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Design Optimization of Novel Compact Circular Polarization Antenna

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***Abstract*—The paper describes a structure and a design optimization procedure of a miniaturized circular polarization antenna with elliptical ground plane slots and feed line with stepped-impedance stubs. Constrained optimization of all antenna parameters is executed in order to explicitly reduce the antenna size while maintaining required impedance axial ratio bandwidth of 5 GHz to 7 GHz at the same time. The size of the optimized antenna is only 16.2 mm × 16.7 mm (footprint of 271 mm^2). At the same time, the electrical and field properties of the structure are competitive for state-of-the-art designs as indicated by the comparison provided in the paper.**

Keywords—axial ratio, circular polarization antennas, compact antennas, design optimization, EM-driven design.

I. Introduction

Circular polarization (CP) antennas are of high interest for contemporary mobile communication systems [1], [2] due to advantages of CP such as simplifying a TX/RX path, mitigation of the effects of weather conditions, or multipath reflections on the antenna performance. In case of planar antennas, the simplest way of establishing CP operation is utilization of appropriate feeding networks [3], which, however, hinders miniaturization attempts. Compact CP antennas can be realized using various geometrical modifications involving notches, stubs and slots [4], [5]. Clearly, proper adjustment of geometry parameters is necessary in order to achieve reduction of the physical dimensions of the structure while controlling the antenna reflection response and—even more importantly—the axial ratio (AR) bandwidth. A standard approach is parameter sweeping [6], [7], which fails to provide optimum results for miniaturization.

In this paper, we discuss a structure and a design procedure of a novel CP antenna which is a modification of the design proposed in [6]. In order to permit improved miniaturization, the asymmetrical stubs allocated on the opposite sides of the feed line are loaded with low-impedance lines and the ground plane structure is simplified by removing rectangular slots. Rigorous constrained optimization of all geometry parameters of the antenna allows to reduce its size to only 16.2 mm × 16.7 mm (footprint of 271 mm^2). At the same time, the required 3dB AR bandwidth of 5 GHz to 7 GHz is preserved, similarly as the impedance bandwidth. Comprehensive benchmarking indicates that the presented antenna is competitive to state-of-the-art CP structures reported in the literature. Given its operating bandwidth, the antenna may be suitable for C-band applications exploiting Industrial, Scientific and Medical (ISM) frequencies, as well as 5.2 GHz and 5.8 GHz WLAN.

II. CP Antenna Structure

The antenna structure is shown in Fig. 1. The substrate is Taconic RF-35 ($\varepsilon_r = 3.5$, $h = 0.762$ mm). The antenna is based on the design of [6], where CP operation is obtained by means of two stubs connected to the feed line. Here, to improve AR bandwidth, the low-impedance load is attached to one of the stubs. Also, the rectangular ground plane slots are removed. The antenna geometry is parameterized by fifteen variables $\boldsymbol{x} = [l_{fr}, l_{1r}, l_{2r}, l_3, l_4, l_5, w_{1r}, w_{11}, w_{2r}, w_3, w_{4r}, g_1, g_{11}, g_3, o]^T$, whereas $w_f = 1.7$ to ensure 50 ohm input impedance. Relative parameters are $l_f = (l_3 + 2l_5 + l_6 + o)l_{fr}$, $l_1 = (l_f - g_1)l_{1r}$, $l_2 = (l_f - g_2)l_{2r}$, $w_1 = 0.5(2w_3 + 2o - w_f)w_{2r}$, and $w_4 = 0.5(2w_3 + 2o)w_{4r}$. The computational model of the antenna is simulated in CST (1,700,000 mesh cells, evaluation time 10 min). The model contains an SMA connector. The desired bandwidth (reflection- and AR-wise) is 5 GHz to 7 GHz.

III. Design Optimization Methodology

The goal is to obtain the minimum antenna size $A(\boldsymbol{x})$ while satisfying the following two conditions: (i) $S(\boldsymbol{x}) \leq -10$ dB, and (ii) $AR(\boldsymbol{x}) \leq 3$ dB, where $S(\boldsymbol{x})$ is the maximum in-band reflection, and $AR(\boldsymbol{x})$ is the maximum axial ratio, both within the 5 GHz to 7 GHz frequency range. The design problem can be posed as a nonlinear minimization task of the form

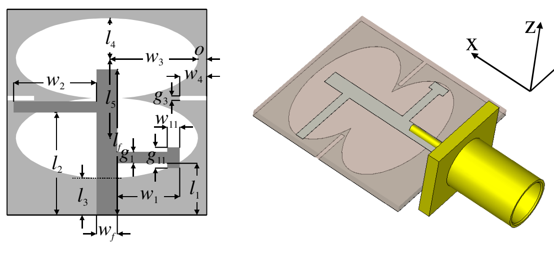
$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x}} \{A(\boldsymbol{x})\}, \quad S(\boldsymbol{x}) \leq -10 \text{ dB}, \quad AR(\boldsymbol{x}) \leq 3 \text{ dB}. \tag{1}$$

Because both constraints are expensive (in computational terms), they are handled implicitly using a penalty function approach. Thus, the design task is reformulated as

$$\boldsymbol{x}^* = \arg\min_{\boldsymbol{x}} U(\boldsymbol{x}), \tag{2}$$

where the objective function U is defined as

$$U(\boldsymbol{x}) = A(\boldsymbol{x}) + \beta_1 \max\left\{\frac{S(\boldsymbol{x})+10}{10}, 0\right\}^2 + \beta_2 \max\left\{\frac{AR(\boldsymbol{x})-3}{3}, 0\right\}^2. \tag{3}$$



(a) (b)

Fig. 1. Proposed compact CP antenna: (a) structure geometry, and (b) visualization of the antenna EM model.

The penalty terms increase the objective function value if the reflection and AR thresholds are violated. The problem (2), (3) is solved using a trust-region gradient search [8] with derivatives of the antenna responses obtained using finite differentiation. Penalty coefficients β_1 and β_1 are set to 20.

IV. Results and Benchmarking

The antenna of Fig. 1 has been optimized using a technique of Section III. The final design is $\boldsymbol{x}^* = [0.71, 0.38, 0.76, 2.99, 3.27, 6.45, 0.7, 1, 0.93, 7.38, 0.27, 0.93, 1.68, 0.36, 0.72]^T$. Another design has been obtained for comparison purposes with the optimization process oriented towards AR improvement with reflection constraints: $\boldsymbol{x}^\# = [0.72, 0.4, 0.76, 3.1, 3.48, 6.58, 0.68, 1, 0.93, 7.6, 0.27, 0.93, 1.69, 0.36, 1.05]^T$. The reflection and AR characteristics are shown in Fig. 2. The antenna footprint is only 271 mm^2 versus 306 mm^2 for the structure optimized for minimum AR. At the same time, AR is below 3 dB and reflection does not exceed –10 dB for the entire frequency range of interest. For additional comparison, the antenna of [6] was re-optimized for the frequency range 5 GHz to 7 GHz, resulting in the maximum AR of 2.65 dB but much larger size of 396 mm^2. Fig. 3 shows comparison of the right- (RHCP) and left-handed circularly polarized patterns (LHCP) obtained in the xy-plane (cf. Fig. 1) at 5 GHz, 6 GHz, and 7 GHz. Fig. 4 shows realized gain in z-direction (see Fig. 1) and total efficiency of the antenna of Fig. 1 optimized for minimum size. The average in-band gain and efficiency are over 2.8 dB, and around –0.3 dB (or 93 percent), respectively.

Table I shows comparison between the proposed structure and several state-of-the-art CP antennas. For fair comparison, dimensions reported in Table I are expressed in terms of guided wavelength λ_g calculated at the low edge f_L of the bandwidth determined by –10 dB reflection for the substrate parameters. It is observed that our antenna offers the broadest AR bandwidth and the smallest size (in terms of λ_g) among the compared radiators. At the same time, it offers competitive impedance bandwidth. Note that re-optimized antenna of [6] features narrower AR bandwidth and larger size. This indicates the relevance (in the miniaturization and performance context) of the topological modifications introduced in the proposed antenna.

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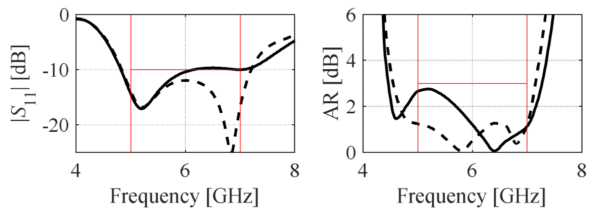
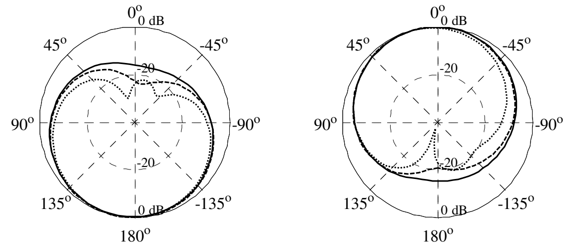


(a) (b)

Fig. 2. Responses of the proposed compact CP antenna, optimized for minimum size (—) and optimized for best in-band AR (- - -): (a) reflection and (b) axial-ratio.



(a) (b)

Fig. 3. E-field radiation patterns obtained in xy-plane for the antenna optimized for minimum size at 5 GHz (—), 6 GHz (– –) and 7 GHz (····) frequencies: (a) LHCP and (b) RHCP.

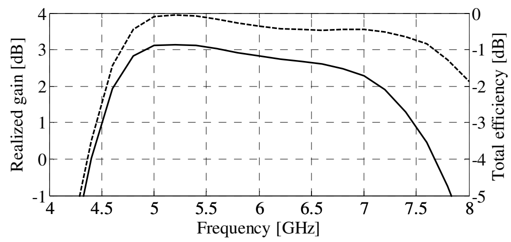


Fig. 4. Realized gain (—) obtained in z-direction and total efficiency (– –) of the size-optimized antenna of Fig. 1.

Table I. Comparison with State-of-The-Art CP Antennas

Structure	f_L [GHz]	AR BW [GHz]	$\lvert S_{11}\rvert$ BW [GHz]	Dimensions [mm]	Dimensions [λ_g]	Size [λ_g^2]
[9]	2.40	0.05	0.14	60.0 × 60.0	0.88 × 0.88	0.77
[10]	4.20	1.00	1.50	34.5 × 28.0	0.88 × 0.72	0.63
[11]	1.82	1.39	1.26	70.0 × 70.0	0.80 × 0.80	0.64
[6] (see Fig. 2)	4.66	2.10	3.10	20.5 × 19.2	0.53 × 0.49	0.26
[6]	4.41	2.27	3.52	20.0 × 20.0	0.54 × 0.54	0.29
This work	4.82	2.82	2.20	16.2 × 16.7	0.43 × 0.44	0.19

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