Design of axis-symmetrical dome antennas with secant-squared beams
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Abstract — In this paper we describe the design of shaped dielectric dome antennas radiating a secant-squared beam at 60GHz. The design methodology consists in a binary Genetic Algorithm combined with an asymptotic method of analysis based on the Geometrical Optics / Physical Optics technique. The dome antenna is made in Rexolite and is excited by a compact pyramidal horn antenna. The use of matching layers coated on both sides of the dome enables one to reach a 5GHz band around the central frequency.

I. INTRODUCTION

Dielectric lens antennas have been extensively studied, and many homogeneous and non-homogeneous configurations have been proposed [1][2]. Among those, the so-called Integrated Lens Antenna (ILA) is probably the most popular one, due to its low cost and high performance. A number of papers have reported their use for millimeter and sub-millimeter wave applications, like point-to-point and point-to-multipoint radio links [3][4], imaging systems and quasi-optical receivers [5][6], satellite communications and instrumentation [7][8]. In these works, two main kinds of lenses are employed, namely the extended hemispherical lenses and the shaped lenses. In the second case, the shape of the lens profile is computed so that its radiation pattern complies with given specifications. The appropriate configuration for the lens is generally selected according to the target application (high-gain, multiple-beam or shaped beam antennas). In any case, the lens is bulky and heavy, and is usually fed by a planar antenna or an open-ended metallic waveguide in direct contact with the lens body.

The objective of this paper is to analyze the capabilities of dome antennas [9][10] for beam shaping applications [11]. In contrast to standard ILAs, the dome antennas have a much lower weight and are compatible with the use of 3-D primary feeds.

This paper is organized as follows. The design tool developed at IETR for the analysis and optimization of multi-shell arbitrarily-shaped lenses is described in Section II. Then a shaped dome antenna is designed at 60GHz in Section III; both dielectric interfaces of the dome are optimized in order to radiate an axis-symmetrical secant-squared beam. The role of the multiple internal reflections is also briefly highlighted. Conclusions are finally drawn in Section IV.

II. DESCRIPTION OF THE OPTIMIZATION TOOL

One possible approach for the optimization of ILAs is a two-step method [12]. It first consists in 1) resolving the inverse problem using GO laws in order to determine the theoretical lens profile satisfying the far-field specifications, and then 2) in locally optimizing this shape using a more accurate method of analysis, such as the geometrical / physical optics (GO/PO) approach [6][12]. However, in the first step, it is assumed that the lens dimensions are large compared to the operating wavelength. If this GO-based algorithm is applied to reduced size lenses (diameter smaller than a few wavelengths), it cannot be stated that the shape found with the inverse method is close enough to the optimal solution so that the local optimization could be performed efficiently.

To overcome this limitation, we propose to use a single-step optimization procedure based on a genetic algorithm (GA) [13] combined with the hybrid GO/PO method.

The flowchart of the design methodology is represented in Fig. 1. The main input parameters of the optimizer are the following: 1) design specifications (far-field patterns, power transfer efficiency), 2) design constraints (central height of the lens, assembling constraints when dealing with multi-shell ILAs), 3) far-field radiation patterns of the primary source (in amplitude and phase), and 4) available dielectric material(s).

The design procedure comprises three main steps:
- A set of optimum lens shapes is computed using a GA combined with a method of analysis of 3-D generic ILAs based on the GO/PO;
- Then, for further validation purposes, the GO/PO radiation characteristics of the optimized ILAs (3-D far-field patterns, axial ratio, etc.) are compared to those computed with a global electromagnetic software (in our case, a 3-D home-made FDTD solver);
- Finally, the optimized antenna prototype is fabricated using computer numerically controlled (CNC) milling facilities for experimental validation.

The GA chosen here is a standard implementation of this class of optimization methods. The parameters to be optimized are encoded with a binary representation. The genetic operators are a tournament-based selection associated to a double-point crossover of the chromosomes, and a binary mutation operator. As we do not consider any initial
guess for the lens shape, the initial population of individuals is a set of random binary chromosomes.

The shape of the lens is represented by a binary string (i.e. a chromosome). The relation between a physical dome shape and a chromosome is obtained from the discretization of a given number of control-points uniformly distributed over each dome interface. Their shape is reconstructed from these control-points using a two-dimensional cubic splines interpolation. This step is of crucial importance because it represents the link between the real space of possible solutions and the space of solutions attainable by the optimizer.

One of the major issues of GA optimization is to get the most compact chromosome, with the largest feasible solution space, because most compact the chromosomes are, the fastest the convergence is. To this end, we implemented a differential coding [14] of the control-points so as to get a compact description of the lens shape.

The far-field properties of each individual of the GA population are used to assess its performance, in comparison with the desired specifications. The value of the user-defined cost function, called Fitness in GA terminology, is defined as follows:

$$
\text{Fitness} = \Delta \theta \times \Delta \phi \times \sum_{u=0}^{N-1} \sum_{v=0}^{M-1} [G_{GOPO}(\theta_u, \phi_v) - h(\theta_u, \phi_v)]^2
$$

where $G_{GOPO}$ and $h$ denote the far-field radiation pattern of the ILA under test and the target specifications, respectively. These patterns are computed for an arbitrary number of observation points ($\theta_u, \phi_v$) distributed in space.

More details about the optimization algorithm are given in Ref. [15].

III. DESIGN OF A DOME ANTENNA

A. Antenna specifications and primary source

The target pattern of the dome antenna is a rotationally symmetric secant-squared beam at 60GHz. It is represented in Fig. 2. The primary feed is a TE$_{10}$-mode distribution aperture on ground plane. Its radiation pattern is nearly axis-symmetrical and has a very small cross-polarization component (Fig. 3).
B. Optimized dome antenna

The dome antenna is in Rexolite ($\varepsilon_r=2.53$, $\tan\delta=6\times10^{-4}$). Both interfaces are optimized with the following set of parameters: 1) the size of the chromosomes and population is equal to 104 bits and 1024, respectively; 2) the mutation and crossover probabilities are set to conventional values recommended in the literature (5% and 90%, respectively).

Figs. 4a and 4b represent 1) the variation of the fitness for five independent runs of the optimization tool as a function of number of evaluations, and 2) the best fitness value obtained for each run. The average value of the fitness function is very small ($<10^{-4}$), confirming thereby that the performance of the synthesized domes is in satisfactory agreement with the specifications.

The corresponding profiles of the five domes antennas are given in Fig. 5. Their maximum thickness and external diameter are in the order of 33mm and 32mm respectively.

The 3-D shape and the far-field radiation patterns of the best individuals obtained from run #2 (fitness=$4\times10^{-4}$) and run #5 (fitness=0) are given in Figs. 6a and 6b, respectively. Their radiation performance is in full agreement with the target specifications. The largest ripples observed in Fig. 6a in the secant-squared part of the beam explain why the minimum fitness of run #2 is higher than for run #5 (Fig. 4b).

The radiation patterns computed over a 5GHz frequency band are plotted in Figs. 7 and 8. They are in excellent agreement with the target template. The moderate side lobe level obtained in E-plane for grazing incidence (-18dB) originates from the feed pattern itself (Fig. 3). It could be reduced significantly using a different feed, such as a double-slot antenna [6].
Further numerical simulations with GO/PO and FDTD have highlighted the considerable effects of the multiple internal reflections [16]. The use of quarter wavelength matching layers coated on both sides of the dome enables one to improve significantly the lens performance. The corresponding results will be given and discussed during the conference.

**IV. CONCLUSIONS**

In this preliminary study, we have investigated the performance of shaped dome antennas for shaped beam applications. Our design methodology is based in a binary Genetic Algorithm combined with the Geometrical Optics – Physical Optics method of analysis.

To illustrate the capabilities of these antennas, both dielectric boundaries of a rotationally symmetric dome made in Rexolite have been optimized at 60GHz. The dome antenna is fed by a compact pyramidal antenna etched in a metallic plane. The use of anti-reflection coatings enables one to reduce significantly the influence of multiple internal reflections.

**REFERENCES**


