Synthesis of Arbitrary-shaped Lens Antennas for Beam-switching Applications

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Abstract— Paper describes a successful attempt to design numerically a two-dimensional shaped beam-switching dielectric lens antenna (DLA) with improved angular (scanning) characteristics. Reduction of the directivity degradation for off-axis feeds is achieved thanks to joint optimization of the lens shape and feeding array parameters. Synthesis of the antenna is performed using highly-efficient in-house software based on the Muller Boundary Integral Equations (MBIE) solver and Hybrid Genetic Algorithm (HGA) optimization routine.

I. INTRODUCTION

Dielectric lens antennas (DLAs) fed by focal arrays are good candidates for imaging and wireless communication systems [1-9]. The desirable feature of such antennas is a stable beam profile for all feeds (with no directivity degradation off-axis ones). This requirement is naturally satisfied in spherical DLAs with homogeneous or multi-shell lenses fed by multiple feeds placed along the lens periphery, e.g. [4, 10]. Although widely used up to K-bands, the multi-shell lens antennas are less attractive at higher frequencies due to a fabrication and mounting complexity and sophisticated feeding structure. To overcome these difficulties and simplify the technology, elliptical DLAs fed by planar arrays were proposed [1-3]. Such antennas have homogeneous hemielliptical (or hemispherical) lenses extended with cylindrical extensions up to the true ellipse geometrical focus. This design provides efficient focusing of the rays propagating parallel to the lens axis and enables direct mounting of the lens on a dielectric substrate supporting the feeding system and detectors. The inherent drawback of such a configuration is that, unlike spherical lenses, elliptical ones have only one focus and therefore their focusing and collimating capabilities suffer in the case of non-symmetrical excitation [2, 3, 11]. The strong beam distortion, observed for compact-size lenses fed by an off-axis feed, restricts the relative size of the feeding array (with respect to the lens bottom size) that is critical for multi-beam antenna design. As to our best knowledge, no successful attempts of improving the angular characteristics of integrated DLAs have been reported until now. Being inspired by recent achievements in design of shaped DLAs for single-beam application [12, 13], we decided to approbate this optimization strategy for design of a multi-beam shaped DLA.

II. MODEL DESCRIPTION AND METHOD OF ANALYSIS

To assess the principle possibilities for design of beam-switching dielectric lens antennas (BS-DLA) with improved scanning characteristics, we perform a test-case study of the antenna made of Rexolite (ε = 2.53) with the flat bottom of approximately 6 free-space wavelengths (a = 3λ₀).

We consider the problem in the two-dimensional (2-D) formulation and model the BS-DLA as an arbitrary-shaped lens illuminated by an array of feeds with variable radiation patterns. Results are reported for the case of E-polarization.

The lens in modelled as a homogeneous dielectric cylinder whose contour is defined by a given number of spline nodes connected by cubic splines (Fig. 1). The initial profile of the lens corresponds to a conventional extended hemielliptical DLA whose eccentricity equals the inverse of the material refracting index \( e = 1/\sqrt{\epsilon - 1} \) (that gives \( l_2 = [\epsilon - 1]/2 \), \( f = [1/(\epsilon - 1)]^{1/2} \)). During optimization the lens bottom size remains fixed; the number of nodes determining the profile of the lens front part equals 10 (that gives the distance between the neighbouring nodes of about one wavelength in dielectric, \( \lambda_0 \)); and the relative increment of the radius vector for each spline node (defined with respect to the initial lens profile and location of the neighbouring node) is limited to 1\( \lambda_0 \).

![Geometry and notations of the 2-D model a shaped DLA fed by a focal array.](image)

Fig. 1. Geometry and notations of the 2-D model a shaped DLA fed by a focal array. The lens is symmetric with respect to the x-axis (the mirrored part is shown in grey color). Curvy lines associated with CSP feeds indicate the branch cuts in the real space due to CSPs.
The feeding array elements are modelled by complex-source point (CSP) beams radiated from the branch cuts appearing in the real space due to CSPs [14-16]. Note that position of the CSP feed and size of the corresponding branch cut is proportional to the real and imaginary parts of the CSP coordinate, respectively. The imaginary part of the CSP coordinate also determines the width of the CSP beam that makes CSP a convenient (compact-form) model of an aperture feed [16]. In computations, CSP feeds are located outside the lens close to its flat bottom ($\delta = \lambda_e/10$) and oriented to radiate in the opposite x-axis direction ($\varphi = 180^\circ$). Parameters included in optimization: CSP feeds locations along y-axis ($d_y$) and beam-width parameters ($b_y$). The array is assumed to be symmetrical with respect to the x-axis, so only 3 feeds are considered. The ranges of parameters variations are the following: feeds spacing $d/\lambda_e = 0.69 \pm 0.18$ and beam-width parameter $kb_y = 1.5 \pm 0.8$ ($k = 2\pi/\lambda_0$ is the free space wavenumber). The reference solution is computed for the conventional extended hemielliptic lens made of the same material and having the same flat-bottom size. Note that main-beam directions for each feed of the focal array exciting the conventional DLA fed by a uniform array with $d/\lambda_e = 0.69$.

Analysis is performed using the in-house CAD tool based on a combination of the MBIE solver and HGA optimization routine. The optimization goal is defined as: to achieve the best possible main-beam directivity for each feed with a minimal relative degradation for the off-axis ones.

The Muller Boundary Integral Equations (MBIE)

The MBIEs are known to be a very attractive approach for implementation in numerical codes for fast and reliable analysis of open dielectric scatterers [17-19]. Their favourable feature is the guaranteed and exponentially-fast monotonic convergence of the numerical solution that enables one to control the computational accuracy for any set of scatterer parameters. This makes the MBIE-solver a power engine for synthesis-oriented CAD tools.

Hybrid genetic algorithm (HGA)

Genetic algorithms are known to be powerful instruments for electromagnetic synthesis [20-22]. Their main advantage is the possibility of dealing with multi-parameter problems with complicated design spaces. This capability is provided thanks to the two-fold strategy that combines a stochastic global exploration and a pseudo-local search implemented in the form of iterative modification and reproduction of already known solutions. The key to an effective optimization strategy is the optimal division of labour spent for the global exploration and local exploitation which can be achieved via hybridization of global and local techniques [23].

The algorithm developed and applied for the current study is a hybrid genetic algorithm (HGA) based on a combination of a classical genetic and a steepest descent gradient (SDG) algorithms. A distinctive feature of the implemented algorithm is that it aims not only at the very best solution but also identifies a given number of the next-to-the-best solutions to be then investigated with the aid of a gradient-based local optimizer. Such a two-step approach enables one to reduce significantly the GA stagnation period often observed at the later stage of optimization. The algorithm has been carefully apprroved on a set of standard test functions as well as antenna array synthesis problems [24, 25]. Its integration with the MBIE-based electromagnetic solver enabled us to build highly-efficient full-wave synthesis-oriented software capable of fast preliminary design of shaped dielectric-based antennas.

III. NUMERICAL RESULTS

A representative optimization run is shown in Fig. 2. Here the optimization process is described both in terms of the cost-function and main-beam directivity values. After first 20 iterations performed by the genetic algorithm, the best found solution is delivered to the SDG optimization loop which works until no further improvement is achieved. Keeping in mind the total number of unknowns (that is 15, i.e. 10 parameters for the lens profile and 5 for the array spacing and feed beam-widths), the total number of iterations is much smaller than might be expected if GA works along. Stability in hitting this extremum observed in multiple independent runs (skipped for brevity) confirms the reliability of the found solution as well as the strong potential of the proposed hybrid optimization algorithms in dealing with multi-extremum and multi-parameter functions.

The advantage in the antenna performance characteristics is also remarkable. Comparison between the performance characteristics of the conventional and shaped DLAs shows that directivity degradation for the most offset feed is reduced to less than 10% compared to the central feed (in contrast to more than 25% difference observed for the conventional design). Moreover, the relative advantage in absolute value of feeds directivity compared to the reference solution achieves roughly 12%, 30%, and 38% for the central and offset feeds, respectively.

Fig. 2. Cost-function (left axis) and main-beam directivity (right axis) vs. number of iteration of the optimization routine. The three curves associated with the right axis indicate directivities of three independent feeds of the CSP array when assisted by the shaped lens. The reference values of the main-beam directivities for the conventional hemielliptic DLA are indicated by hollow circles.
The shaped lens profile and feed array parameters obtained via optimization are given in Fig. 3, whereas the CSP feeds radiation characteristics are shown in Fig. 4. As one can see, the optimal performance of the antenna is achieved when the shaped lens is illuminated by the uniformly-spaced array of non-identical feeds whose directivities decrease proportional to their off-axis displacement. It is interesting to note that the central feed provides the optimal edge illumination for the lens aperture [26]. Whereas the wider patterns of the off-axis feeds can be explained by exploitation of larger surface areas that becomes available (leave the shadow region) because of the tilted main-beam direction for off-axis feeds.

The values of the main-beam directivities for the shaped (optimized) and two conventional hemielliptic lenses (with flat-bottom sizes corresponding to the aperture sizes of the initial hemielliptic lens and the shaped one) are shown in Fig. 5. The improvement is observed both in the absolute values of the directivities and for the level of the directivity degradation for the off-axis feeds which is much lower than for the conventional DLAs. As one can see in Fig. 6, the advantage is gained thanks to sharpening of the main-beams as well as the side-lobe suppression.

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**Fig. 3.** Lens profiles and feeding array parameters for the initial and optimized configurations. Black solid line depicts profile of the shaped lens; grey solid line depicts profile of the conventional lens \((a = 3\lambda_0)\); and grey dashed line depicts profile of the conventional hemielliptic lens whose flat-bottom size equals to size of the aperture of the shaped (optimized) DLA \((a = 3.35\lambda_0)\).

**Array parameters**

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<th>Feed apertures (directivity)</th>
<th>Initial</th>
<th>Optimized</th>
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<td>(k_b_1) = 1.5 (k_b_2) = 1.5 (k_b_3) = 1.5</td>
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**Spacing**

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<th>(d_1/\lambda_e) = 0.69</th>
<th>(d_1/\lambda_e) = 0.8</th>
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**Fig. 4.** Characteristics of a 2-D CSP feed radiating in free space: (a) normalized radiation pattern for different values of the beam-width parameter that correspond to the optimal values found during optimization, (b) broadside directivity (linear scale) vs. beam-width parameter.

**Fig. 5.** Main-beam directivities of the optimized BS-DLA and the two hemielliptic ones, namely: the initial hemielliptic DLA \((a = 3\lambda_0)\) and the one whose flat-bottom size equals to size of the aperture of the shaped (optimized) DLA \((a = 3.35\lambda_0)\).

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**Fig. 6.** Normalized radiation patterns for each feed of the focal CSP array assisted by the shaped (black line) and hemielliptic (grey line) lenses.
IV. CONCLUSIONS
Advanced synthesis-oriented software based on a combination of the MBIE-solver and HGA optimization routine has been developed and successfully applied for optimization of a 2-D small-size shaped DLA fed by a focal array.

Our analysis has revealed that the inherent problem of conventional hemielliptical DLAs, namely directivity degradation for off-axis feeds, can be solved via joint optimization of the lens shape and feeding array parameters. For instance, it has been shown that a properly designed shaped lens can simultaneously and efficiently collimate beams radiated by several independent feeds placed along its flat bottom (in the lens focal plane). Moreover, it was demonstrated that the best performance of a BS-DLA (in terms of the main-beam directivity values for each feed and level of the directivity degradation for off-axis feeds) can be achieved if an optimally-shaped lens is excited by a uniformly-spaced array of non-identical feeds (this recommendation is in contrast to all previously reported designs where arrays of identical feeds were used).

Comparison with beam distortions obtained for conventional hemielliptic lenses showed that accurate synthesis of BS-DLAs enables one to improve the angular characteristics of such antennas, which is of particular interest for beam-switching antenna applications and imaging systems.

The developed software and design methodology can be directly applied for development of planar DLAs [8, 27] using the effective permittivity approach. Moreover, the outlined recommendations for design of shaped DLA fed by focal arrays can be considered as a guideline for design of axisymmetric 3-D BS-DLAs, although our 2-D model does not account for the cross-polarization effects.

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