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RECENT ADVANCES IN SHAPE OPTIMIZATION TECHNIQUES OF 3-D INTEGRATED LENS ANTENNAS

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Abstract. We describe here two design methodologies for the shape optimization of a particular kind of focusing devices, the so-called 3-D integrated lens antennas (ILAs). The objective is to determine the best lens shapes that comply with given radiation characteristics. The first technique is a step-wise approach: the first step consists in solving the synthesis problem using Geometrical Optics (GO) principles, and, in the second one, the GO shape is optimized locally to fulfill the target specifications. This approach leads to an ill-posed problem and is only applicable to single-shell configurations. To overcome these limitations, an alternative technique consists of a global optimization of the ILA, using genetic algorithms (GAs) for instance. The capabilities of both design tools are highlighted numerically. Future trends in the shape optimization of lens antennas are also discussed.

Résumé. Dans cet article, nous décrivons les deux méthodologies principales actuellement utilisées pour l'optimisation de forme de dispositifs de focalisation du type antennes lentilles intégrées 3-D. L'objectif principal du processus d'optimisation consiste à définir une forme optimale de lentille de façon à satisfaire des propriétés en rayonnement prédéfinies. La première méthodologie comporte deux étapes successives : elle consiste d'abord en une résolution préalable du problème inverse au sens de l'optique géométrique, puis en une optimisation locale de la forme ainsi prédéterminée. Le problème non linéaire à résoudre est mal conditionné et cette approche ne s'applique aujourd'hui qu'à des configurations simple coque. Afin de s'affranchir de ces limitations, une solution alternative consiste à effectuer une optimisation globale de l'antenne en couplant un noyau générique de calcul asymptotique à un algorithme d'optimisation globale (du type algorithme génétique par exemple). Les potentialités de ces deux techniques sont illustrées grâce à plusieurs exemples numériques. Enfin nous définissons les principaux besoins actuellement exprimés en optimisation de dispositifs focalisants.

1. Introduction

Many millimeter-wave front-end modules use quasi-optical devices for power budget or high resolution purposes. Among the available antenna technologies, a number of prior works suggest that lens antennas are very promising for shaped-beam or multiple-beam applications [1]. In this paper, we focus our attention on a particular kind of lenses: the so-called integrated lens antennas (ILAs). The latter have been employed in many applications, like point-to-point and point-to-multipoint indoor and outdoor radio links [1][2], ACC (Automotive Cruise Control) radars [3], imaging systems and SIS receivers [4], maritime communications in Ku-band, satellite communications in Q- and Ka-bands [5][6]. A recent state of the art is given in Ref. [7].

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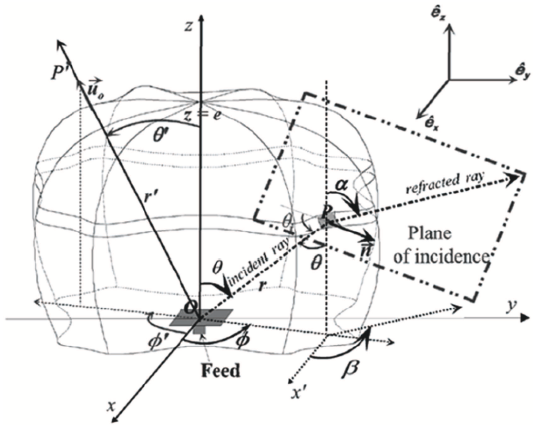

FIGURE 1. Single-shell integrated lens antenna. Geometry and notations.

In contrast to shaped reflector antennas, the synthesis and optimization of shaped lenses has been considerably less studied because lenses have been often considered as heavy and bulky, and the mathematical formulation and numerical computations in dielectric lens shaping may be a delicate task, especially for arbitrary three-dimensional (3-D) lenses [8]. Specific design methodologies have been proposed for the synthesis of (i) axisymmetric, nearly axisymmetric and arbitrarily-shaped ILAs in single- and double-shell configurations (e.g. [6][8]-[11]), and (ii) non-homogeneous lenses [12].

This paper is organized as follows. We describe recent advances in the local and global optimization of arbitrarily-shaped 3-D ILAs in Sections 2 and 3, respectively. Numerical results are also given to illustrate the capabilities of these techniques. Conclusions and future trends are finally drawn in Section 4.

2. LOCAL OPTIMIZATION AND NUMERICAL RESULTS

2.1. Geometry and notations

An ILA is defined as a dielectric lens body ($\epsilon_{r,d}$, $\tan\delta_d$) in direct contact with a primary feed. The geometry of a single-shell arbitrarily-shaped ILA is represented in Fig. 1. In this figure, it is assumed that the feed is a planar antenna radiating towards the z>0 direction (it is assumed that the phase centre coincides with the origin O). The lens profile $r(\theta, \phi)$ is shaped so that the far-field radiation pattern of the ILA coincides with a desired pattern $h(\alpha, \beta)$ for a given primary source $g(\theta, \phi)$. The incident and refracted rays are denoted by (θ, ϕ) and (α, β), respectively. P' is an observation point and P denotes any secondary source point located on the lens surface.

2.2. Formulation and algorithm

This procedure comprises two successive steps. In the first one, a synthesized lens profile, $r_{GO}(\theta, \phi)$, is computed from the Geometrical Optics (GO) principles, namely the power conservation in an elementary ray tube and the vectorial Snell's laws. This leads to the following set of partial differential equations:

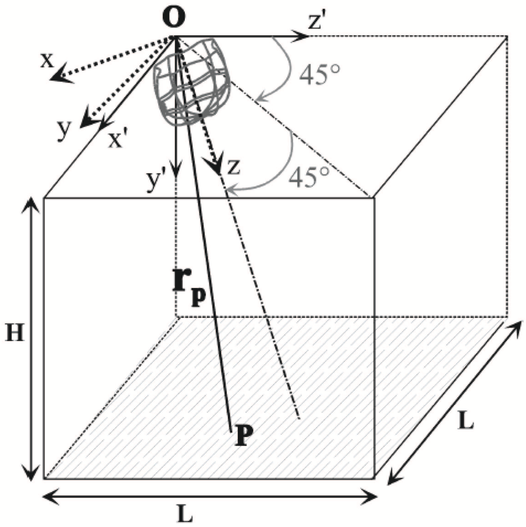

FIGURE 2. Room geometry. The base station (BST) antenna is located at the origin O and illuminates the floor with a constant flux.

$$\frac{\partial r}{\partial \theta} = \frac{(\sin\alpha\cos\theta cos(\beta-\phi)-\cos\alpha\sin\theta)r}{n_d-(\sin\alpha\sin\theta\cos(\beta-\phi)+\cos\alpha\cos\theta)} \quad (1)$$

$$\frac{\partial r}{\partial \phi} = \frac{\sin\alpha\sin(\beta-\phi)r\sin\theta}{n_d-(\sin\alpha\sin\theta\cos(\beta-\phi)+\cos\alpha\cos\theta)} \quad (2)$$

$$\frac{\partial^2 r}{\partial\theta\partial\phi} = \frac{\partial^2 r}{\partial\phi\partial\theta} \quad (3)$$

Where $n_d = \sqrt{\epsilon_{r,d}}$. After some manipulations, Eqns (1)-(3) are transformed into a second-order Monge-Ampere (M.A.) equation; the latter is solved iteratively after linearization and discretization using first-order centered finite differences [8]. It is noteworthy to mention that the synthesized profile - solution of the M.A. equation - is an approximate solution of the problem since the diffraction effects are not taken into account in the GO formulation. To circumvent these limitations and improve the accuracy of the solution, the synthesized profile is optimized locally using a gradient-type technique (second step) so that its theoretical power pattern G_{GO-PO} coincides with the target pattern h. G_{GO-PO} is computed with the hybrid GO-PO (GO-Physical Optics) method [4][8]. This algorithm is described in detail in Ref. [11].

2.3. Numerical results and discussions

This technique has been applied successfully for the design of shaped ILAs radiating Gaussian, flat-top, conical and exotic beams [13][14]. In particular, ILAs are one relevant antenna technology for 4-G wireless local area networks (WLANs) in the 60-GHz band. In this context, several communication scenarii suggest to fix the base station (BST) antenna at the upper corner of the room (height H, square area L×L). For this configuration (Fig. 2), in order to compensate for the free-space attenuation and avoid multiple reflections on the walls, the radiation pattern of the BST should comply with the following specification:

$$h(\alpha,\beta) \propto \begin{cases} r_p^2, & \text{for} \quad 0 < x' < L \quad \text{and} \quad 0 < z' < L \\ 0, \text{otherwise} \end{cases} \quad (4)$$

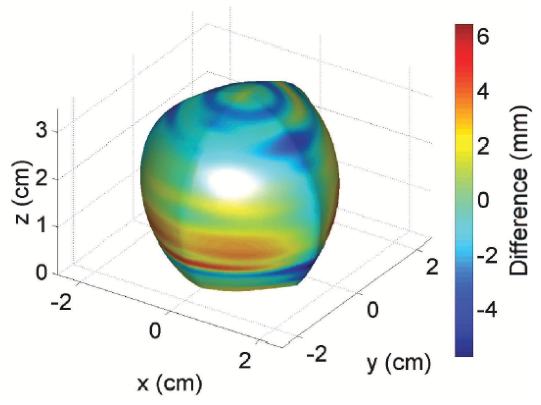

FIGURE 3. Synthesized and optimized 3-D lenses for WLANs at 60-GHz. The 3-D shape corresponds to the synthesized lens and the color scale indicates the difference (in mm) between the optimized shape and the synthesized one.

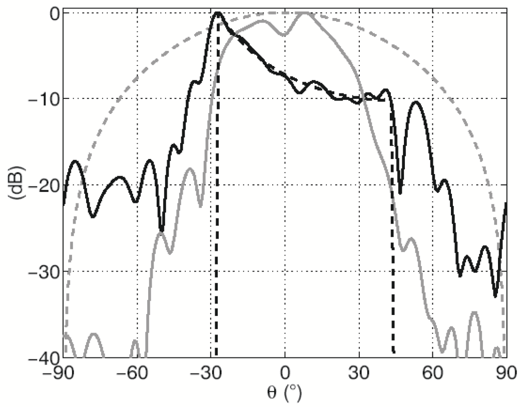

FIGURE 4. Theoretical radiation patterns (ϕ=0°) computed with the GO-PO method at 60 GHz. Dashed grey line: Radiation pattern 'g' of the open-ended waveguide. Black dashed line: Power template 'h'. Solid grey line: Before optimization. Solid black line: after optimization.

The corresponding synthesized and optimized lens shapes are represented in Fig. 3. It is assumed that the lens is in Teflon ($\epsilon_{r,d} = 2.1, tan\delta_d = 5 \times 10^{-3}$) and is illuminated by an open-ended rectangular metallic WR-15 waveguide.

The theoretical co-polarization components of the primary feed, the synthesized ILA and the optimized ILA are compared in Fig. 4 in one principal plane (ϕ=0°). The radiation patterns of the synthesized ILA are in strong disagreement with the amplitude template. As expected, this result confirms that the synthesis procedure should be generally followed by an optimization of the lens shape. On the other hand, there is a satisfactory agreement between the target and optimized patterns, despite the -10dB side lobes appearing beyond 55°. This result is one of the first numerical validations highlighting the possibility to obtain strongly shaped beams using 3D-shaped ILAs [13].

Due to the range of validity of ray tracing techniques, this algorithm is only valid for electrically-large ILAs. In addition, in some cases, it might be delicate to apply because the M.A. problem is ill-posed and the existence of a solution has been established only for single shaped reflectors [15]. Moreover, due to its complexity, the formulation has never been extended to the optimization of multi-shell ILAs. To circumvent these limitations, alternative global optimization procedures have been proposed recently, as described in the next Section.

3. GLOBAL OPTIMIZATION AND NUMERICAL RESULTS

3.1. Methodology

This design procedure (Fig. 5) consists in combining a genetic algorithm (e.g. [16]) with a powerful GO-PO kernel developed for the analysis of multi-shell generic 3-D ILAs.

The parameters to be optimized, namely the shape of each shell boundary, are encoded with a binary representation (chromosomes). The genetic operators are a tournament-based selection associated to a double-point crossover of the chromosomes, as well as mutations to explore the solution space. Cubic splines are used to reconstruct the shell profiles from user-defined control points. The use of a differential coding enables one to minimize the length of the chromosomes while maintaining the largest feasible solution space. After each

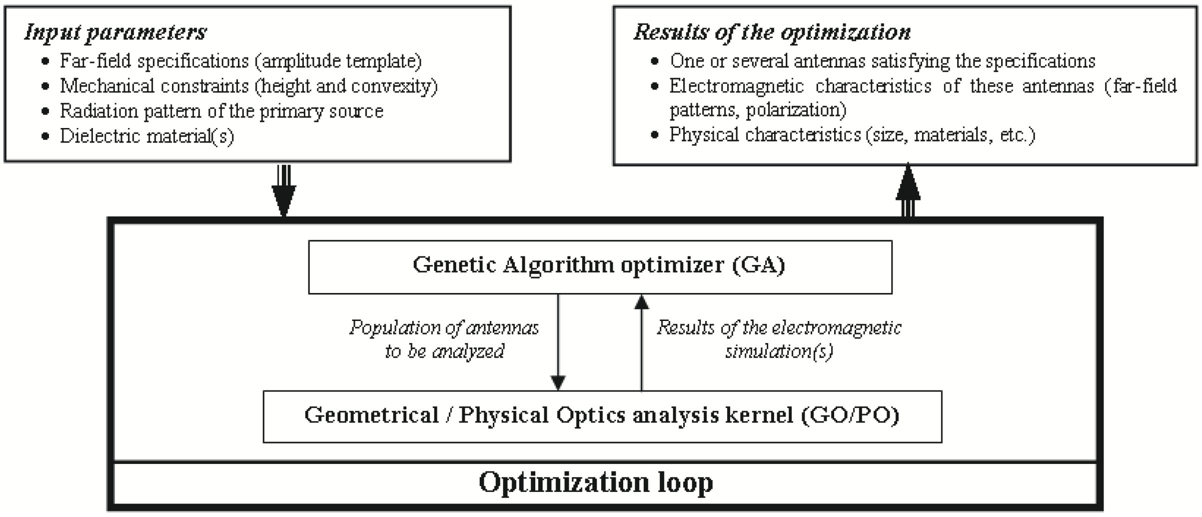

FIGURE 5. Flowchart of the optimization tool.

iteration of the optimization loop, the electromagnetic characteristics of an ILA generated by the optimizer are analyzed with the GO-PO tool and its performance is compared to the desired far-field specifications. Further information is available in Refs. [17][18].

3.2. Numerical results

Two examples are discussed here in order demonstrate the flexibility and capability of this design tool.

3.2.1. *Single-shell lens*

In this example, the objective is to design a lens antenna radiating a flat-top beam at 28GHz. The lens is in Rexolite ($\epsilon_{r,d} = 2.53, tan\delta_d = 5 \times 10^{-3}$) and is fed by an aperture-coupled microstrip patch antenna. Fig. 6 and 7 represent the 3-D optimized ILA and its radiation patterns, respectively. Comparison with the amplitude template shows that the ripples of the sectoral beam (≈3dB) are slightly larger than the target value. In addition, the roll-off is less rapid than the desired one. These effects are due to the reduced size of the lens. The radiation performance could be improved significantly by optimizing a larger ILA (whose central thickness is roughly $12\times\lambda_0$, instead of $4\times\lambda_0$).

3.2.2. *Double shell lens*

Global Earth observation antennas for low orbit satellites require a shaped beam radiation pattern that provides constant flux coverage of the Earth surface within a $\Theta < \Theta_{max}$ subtended angle measured with respect to nadir. Taking into account Earth curvature and path loss attenuation dependence with Θ, the constant flux coverage requirement translates approximately into a Sec(kΘ) radiation pattern template, where k is a constant related to the desired Θ_{max}.

An ILA satisfying these requirements is designed in Ka-band. A double-shell configuration is selected in order to reduce the overall size and weight of the lens. The optimized ILA is represented in Fig. 8; the inner and outer shells are made of Macor ($\epsilon_{r,d}$=5.67) and Rexolite in order to enhance the power transfer efficiency and minimize the spurious effects of multiple internal reflections. The theoretical radiation patterns are represented in 2-D and 3-D in Figs. 9 and 10; they are in excellent agreement with the desired specifications.

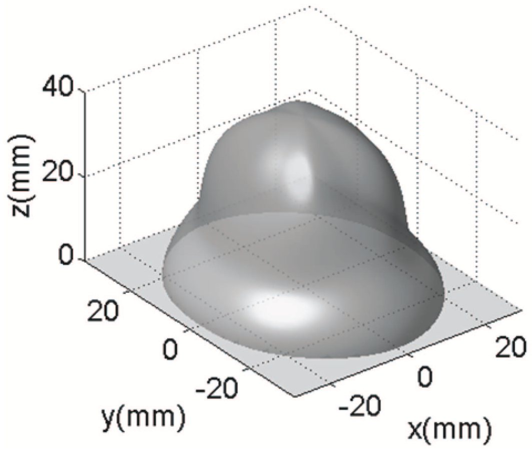

FIGURE 6. Optimized shape of the lens for a flat-top illumination.

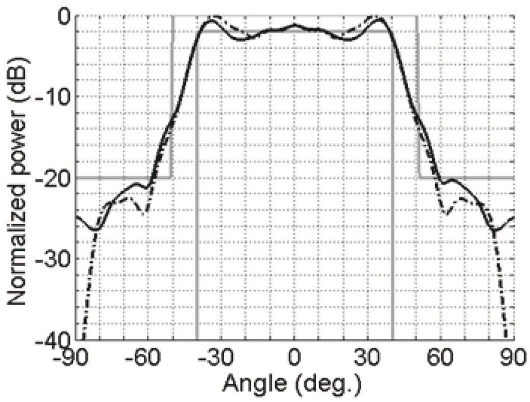

FIGURE 7. Computed radiation patterns in both principal planes at 28GHz. Solid grey line: power template. Solid and dotted black lines: copolarization components in E- and H-planes.

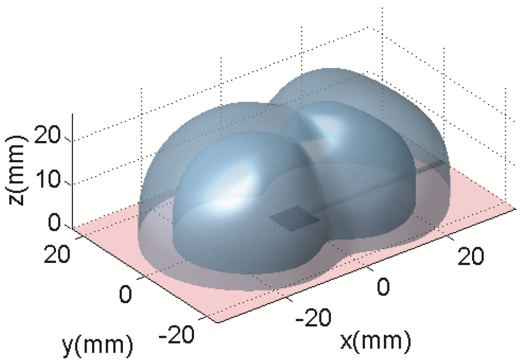

FIGURE 8. Double-shell optimized ILA.

4. CONCLUSION AND FUTURE TRENDS

This paper describes two design methodologies for the optimization of shaped Integrated Lens Antennas (ILAs) for shaped beam applications at millimeter waves. The first approach is based on the local optimization of a synthesized lens profile, solution of a Monge-Ampère problem. Although powerful, this technique is presently restricted to the design of large and single-shell ILAs. An alternative solution consists in combining a global optimization algorithm (like a Genetic Algorithm) to high-frequency techniques (like the Geometrical Optics - Physical Optics method). Numerical examples have highlighted the main characteristics and limitations of these design tools.

Future trends concern the size reduction or the achievement of very large bandwidth ILAs. To this end, multi-shell structures or complex-media based devices are possible candidates. The improvement of the radiation characteristics of lenses (high-efficiency beam formers, low-cost multiple-beam lenses, reconfigurable focusing systems) should also be considered. To meet these requirements, specific and efficient numerical tools must be

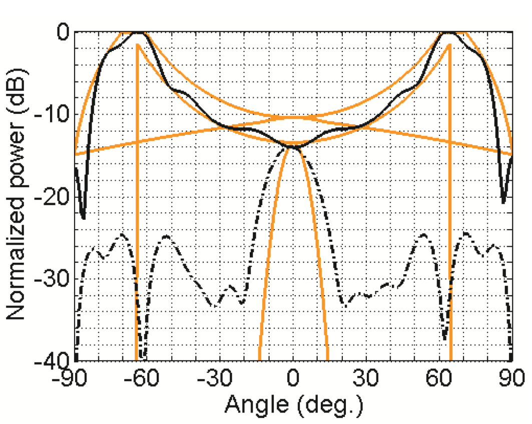

FIGURE 9. Radiation patterns in both principal planes at resonance (26GHz). Solid orange line: power template. Solid and dotted black lines: co-polarization components in E- and H-planes.

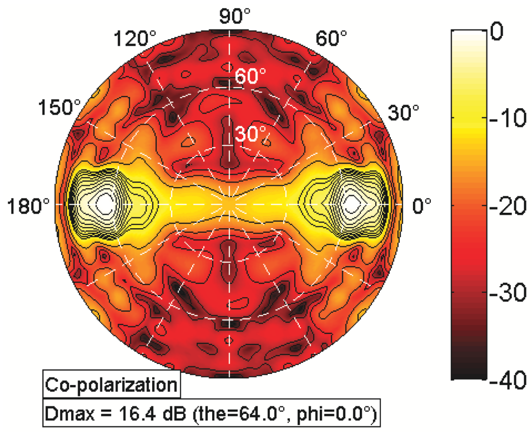

FIGURE 10. 3-D co-polarization pattern at resonance (26GHz).

implemented and validated for the analysis and the global optimization of lens antennas. Among those, the development of fast and accurate full-wave electromagnetic solvers seems to be a very promising approach. A recent contribution has demonstrated its feasibility in 2-D [19]. Extension in 3-D and combination with fast computational techniques (such as the FMM) is an exciting challenge.

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