Low-Permittivity Elliptical Lens Fed by a Broadband Leaky-Wave Antenna for Communications Applications

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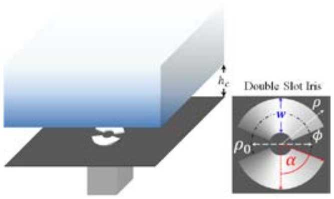
***Abstract*— In this paper, a leaky-wave fed lens antenna working at G-band for future XG communications is presented. A lens with a diameter of $16\lambda_0$ is proposed in HDPE material with a feed matching better than -10dB over a 44% of relative bandwidth. Analytical tools have been applied to achieve an aperture efficiency higher than 80% in the entire frequency band, validating the results via full wave simulations. A prototype has been fabricated and is now under test.**

Keywords— leaky-wave, lens, wideband communications

I. INTRODUCTION

Massive events as the Super Bowl represent the ultimate connectivity challenge. The solution will require wireless links with orders of magnitude larger capacities. One of the most reasonable approaches is moving the RF carrier frequency up, where larger bandwidths can be exploited to increase the maximum achieved throughput. In [1] an innovative base station (BS) architecture for a football stadium scenario at D-band was proposed. The system is capable of providing 80.000 spectators with 12 Tbps of total capacity, which could be translated in a data rate of 150 Mbps per user. The BS consists of a central 3D elliptical lens antenna array containing 1500 transceivers. In order to achieve the claimed capacity, antennas with 34 dB of directivity and 24 GHz of bandwidth have been considered. The use of lens antennas allows us to reach these high directivities avoiding the losses in feeding networks, which would be extremely high in these high frequency bands. Indeed, the optimization of the aperture efficiency for these lenses is crucial, as every dB lost in reflection and ohmic loss has a direct impact in the base station achieved data-rate and its power consumption, moreover a high taper efficiency leads to a more compact lens array and therefore BS.

In most of the reported works, the lenses are fed efficiently over a narrow band, using double slot antennas [2] or patches [3]. Other works present well matched and stable phase center over a very wide band but the reported aperture efficiency is low [4]. In [5] a Leaky-Wave Antenna (LWA) was proposed as a promising solution to act as lens feeders, because of its high directivity, symmetric patterns and compatibility with silicon fabrication processes. As the proposed resonant LWA is radiating into a semi-infinite dielectric medium, the achieved relative bandwidth is enhanced w.r.t. standard LWA. This paper focuses on the analysis and design of low-density elliptical lenses illuminated by resonant LWAs, for broadband wireless communication applications. The goal is to maximize the aperture efficiency (>80%) over a large frequency band.



a) b)

a) LWA radiating in a semi-infinite dielectric (the air-gap height is $\lambda_o/2$). b) parameters of the double-slot iris. The waveguide dimensions are always kept smaller than λ_0.

I. THE BROADBAND LEAKY-WAVE FEED

The physical phenomenon exploited in resonant LWA is the excitation of a pair of nearly degenerated TM_1/TE_1 leaky-wave modes. These modes propagate in a resonant cavity by means of sub-critical reflections between the ground plane and the dielectric (Fig. 2a), increasing the antenna effective area and thus its directivity. But this LWA generates also an undesired spurious TM_0 leaky-wave mode that does not radiate in broadside direction, and therefore degrades the beam shape. The effect of the TM_0 can be reduced by using a double slot opening in a ground plane as proposed in [7]. The current distribution on the double-slots is shown in Fig. 1b and can be approximated as the one imposed by the incident TE_{01} waveguide mode. The primary fields (inside the dielectric) can be evaluated by using an asymptotic evaluation of the spectral Green function SGF [6] with an infinite dielectric super-layer ($\underline{\underline{G}}^{em}(k_{xs}, k_{ys}, z, z')$) and the Fourier transform of the currents on the double slot iris $M(k_{xs}, k_{ys})$:

$$\vec{E}_{LWA}(\theta,\phi) \approx 2jk_{zs}\underline{\underline{G}}^{em}(k_{xs},k_{ys},z,z')M(k_{xs},k_{ys})e^{jk_{zs}z}\frac{e^{-jkr}}{4\pi r} \tag{1}$$

where $k_{xs} = k_0\sqrt{\varepsilon_r}\sin\theta cos\phi$, $k_{ys} = k_0\sqrt{\varepsilon_r}\sin\theta sin\phi$ and $k_{zs} = k_0\sqrt{\varepsilon_r}\cos\theta$.

II. OPTIMIZATION OF THE APERTURE EFFICIENCY

Lenses are characterized by an intrinsic critical angle θ_c after which the energy coming from the ellipse focus suffers from total reflection. In order to achieve high reflection efficiency, only the lens region above $\theta_c = \tan^{-1}(\sqrt{\epsilon_r - 1})$ should be illuminated. As a consequence, lenses with lower ϵ_r need to be illuminated with more directive feeds than denser lenses. Moreover, in order to maximize the aperture efficiency, the lens should be truncated at edge angle, θ_{edge}, lower than θ_c (see Fig.2a).

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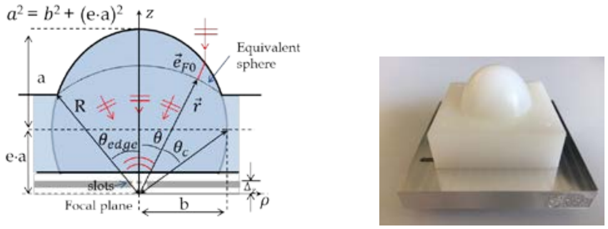


(a) (b)

Fig. 2. a) Elliptical lens geometric parameters and fields used in the FO calculation of the aperture efficiency. b) Photo of the fabricated prototype.

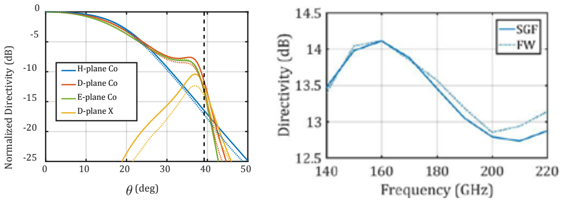
The aperture efficiency is calculated by evaluating the lens antenna in reception as described in [8]. The power received by the antenna ($V_{oc}I_0$) can be related to the field correlation between the primary field, $\vec{E}_{LWA}(\theta,\phi)$, and the field incident on the lens, over a sphere surrounding the feed (see Fig.3a). The field incident on the lens $\vec{e}_{FO}(\theta,\phi)$ can be evaluated analytically as derived in [9]..

$$V_{oc}I_0 = \frac{2}{\zeta_d}\int_0^{2\pi}\int_0^{\theta_{edge}} \vec{e}_{FO}(\theta,\phi)\cdot\vec{E}_{LWA}(\theta,\phi)\cdot e^{jk\Delta_z cos\theta} r^2 sin\theta d\theta d\phi \quad (2)$$

This technique (FO) allows us to obtain the lens aperture efficiency, assuming an impedance matched condition, for a known primary pattern and lens θ_{edge}, with no need to perform the secondary pattern computation, which is more time-consuming. With this procedure, the double slot iris geometry, the primary field phase centre Δ_z and the lens θ_{edge} can be optimized applying an iterative process. The actual impedance matching of the antenna is optimized with full-wave simulations.

III. PROTOTYPE DESIGN

Fig. 3a shows the feed radiation pattern at $f_0 = 160GHz$ while Fig. 3b shows the broadside directivity over frequency for a semi-infinite medium with $\epsilon_r = 2.5$. In both cases there is a good agreement between analytically computed results (SGF) and full wave validation on CST (FW). The maximum variation of the directivity over the entire frequency band is around 1 dB.

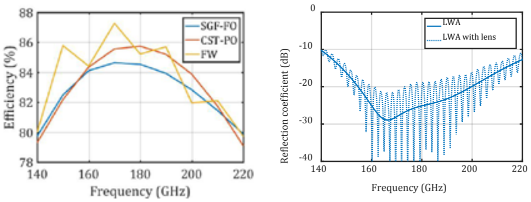


(a) (b)

Fig. 3. a) Feed radiation patterns and b) feed broadside directivity over frequency at f_0=160GHz. Solid lines: SGF solution, dashed lines: full-wave simulations in CST.

A. *Final lens performance*

In this section the simulation results for a G-band HDPE lens ($\epsilon_r = 2.32,\ tan\delta = 3.39x10^{-4}$) are shown, optimized at $f_0 = 160GHz$. After tuning the iris (to achieve a good matching and symmetrical patterns over the whole bandwidth), a fine optimization of the feed Δz and lens θ_{edge} has been performed with the FO method, using this time the primary patterns extracted from a full-wave simulation. PO and full-wave simulations (CST) have been performed to validate the optimization and to obtain the lens far-field radiation patterns. Fig. 4a shows the comparison between aperture efficiencies calculated using three methods: SGF/FO, CST/PO and full wave analysis. This aperture efficiency η_{ap}^{FO} includes the taper efficiency η_{tap}, the spillover efficiency η_{so} and the reflection efficiency η_{ref}. Fig. 4b shows the comparison of the PO and full wave simulated reflection coefficient (including multiple reflections) in EMPIRE-XPU which is lower than -10dB over the whole operational bandwidth. The maximum ohmic loss in the entire band is about 0.5dB at 220GHz.



(a) (b)

Fig. 4. a) Lens aperture efficiency over frequency and b) simulated secondary radiation patterns at f_0.

IV. CONCLUSIONS

In this work a design methodology to achieve broadband and high-efficiency elliptical lenses fed by resonant leaky-wave antennas has been presented. SGF and FO based analytical tools have been applied in order to maximize the lens aperture efficiency and bandwidth. A validation case with a lens in HDPE material has been reported, achieving an aperture efficiency higher than 80% over a 44% of relative bandwidth, with a reflection coefficient lower than -10dB.

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