Circularly Polarized Flat-Topped Beam Using Concentric Circular Arrays of Microstrip Patches

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Abstract. A circularly polarized flat-topped beam is synthesized by concentric circular arrays of microstrip patch antennas using the particle swarm optimization (PSO). The beam synthesis is performed by controlling only the magnitudes of excitation of the array elements where all the array elements are excited in phase. To get circularly symmetric radiation pattern, the elements on the same circle are fed with the same magnitude. The numerical investigations show that the obtained beam shape is very close to the desired one with almost no ripples on the flat top. The final antenna design show acceptable performance regarding the impedance matching, the axial ratio and the sidelobe level over the operating bandwidth of the array.

Keywords: Flat-topped pattern, Concentric circle array, Circular polarize, Particle swarm optimization.

1. Introduction
The flat-topped beam antennas have uniform gain in a given sector of scan that produces equal signal quality for all customers within the coverage area [1,2]. It has many important applications including satellite communication systems, wireless personal area networks and radio-frequency identification (RFID). Moreover, for satellite communications with the ground stations it is commonly required to use antennas with circular polarization to cancel, or even reduce, the effect of Faraday’s rotation when the electromagnetic waves pass through the ionosphere. An array whose elements are arranged on concentric circles is the most appropriate candidate to produce circularly symmetric flat-topped beam with circular polarization [3-6]. In [3, 4, 6, 7], a steerable flat-topped beam with low SLL is using the differential evolution (DE) algorithm. In [5], a flat-topped beam is synthesized using the particle swarm optimization (PSO).

To obtain circular polarization of the radiated field, the circularly polarized microstrip patch antenna described in [8] is chosen to be the element of the proposed array. The numerical results of the present work are concerned with the application of the PSO to concentric circular arrays of isotropic point sources and of printed microstrip patches as well. The presentation and discussions of the numerical results focus on the investigation of the performance of the single element as well as the constructed array. The commercially available packages CST® and HFSS® are used for...
electromagnetic simulation for the purpose of ensuring the correctness and accuracy of the obtained results.

2. Beam Shaping Using Concentric Circular Arrays

In concentric circular arrays as those shown in Figure 1, each circular array has a number of elements proportional to its radius so as to keep equal circumferential distances between the elements. The distribution of the excitation magnitudes in the radial direction controls the beam shape with the elevation angle whereas the magnitudes distribution in the circumferential dimension controls the beam shape with the azimuth angle. A central element may be added to the concentric circular array.

2.1. Concentric circular arrays for circularly symmetric radiation pattern

Let the antenna array be arranged as \( N_R \) concentric circular arrays with growing number of elements. Assume that the radii of the concentric circles are uniformly increasing; this means that the radius of the circle number \( m \), \( (m = 1,2,\ldots,N_R) \) is \( R_m = m \Delta R \). The arrangement of the elements of such concentric circular array is shown in Figure 1. On the \( m \)th circle, a number of \( N_P(m) \) elements are uniformly arranged over the circle circumference. To enforce circular symmetry of the synthesized radiation pattern, all the elements on the same circle must have the same magnitude of excitation. Assuming that the elements are isotropic point radiators and that all the elements have the same phase of excitation, the radiation pattern can be calculated as follows.

\[
E(\theta, \phi) = A_0 + \sum_{m=1}^{N_R} A_m \sum_{n=1}^{N_P(m)} e^{ikR_m \sin \theta \cos (\phi - \Phi_{m,n})}
\]

(1)

where \( \Phi_{m,n} \) is the angular position (with the positive x-axis) of the \( n \)th array element on the \( m \)th circular array, \( \Phi_{m,n} = 2\pi n / N_P(m); \ m = 1, \ldots, N_R; \ n = 1,2,\ldots,N_P(m) \).

![Figure 1. Concentric circular arrays to produce flat-topped beams with circular symmetry.](image)

2.2. Application of the particle swarm optimization for shaping the beam of concentric circular arrays
In PSO, the movements and interactions of the particles within the swarm are considered during the calculation of the improved positions that make the overall swarm approaches the required goal. In the problem of beam shaping by an antenna array, each particle position represents a possible set of magnitudes and phases of the feed of the elements of the array, i.e., it represents one point in the optimization space. The velocity and position update equations for the swarm particles are given in [8]. The desired flat-topped radiation pattern, \( \hat{E}(\theta) \), can be described as follows.

\[
\hat{E}(\theta) = \begin{cases} 
E_0, & 0 < \theta \leq \frac{1}{2}\Theta_a, \quad 0 < \phi < 2\pi \\
0, & \frac{1}{2}\Theta_a < \theta < \pi, \quad 0 < \phi < 2\pi
\end{cases}
\] (2)

where, \( E_0 \) is a constant magnitude, and \( \Theta_a \) is the desired beam width. Thus, the cost function can be, simply, the absolute difference between the achieved and the desired (ideal) patterns of the electric field as follows,

\[
F_c = W_F(|E - \hat{E}|) + W_S(|E - \hat{E}|)
\] (3)

where \( W_F \) is a weighting coefficient of the part of the cost function ensuring the required beam shape over the illuminated angular zone defined by: \( 0 < \theta \leq \frac{1}{2}\Theta_a \), \( W_S \) is a weighting coefficient for the part of the cost function ensuring cancelation of the sidelobes over the angular zone: \( \frac{1}{2}\Theta_a < \theta < \pi \).

3. Results and Discussions

A planar concentric circular array with inter-radial spacing of 0.5\( \lambda \) is optimized to produce a flat-topped beam. The array is arranged in the \( x \)-\( y \) plane and is composed of 5 coplanar circular arrays, where 92 elements are distributed over the 5 circles and an extra element is located at the center of the array.

3.1. Flat-topped beam using concentric circular arrays of point source elements

The PSO is applied to produce a flat-topped beam by concentric circular arrays of isotropic point sources. The magnitudes of excitation of the elements on the same circle are kept equal to each other. Thus, during the optimization process, the magnitudes only are allowed to vary in the radial direction to achieve the optimization goals. To produce a flat-topped beam of width 60\(^\circ\), the excitation magnitudes are those listed in Table 1.

| Circle number | 0 | 1 | 2 | 3 | 4 | 5 |
|---------------|---|---|---|---|---|---|
| Number of elements | 1 | 6 | 12 | 18 | 25 | 31 |
| Radius       | 0 | \( \Delta R \) | 2 \( \Delta R \) | 3 \( \Delta R \) | 4 \( \Delta R \) | 5 \( \Delta R \) |
| Magnitudes   | 1.1564 | 6.2017 | 1.609 | -1.0098 | -0.3772 | 0.3387 |

The decay of the cost function with the iterations of the PSO algorithm is presented Figure 2(a). It is clear that the iterative algorithm is rapidly convergent as it takes less than 70 iterations to reach a steady state value of the cost function of about 15% of its initial value. Such fast convergence and low final value of the cost function reflect the efficiency of the PSO algorithm. The desired and achieved radiation patterns are presented in Figures 2(b) and 2(c), respectively.
Figure 2. Flat-topped radiation pattern obtained from the application of the PSO on 92 elements arranged on 5 concentric circle arrays with an extra central element, (a) Decay of the cost function with the iterations (b) Desired beam, (c) Achieved beam.

3.2. Circularly-polarized flat-topped beam using printed antenna array
This section proposes a practical and cost effective method of implementing the concentric circular array with the same distribution of the excitation magnitudes obtained for the point source array as described in Section 3.1. The microstrip patch antenna described and fabricated in [8] is proposed as an element for the concentric circular array to produce a flat-topped beam with circular polarization. Concentric circular arrays of such patches have the advantages of low profile, light weight and ease of fabrication using printed circuit techniques.

3.2.1. Circularly polarized microstrip patch antenna
A circularly polarized microstrip patch antenna is proposed for the implementation of the concentric circular arrays to produce the flat-topped beam. As shown in Figure 3, the patch is square and has four unequal circular sectors cut at the corners and four slots cut along the horizontal and vertical axes of symmetry. The substrate material is FR4 with dielectric constant \( \varepsilon_r \) and loss tangent \( \delta \). The unequal truncated 90° circular sectors cut at the four corners of the square patch produce two phase quadrature and spatially orthogonal modes with equal magnitudes. This is required to produce circularly polarized radiated field. The patch is designed to work in the frequency band (3.91 to 4.11 GHz). The optimal design parameters of the patch antenna to produce RHCP are: \( L_p = 16.4 \text{ mm} \), \( G = 44 \text{ mm} \), \( r_1 = 3.65 \text{ mm} \), \( r_2 = 3 \text{ mm} \), \( r_3 = 2.31 \text{ mm} \), \( r_4 = 1.1 \text{ mm} \), \( L_q = 3.6 \text{ mm} \), \( W_q = 0.8 \text{ mm} \), \( F = 3.2 \text{ mm} \), \( h = 1.5 \text{ mm} \), \( \varepsilon_r = 4.4 \text{ mm} \), and \( \delta = 0.02 \). It should be noted that in the following presentation and discussions of the numerical results the patch antenna has the same design parameters listed above unless otherwise indicated.

For a single patch, the dependence of the return loss at the antenna port (50Ω feed line) and the axial ratio of the radiated field on the frequency are presented in Figure 4. The radiation patterns of the circularly polarized fields are presented in Figure 5. The radiation is dominated by right hand circularly polarized field. The radiation pattern produced by such single element has a balloon shape with high front-to-back ratio, which is suitable for subsequent application of beam shaping algorithms.
Figure 3. Geometry of the circularly polarized patch.

Figure 4. Reflection coefficient and axial ratio versus frequency.

Figure 5. Radiation patterns in the planes $\phi = 0^\circ$ for the patch.

3.3.2. Flat-topped beam using concentric circular arrays of circularly polarized microstrip patches

The patch antenna described above is used to construct five concentric circular arrays with a central element. The patches are excited in phase with the magnitudes listed in Table 1. The produced 3-dimensional radiation pattern is presented in Figure 6 at 4.0 GHz. Polar plots of the beam are presented in Figure 7 at the frequencies 3.9, 4.0 and 4.1 GHz.

Figure 6. Flat-topped radiation pattern produced by concentric circular arrays of the patch antennas, $f = 4$ GHz.

Figure 7. Radiation pattern produced by concentric circular arrays of the patch antennas at different frequencies.

The radiation pattern achieved by the concentric circular arrays of the microstrip patch antennas in the plane $\phi = 0^\circ$ is presented in Figure 8 and compared with the desired shape at $f = 4.0$ GHz. Figure 9 shows the pattern of the axial ratio, which is maintained below 3 dB over almost the angular zone of the beam width ($60^\circ$) at $f = 4.0$ GHz.

4. Conclusion

Concentric circular arrays of circularly polarized microstrip patches are used to produce a flat-topped beam by applying PSO to control only the magnitudes of excitation of the array elements where all the array elements are excited in phase. The concentric array is designed to operate at 4.0 GHz with bandwidth of about 200 MHz. The obtained beam is very close to the desired one with almost no ripples on the flat top. The constructed array of printed patches shows acceptable performance regarding the impedance matching, the axial ratio and the sidelobe level over the operating bandwidth of the array.

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