Hybrid-type Integrated Lens Antenna with Improved Gain and Aperture Efficiency in Ka-band

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Abstract- **A shaped integrated lens antenna fed by a circular waveguide with a flange is designed and optimized in *Ka*-band (29.5 GHz) using BoR-FDTD software. The lens with an optimized dielectric taper is fabricated in Rexolite. As demonstrated both numerically and experimentally, the proposed antenna outperforms its conventional hemielliptic analog in terms of gain and aperture efficiency. The advanced performance is achieved thanks to exploiting the focusing and resonant features of the compact-size optimally-shaped dielectric lens.**

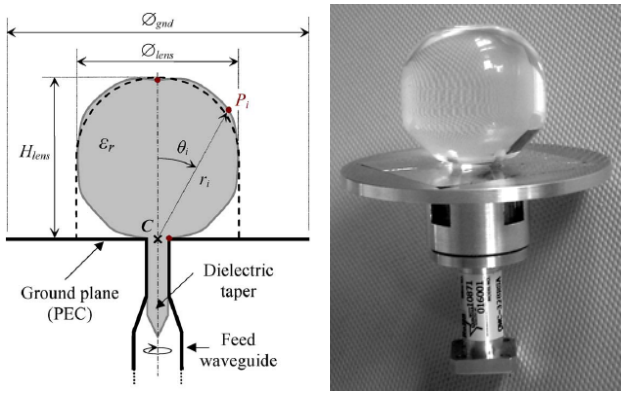
I. INTRODUCTION

Dielectric lens antennas (DLA) are widely used in mm-wave communication and radar systems, e.g. [1-3]. In most cases lens shapes are either defined analytically (e.g. [1]) or synthesized numerically using advanced surface optimization algorithms. The latter enables creation of compact-size DLAs with advanced performance characteristics: better aperture efficiency [4, 5], enhanced gain [6, 7], improved steering capabilities [8, 9], shaped radiation patterns [2, 10], etc.

Although lens profile optimization seems to be a well-established way of DLA design whose strong potential has been demonstrated in many publications, in reality until now there exists no full-wave synthesis-oriented CAD tools capable of fast and reliable optimization of miniaturized arbitrary-shaped DLAs. This is because most of available tools are still based on high-frequency techniques (e.g. [2, 6, 10]), which makes them fast but limits their range of reliable applicability by electrically large lenses with gently curved surfaces.

To overcome these limitations, full-wave synthesis-oriented software has been developed based on the Finite-Difference Time-Domain technique for bodies of revolution (BoR-FDTD) and genetic algorithm [11]. Utilization of this new software enabled us to design the first integrated DLA whose operation principles are based on a combination of the optical-type focusing and excitation of an internal resonance which is used to improve matching and to sharp the antenna radiation pattern.

This paper describes the design procedure and radiation characteristics (theoretical and measured) of the hybrid-type DLA whose performance is superimposed with that of a conventionally-shaped extended hemielliptic DLA of the same dimensions. As will be demonstrated below, careful accounting for both optical and modal features of compact-size lenses opens doors for creation of DLAs with improved gain and very high aperture efficiency.



(a) (b)

Figure 1. Axisymmetric DLA fed by a standard air-filled circular waveguide with finite-size circular flange: (a) Generic view and notations, (b) Antenna prototype. The lens and dielectric taper are fabricated in a single block – shown in grey color in (a).

II. DESIGN PROCEDURE

The generic configuration of the antenna is shown in Fig. 1. The lens is made in a low-permittivity and low density material (Rexolite, $\varepsilon_r = 2.53$, $tan\delta = 6\times10^{-4}$ at 60 GHz) and is fed by a standard air-filled circular waveguide operating in its fundamental mode TE_{11}. Such a feed ideally fits the selected design methodology thanks to its axisymmetric geometry and azimuthal-mode decomposition required by the BoR-FDTD formulation.

In simulations the optimization goal is defined as to find the antenna configuration providing the best broadside directivity and fitting the antenna family defined in Fig. 1. In addition, the maximum side lobe level (*SLL*) is fixed at -15 dB, and the maximum authorized reflection coefficient value (S_{11}) at the design frequency is set to -12 dB. As we focus our attention on reduced-size DLAs, the search space for the lens profile has been bounded as follows

$$\varnothing_{lens} \le 4\times\lambda_0, \quad H_{lens} \le 4\times\lambda_0, \quad \varnothing_{gnd} \le 8\times\lambda_0, \qquad (1)$$

where λ_0 is the wavelength at the design frequency $f_0 = 29.5$ GHz ($\lambda_0 = 10.17$ mm).

As a reference solution, an extended hemispherical (EHS) lens antenna made of Rexolite and fed by the same feeding structure is considered. The lens diameter and height are fixed at $4\times\lambda_0$. For the selected material, this design provides a close

geometrical agreement with the extended hemielliptic (EHE) lens [1]. The fabrication simplicity and the very small difference in the performance characteristics of the EHS and EHE DLAs with defined parameters explain why we selected the former for the fabrication and measurement purposes.

To guarantee the accuracy of simulations when dealing with small-size shaped dielectric lenses [12], we solve this optimization problem using an advanced synthesis tool recently developed by the authors based on the combination between a BoR-FDTD solver and a real-valued genetic algorithm (GA) implemented on a grid computing platform to speed up the design process [11].

The design procedure is split in two successive steps. First, the lens profile (defined by 10 nodes connected with cubic splines) and ground plane size are optimized to comply with the radiation specifications defined above. Here we assume that the antenna is fed by a matched waveguide filled by Rexolite. Second, the dielectric and metallic tapers are optimized to match the antenna at f_0 (in this case, the lens shape and ground plane size are those determined in step 1).

III. Results

The best antenna configuration found is shown in Fig. 1a. Its dimensions are: $\varnothing_{lens} = 40.68$ mm, $H_{lens} = 40.68$ mm, $\varnothing_{gnd} = 76.59$ mm. Note that height and diameter has reached the maximum allowed values ($4\times\lambda_0$) whereas the ground plane size is slightly smaller than its allowed upper limit.

To assess the design quality experimentally, two antenna prototypes have been fabricated using a computer-numerically-controlled lathe: shaped DLA (Fig. 1b) and EHS with the same dimension used as a reference solution (not shown). The lenses and their tapers were made in a single block of Rexolite.

The simulated radiation patterns for the optimized shaped DLA and its conventional analogue are shown in Fig. 2 at 29.5 GHz. The radiated beam of the shaped DLA has a narrower main beam and *SLL* below -16 dB, that is ~ 5dB better than for EHS DLA. Other radiation characteristics of the shaped DLA are the following: the directivity equals 23.7 dBi (which is 2.7 dB better than the reference solution, Fig. 3), and the reflection coefficient is -17 dB at the central frequency and remains below -12 dB over a relative band of ±4% (skipped for brevity). Finally, the aperture efficiency of the shaped antenna is calculated as $\eta_{ap} = A_{eff}/A_{phys}$, where A_{eff} and A_{phys} denote the maximum effective aperture ($A_{eff} = \eta_{loss}\, D\, \lambda_0^2/4\pi$) and the physical aperture (A_{phys}) of the antenna (D is the maximum antenna directivity and η_{loss} represents the antenna losses). Here the physical aperture is defined as $A_{phys} = \pi\varnothing^2/4$, where $\varnothing = \max(\varnothing_{lens}, \varnothing_{gnd})$. The variation of η_{ap} is represented in Fig. 4 at 29.5 GHz as a function of the ground plane size (assuming $\eta_{loss} = 1$). As seen η_{ap} reaches 100% for $\varnothing_{gnd} = \varnothing_{lens}$ (which is already remarkable value for DLAs [5]) and 106% for $\varnothing_{gnd}$ equal to its optimal value 76.59 mm. The latter results can potentially be achieved on practice if the lens is fed by a planar feed whose substrate may serve as the ground plane with no "additional cost".

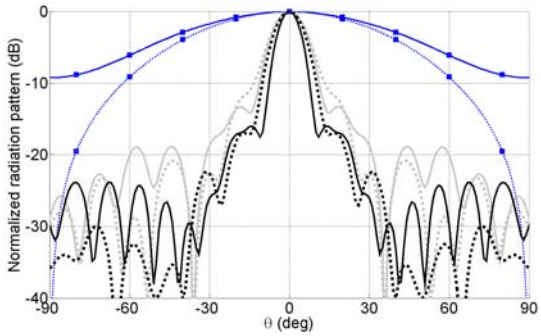


Figure 2. Normalized radiation patterns in both principal planes: E-plane (solid line), H-plane (dotted line). Black line: optimized shaped DLA. Grey line: EHS DLA with the same dimensions, -■- : primary feed.

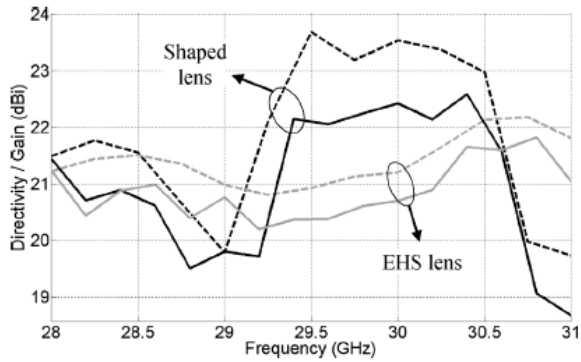


Figure 3. Measured gain (solid lines) and theoretical directivity (dashed lines). Black lines: optimized shaped lens. Grey lines: EHS lens with the same dimensions. The gain was measured with the comparison method using a 20-dBi standard gain horn.

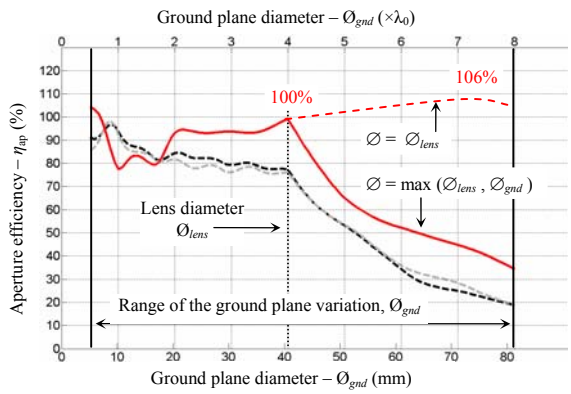


Figure 4. Aperture efficiency at 29.5 GHz of the shaped (▬), EHS (▬ ▬), and EHE (▬ ▬) DLAs vs. diameter of the ground plane in mm (bottom axis) and wavelength (top axis). The solid vertical lines indicate the diameter of the feed waveguide and the maximum allowable size of the ground plane. The solid and dashed red lines depict aperture efficiency of the shaped DLA defined based on two different definitions of the physical antenna aperture.

IV. Discussion: Lens or Resonator?

This question raised in [13] helps understand the origins of the advanced performance of the designed shaped DLA. For compact-size lenses the backscattering from curved surfaces may result in strongly pronounced internal resonances [12-14]. In most cases this is an unwanted property as it typically leads to additional scattering and dissipation losses. From the other

hand, internal resonances provide additional degree of freedom for control over the antenna radiation characteristics (e.g. matching and radiation pattern).

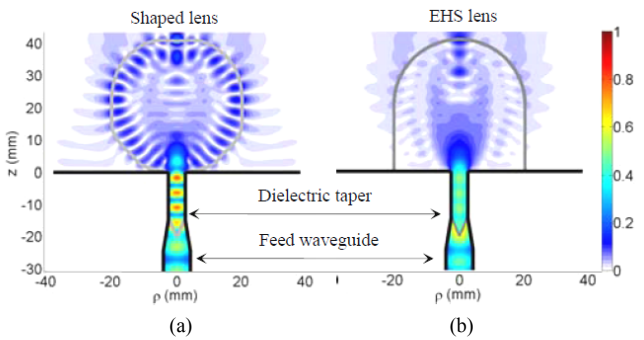


Figure 5. Near-field distribution (E-field) computed with the BoR-FDTD method at 29.5 GHz: (a) optimized shaped DLA supporting a distorted WG mode, (b) EHS DLA with the same dimensions.

Fig. 5 shows computed near-filed patterns of the shaped and EHS DLAs fed by the same feeding structures at 29.5 GHz. As one can see, the former supports a whispering gallery mode (WGM) which is clearly seen thanks to its specific near field pattern, whereas the near-field map of the latter resembles very much the ray focusing picture. The reason why the shaped nearly-spherical lens radiates a well collimated beam becomes evident if one refers to [15] where it is demonstrated that shape distortion of a circular WGM resonator leads to directive emission in two opposite directions: towards and backwards the distortion position.

For the optimized shaped DLA, the slightly distorted spherical shape of the lens first traps the scattered power in the form of a WGM resonance and then reradiates it in the broadside and downside directions. The latter is then mirrored by the ground plane and also contributes in the main beam formation. As a result, all power extracted from the feed is finally guided in the broadside direction that is contrary to conventionally shaped lenses where the scattered power finally contributes to side lobes (Fig. 2). This explains the advanced performance demonstrated by the resonant lens DLA.

V. Conclusions

The first hybrid-type resonant lens antenna has been designed (using BoR-FDTD inhouse software), fabricated and measured at 29.5 GHz. It has been shown that optimally-shaped lens, supporting a distorted WGM resonance and assisted by a finite ground plane, is capable of producing a well collimated beam with low side lobes. The advanced performance (improved gain and aperture efficiency) is observed over a relative band of ±4% around the central frequency as it originates from the resonant behaviour. The inherent filtering capability of the proposed antenna makes it a favourable candidate for advanced narrow-band applications, e.g. satellite based communications or imaging systems.

More details about the resonant lens antenna and its characteristics (calculated and measured) will be given in [16].

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