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Electrically Small High Permittivity Lens Antenna Using Artificially Loaded Thermoplastics at 170 GHz

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***Abstract*— This contribution presents the development of an electrically small lens antenna using an artificially loaded thermoplastic at 140-170GHz. We will present the on-going development of the Fly's Eye front end antenna concept that was presented in [1]. The antenna is composed on a dual plastic lens, a core lens and a shell lens, fed by a double slot. The core-lens, being presented in this contribution, is a spherical lens made from an artificially loaded plastic of permittivity 9.5. To the best of our knowledge, this thermoplastic material has not been used for lens antennas in this frequency range before. A 4mm lens prototype has been developed using this material, which includes an anti-reflective layer synthesized by drilling sub-wavelength holes on the lens contour. Full-wave simulations show a negligible degradation of the performance of the anti-reflection layer compared to an ideal homogeneous matching layer. Physical measurements and antenna measurements confirm that the antenna's performance matches the design specifications.**

I. INTRODUCTION

ARTIFICIALLY loaded thermoplastics promise enhanced performance and cost-effectiveness of next-generation antennas for sub-terahertz band communication and sensing [2]. These materials are being developed to customize their dielectric properties within the range of 2.3 to 36 (PREPERM) and possess dissipation factors around 0.004 at 2 GHz [2]. Additionally, these plastics are not only cheaper than other high-performance materials such as silicon or quartz, which are commonly used in high millimeter wavelengths, but they can also be produced using mass manufacturing techniques like injection molding, CNC machining, and 3D printing.

However, the applicability of these materials above 100 GHz remains uncertain due to their higher losses. This research utilizes a high-permittivity PREPERM thermoplastic to integrate a lens antenna front-end array at 140-170 GHz, as proposed in [1]. The antenna architecture in [1] consists of three parts. The antenna feed is a double-slot antenna fed by a CPW line printed on a 500um fused silica wafer. The fused silica wafer allows the generation of resonant leaky-wave modes that couple to the core-lens. This core-lens is an electrically small spherical lens of high dielectric permittivity ($\varepsilon_r \approx 9.5$) to achieve a high front-to-back efficiency for a large bandwidth. The core-lens does not provide any directivity enhancement of the leaky-wave double slot antenna. Instead, the desired high directivity is achieved by a low permittivity elliptical lens, i.e. shell lens, placed on top of the core lens. In-between the core-shell lens interface an anti-reflective coating is required to mitigate the reflections on both interfaces.

In this contribution, we explain the realization of this double lens concept using an artificially loaded thermoplastic. We present the design, fabrication of measurement of the core-lens antenna which includes an anti-reflective layer machined on its spherical surface.

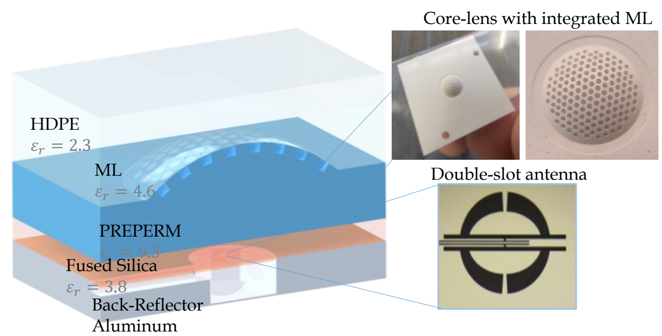


Fig. 1. Schematics of the core-lens antenna with insets of photographs of the fabricated prototype.

II. CORE-LENS ANTENNA WITH INTEGRATED ANTI-REFLECTIVE LAYER TECHNOLOGY

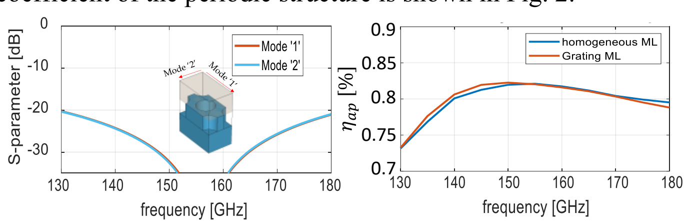
The proposed core-lens is realized using an artificially loaded thermoplastic of permittivity around 9.4. This material is anticipated to have significantly higher losses compared to standard plastics such as HDPE, where the loss tangent is around 6e-4, as it is mainly made up of common plastic (i.e., ABS) infused with ceramic inserts. Consequently, the core lens has been designed to be as small as possible while ensuring the manufacturing process is strong and the radiation performance is maintained.

The first assessment was to evaluate the electromagnetic performance of this thermoplastic in the WR5 frequency band. The measurement was based on a differential measurement $\Delta S_{21} = S_{21,sample}/S_{21,ref}$ obtained using a calibrated VNA + WR5 frequency extenders. The sample was illuminated by two corrugated leaky-wave lens antennas developed in [3] that created an almost perfect collimated beam. Applying and ideal transmission line model and assuming a perfect plane-wave incident, the permittivity and the loss tangent extracted from the sample was 9.2$\pm$0.15 and the $tan\delta \approx$ 5e-3 with isotropic behavior. Several measurements were realized over a surface of 80x40mm along two polarizations. However, among the measurements taken it was clearly visible a strong positional dependency of the performance within the sample.

The significant losses in the thermoplastic result in a compromise between the core lens's loss and its size (which is also associated with the manufacturing intricacy). We assessed this effect by evaluating the aperture efficiency of the overall antenna and the core lens's dielectric loss. Based on these results, we chose to adopt a diameter of $3\lambda_s$ ($\sim 4.5mm$) and a radius of 3.425mm for the antenna prototype, resulting in a dielectric loss of 0.4dB.

The core lens interface between the dense medium and the HDPE medium requires a matching layer to avoid multiple reflections. The ideal one step matching layer requires a permittivity of $\sqrt{9.4 \cdot 2.3} = 4.67$ with a thickness of a quarter wavelength. The proposed technique is to drill subwavelength holes in the core lens surface material as shown in Fig. 1. The matching layer permittivity is then synthesized as a volumetric combination of the thermoplastic material and free-space. To achieve the best electromagnetic performance, the holes are drilled conformably with a 5-axes drilling tool over the lens surface as shown in Fig. 1. Thus, not only is the hole pattern suitable for dual polarization excitation, but the drilling is simpler and faster in fabrication with respect to groove milling.

To design this layer, we assume broadside incidence and a periodic structure. It should be noted that the spherical core-lens has no effect on the spherical waveform from the leaky-wave feed; the field always impinges perpendicularly on the surface of the lens. To optimize and validate the performance of the artificial dielectric layer, simulations were conducted on the unit cell, where a plane-wave at broadside was incident on the structure. The depth of each groove t was equivalent to a quarter wavelength in $\varepsilon_r = 4.6$ material at the central frequency. The period p was kept small enough to avoid grating lobes, and was half a wavelength in the $\varepsilon_r = 4.6$ material at the highest frequency. The diameter of the hole was fixed to $d = 250\mu m$, since the holes were realized using a standard drill bit of $250\mu m$. The rest of the optimized dimensions were: a period $p = 350\mu m$, and a depth of $t = 225\mu m$. The reflection coefficient of the periodic structure is shown in Fig. 2.



(a) **(b)**

Fig. 2. (a) Reflection coefficient of the PREPERM+ML+Air interface unit-cell. (b) Simulated aperture efficiency of the overall antenna using hexagonal holes vs using a homogeneous ML.

The core-lens with this matching layer was simulated in time-domain with CST. The simulation was compared to an ideal (quarter wavelength) homogeneous matching layer in blue. Fig.2b shows that the artificial matching layer has very limited impact on antenna performance compared to a homogeneous ML, in terms of aperture efficiency η_{ap} [1].

A prototype of a 4.5mm diameter core-lens antenna was fabricated, and its 3D surface profile was measured using a confocal microscope. The resulting 3D profiles, as well as a 2D profile of the center hole for reference, are presented in Fig. 3. The analysis of the surface revealed that the holes were within the tolerance of the fabrication process. Only a minor compensation was made for the conical drill tip in the fabrication of subsequent core-lens samples.

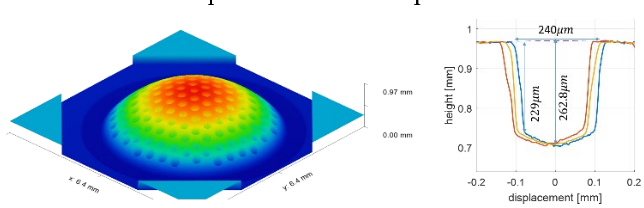


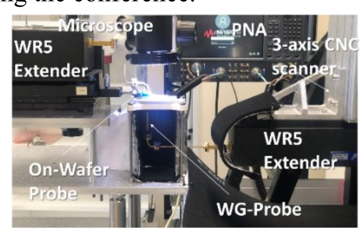
Fig. 3. Measured 3D profiles of the core-lens prototype and 2D profile of the central hole.

III. Antenna Measurements

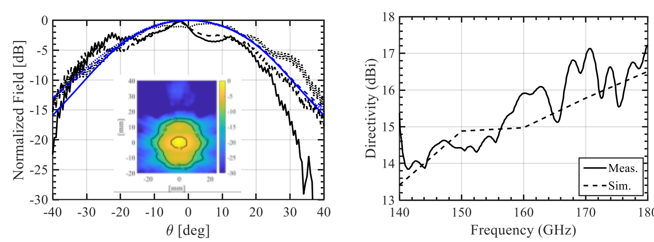
Following the successful fabrication within the expected tolerances, we proceeded to measure the core-lens fed by the double slot depicted in Fig. 1. We set up an antenna measurement setup, as illustrated in Fig. 4a, comprising a VNA and WR5 frequency extenders. One of the frequency extenders was linked to an RF probe, which landed on the double slot antenna through a CPW transmission line. On the other extender, a near-field probe on a 3-stage CNC was employed to measure the electric field on a plane located approximately 3 cm away from the core-lens antenna. An area of 50x60mm with a spacing of 0.7mm was scanned above the antenna.

The radiation pattern at 160GHz is shown in Fig 4a, as well as the directivity as a function of the frequency in Fig 4b. Time gating was applied on the measurements to reduce the contribution of the multiple reflections caused by the antenna measurement setup. Overall, the agreement is fair since the directivity is considerably low and therefore a lot of scattering is present despite the time-gating and multiple absorbers employed. Moreover, reflections are due to the fact that the plastic lens on top of the core lens is not present, and the anti-reflective coating is not properly optimized to radiate towards the air interface.

At the time of writing, this antenna architecture is under preliminary measurements. Complete measurement results are expected during the conference.



(a)



(b) **(c)**

Fig. 4. (a) Photograph of the antenna measurement setup. (b) Measured and simulated radiation pattern at 160GHz. (c) Measured and simulated directivity as a function of the frequency.

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