses on the thickness of the antenna, impedance bandwidth, AR bandwidth, overlapping bandwidth between the impedance and AR, and gain. Although the thickness of the proposed CP antenna is reduced as compared with other works, the gain of the antenna is much improved to over 9.5 dBic. In addition, the impedance and AR bandwidths of the antenna are improved as compared with [5] and [6]. The antenna in [4] has the wider bandwidths but shows an inferior gain response.

IV. CONCLUSION

In this paper, a novel low-profile broadband CP microstrip antenna with improved bandwidth and gain is presented. The broadband CP characteristics are achieved by employing a compact single-feed dual-coupled network that eliminates the need of traditional power dividers and phase shifters and reduces the associated insertion loss. The resonator-based stacked coupling structure significantly increases the bandwidths of the patch antenna while maintaining a low profile. The design concept and the equivalent circuits are provided and discussed. In addition, due to the antenna is directly coupled with other resonant units, broadband filtering characteristics are achieved. This paper provides a new method to achieve a low profile and broadband CP microstrip antenna with improved gain and integrated filtering features.

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