Characterization of Variable Density 3D Printed Materials for Broadband GRIN Lenses

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***Abstract*— In this work we design, simulate, manufacture and measure blocks made of variable density plastic. The density is controlled through varying the size of small cubes at the intersections of a fine grid. This structure is inspired by [1]. Simulations using HFSS show that there is a consistent relation between plastic density and relative permittivity (ε_r), and this is confirmed by measurements of 24 blocks with different density. Finally, an example design utilizing this is presented; a gradient index lens (GRIN) with continuously varying ε_r. 3D printed GRIN lens has been presented in [2], but in that case with stepwise varying ε_r. The GRIN lens was measured in an anechoic chamber, and about 5dB increased gain was demonstrated over the entire bandwidth of 7.5-18GHz.**

Keywords—GRIN; lens; 3D printing; broadband

I. INTRODUCTION

Engineered electromagnetic materials and metamaterials can provide new functionality and improve the overall electromagnetic performance of existing systems, while potentially reducing cost, size, and weight. One group of metamaterials has spatially varying electromagnetic properties (permittivity, ε and permeability, μ).

Dielectric lenses can be used to improve the radiation characteristics of antennas. Fixed refractive index lenses are however normally very bulky and therefore also lossy. Gradient refractive index (GRIN) lenses have been around for several decades [3]. Refractive index n is related to relative permittivity ε_r through $n^2 = \varepsilon_r$. Continuously varying ε_r has been very difficult to achieve with traditional manufacturing techniques, normally resulting in severe compromises and limitations. Modern 3D printing technologies however, provide the capability of producing objects with in principle arbitrary shape and material density. This again results in a capability to provide high fidelity spatially varying ε_r [2]. In this paper we study the relation between plastic density and ε_r through simulations and measurements. Finally we demonstrate an application; a 3D printed broadband GRIN lens.

II. DIELECTRIC CONSTANT INVESTIGATION

To verify that we could in fact control the refractive index (n) or permittivity (ε) by varying the density of the material, we created a lattice structure containing a grid intersection with variable cube-sizes, inspired by [1]. The final design can be seen in Fig. 1 (left), with rod thickness of 0.7mm and cubes at the intersections.

Several block samples with different material density and outer dimensions of 22.86mm x 10.16mm x 7.5mm, as shown in Fig. 1 (right), were designed, simulated, printed and measured. The dielectric constant was measured for each block using N1500A materials measurement software and PNA-X N5245A from Keysight Technologies and an X-band waveguide (8.2-12.4GHz).

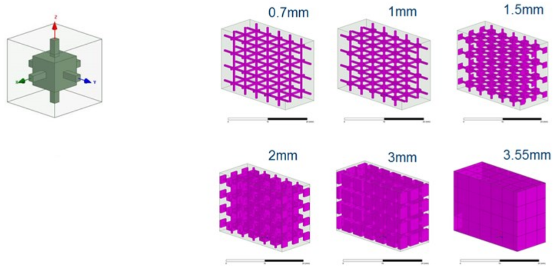

Fig. 1: Left: Unit cell, right: Grid-block structure cube-sizes from 0.7mm to 3.55mm to vary ε_r

Simulation of effective permittivity was performed in HFSS using PEC and PMC boundaries and verified using master/slave boundaries in order to define the periodic structure. S-parameter data were obtained for different cube-sizes from 0.7 to 3.55mm and effective permittivity was calculated using the standard retrieval method in Matlab. Results are shown in Fig. 2.

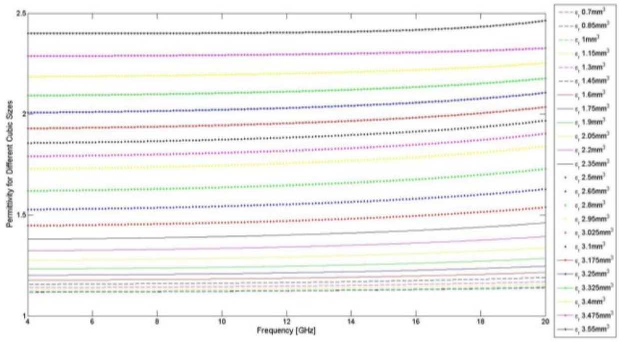

Fig. 2: Simulated permittivity vs frequency for each block with different cube-sizes

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The measured results for each ε_r block can be seen in Fig. 3. The measurements correspond reasonably well with simulations over the frequency band provided by the measurement set-up. The main discrepancy is that achievable ε_r is higher in practice than in simulations. This is due to the thin wall around the block to hold the layers together. A checkerboard wall was also manufactured for cubic size of 0.7mm, ε_r approaches 1.15 (simulated value)

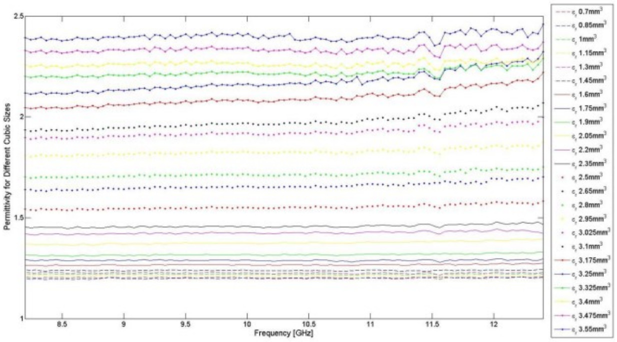

Fig. 3: Permittivity vs frequency for each block with different cube-size

III. LENS DESIGN AND MEASUREMENTS

A number of lenses were designed, manufactured and tested, but in this paper only one lens is presented to demonstrate an application of the results from the previous section. It has linearly varying ε_r with maximum at the center of the lens, and minimum at the lens edges.

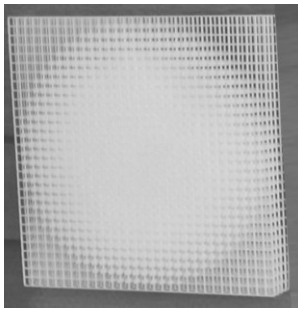

Fig. 4: GRIN lens with five layers and linearly decreasing permittivity with distance from center of lens

The lenses were measured in different situations in an anechoic chamber as shown in Fig. 5. The antenna under test was rotated through 360 degrees in E- and H-plane while the frequency was swept from 7.5 to 18GHz.

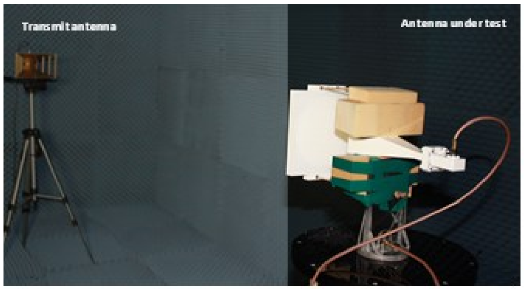

Fig. 5: Setup for measuring gain and radiation diagram

The top plot Fig. 6 below shows antenna gain vs. frequency for the antenna with and without the lens in Fig. 4. The three bottom plots show example H-plane radiation diagrams for 10, 14 and 18GHz. The curves for antenna with lens are shown in blue, while the antenna alone is shown in red. The green curves show results when the lens is mounted at the antenna aperture, demonstrating the importance of mounting it at the focal distance, but more importantly showing that there is little loss in the lens.

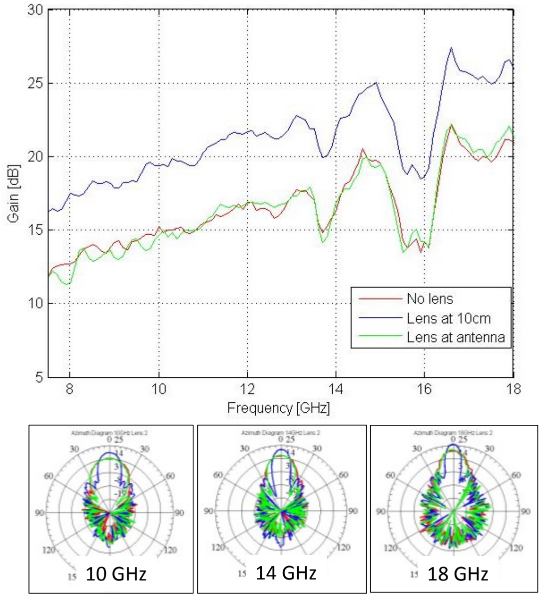

Fig. 6: Top: Bore sight gain vs frequency, bottom: example H-plane radiation diagrams for 10, 14 and 18GHz (red = no lens, green = lens mounted at antenna aperture, blue = lens mounted at focal distance)

CONCLUSIONS

We have studied the dependence of ε_r on plastic density through simulations and measurements, additional deviations from simulation results are due to difficulty of removing powder from structures with less than 0.3mm apart. We have also demonstrated the applicability of the results on an example lens design which offers 5dB gain over the band width 7.5-18GHz.

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