Multi-Material 3D Printed Gradient Dielectric Lens Antennas at mm-Wave Frequencies

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***Abstract*—The emergence of 3D printing has begun to allow antenna engineers to realize devices with novel features such as a graded-dielectric profile. Graded-dielectric interfaces are commonly realised using effective medium techniques, where sub-wavelength intrusions are used to modify the effective dielectric constant of the host material. 3D printers can easily realise these types of mediums by allowing for air-gap intrusions in the 3D printed parts, lowering the overall dielectric constant of the filament. This technique is limited when using a high-permittivity filament and trying to achieve an effective low-permittivity, particularly at high frequencies where the resolution achieved by commercial fused deposition modeling (FDM) 3D printers becomes comparable to the wavelength. Multiple material 3D printing offers a solution that allows for graded-index devices to be realised at mm-wave and THz frequencies. In this paper an analysis of graded index metamaterials and multi-material 3D printing technologies for mm-wave Luneburg lens antennas is presented used with FDM 3D printers is presented.**

I. Introduction

Over the last 10 years, considerable interest in transformation optics has led to the design of many new electromagnetic (EM) devices such as reduced-sized lenses, wave collimators and cloaking devices [1] [2] which require graded dielectric interfaces. In order to achieve graded-index material profiles practically, ceramics with customisable dielectric constants can be developed and integrated within the EM device [3]. However this technique requires time and specialist resources, and is unsuitable for rapid prototyping. Alternatively, effective medium techniques can be utilized where the dielectric constant of a host material can be modified by air-gap intrusions. 3D printing has emerged as an attractive additive manufacturing process for antennas designed at microwave and millimetre-wave frequencies. The technique allows engineers to design and fabricate antennas with finely detailed features and customisable shapes. 3D printing can also be utilized as a simple method for realising devices with graded-index profiles through the effective-medium method, where a unit cell volume is only partially filled with the 3D filament, whilst the rest of the volume is occupied by air. The effective overall permittivity of the unit cell is lower than that of the 3D filament. For example graded-index beam-steerable Luneburg lenses have been realised using such techniques [4]. Recently, filaments with specific dielectric constants have been developed [5], [6] which open up new possibilities for realising complex antenna designs at higher frequencies through multi-material printing.

II. Graded-index materials from FDM 3D printers

In order to vary the permittivity of different 3D printed materials using effective medium techniques, the infill-density of different sections of the model can be controlled, either through design of specific patterns or automatically when slicing the model. When sliced automatically, the infill-density setting defines the ratio of printed filament to air-gap intrusions. Typically, the air-gap intrusions are printed in a specified pattern such as a rectilinear grid or a hexagonal lattice. The unit cell dimensions of the infill patterns are limited by the specifications of the 3D printer. For example, the minimum extrusion width is defined by the nozzle diameter. Using a standard 0.4mm nozzle, Fig. 1 shows the infill pattern dimensions of 3 different infill-density unit-cells formed by a 2D rectilinear grid. For an infill-density of 78%, the unit cell dimensions are 0.75mm^2. This increases to 1.5mm^2 for an infill density of 48%, and to 3mm^2 when the infill-density is 25%. Effectively, the unit cell dimensions increase as the infill-density of the 3D filament is reduced.

Fig. 2a shows the effective permittivity of three commercially available host filament materials [6] with varying filling ratios generated by a 0.4mm diameter nozzle at 60 GHz. As can be seen, the high permittivity (ε_r = 5.5) material deviates from the expected value when the infill-density of filament is low. This is due to resonant effects, as the unit cell dimensions of 3mm^2 are equivalent to half a wavelength at 50 GHz. In Fig. 2b we see a resonance in the effective permittivity at 70 GHz when the infill density is 25% and at 84 GHz when the infill density is 46%.

III. 3D-Printed Graded Index Luneburg Lens Antennas

The Gutman lens is a modified version of the Luneburg lens where the focal point has been moved from the surface of the lens to a point located within the lens [7], [8]. The resulting structure has a graded index profile which varies from a high value at the focal point to a value of 1 on its surface. The direction of the antenna beam can be steered by offsetting the feed position within its focal circle. Two Gutman Lenses were designed to investigate the differences of 3D printed graded index materials. The first lens uses a the effective medium theory to vary the permittivity from 5.5 at its centre to around 2.7 on its surface. The second lens uses materials with 100% infill-density, but with varying filament permittivity of the same values. The permittivity in both lenses

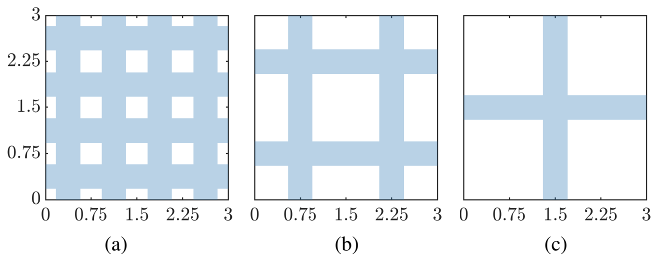

Fig. 1. Unit cell dimensions of the rectilinear grid pattern with infill densities of (a) - 78%, (b) - 46% and (c) - 25% used to obtain effective medium properties. The blue represents filament and the white area represents air.

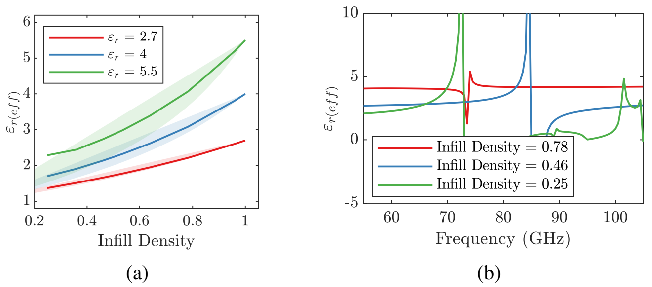

Fig. 2. Effective permittivity from different 3D printer filaments and a rectilinear-grid unit cell with varying infill density at 60 GHz.

is discretized into 3 distinct layers with permittivity values of 5.5, 4 and 2.7 and radii of 1.9λ, 3.15λ and 4.2λ respectively. The sizes of the lenses were modified based on the frequency of operation, however the unit cell size of the metamaterial lenses was not modified. The unit cells had dimensions of 0.75mm^2, and 1.5mm^2 for the sections with $\varepsilon_{r(eff)} = 4.0$ and 2.7 respectively. Fig. 3 depicts the two different lenses designed for operation at 84 GHz, which were fed by a point source positioned in the focal plane behind the lens.

The simulated radiation patterns of the two lenses are shown in Fig. 4 at frequencies of 30 GHz and 84 GHz with various feed-offset positions. As can be seen, at 30 GHz, both the multi-material and metamaterial lenses have directive beams which can be steered by an angle of 32° when the feed is moved by a distance of 1.4λ, with only a 3 dB reduction in the peak gain. However, when the frequency is increased to 84 GHz the beam steering performance for an equivalent feed offset is significantly diminished as the radiation pattern becomes distorted. When the feed is only offset by a factor of 1.1λ, the beam is steered towards an angle of 22°. Interestingly, the metamaterial lens works well for the 22° steering angle at 30 GHz as well as at 84 GHz, despite the large unit cell size when compared to the wavelength used to modify the permittivity using the effective medium theory. At 30GHz the continuous multi-material lenses outperforms the metamaterial lenses in terms of peak signal strength by around 1 dB at all steering angles despite the equivalence of the effective permittivities in each layer.

The lenses designed at 84 GHz were fabricated using a Prussa I3 MK3 3D printer with multi-material upgrade, which allows a total of 5 materials to be printed within the same

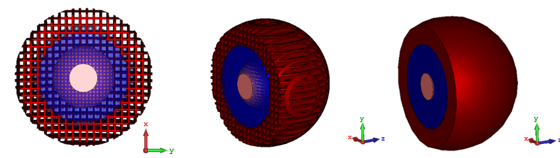

Fig. 3. View of metamaterial (top/center) and multi-material (right) Gutman lens models. In both models the effective permittivity at 60 GHz of the central layer is 5.5, the second layer is 4 and the outer layer is 2.7. The metamaterial lens uses the same filament in each section.

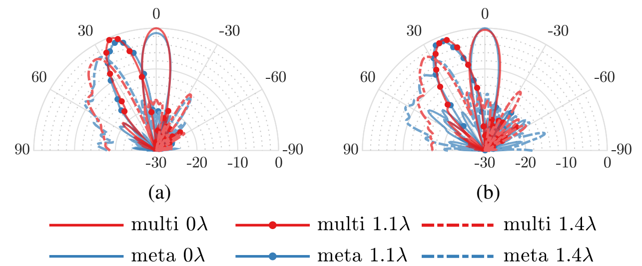

Fig. 4. Normalized Radiation patterns of multi-material and metamaterial 3D printed lenses at (a) 30GHz and (b) 84GHz as feed position is modified

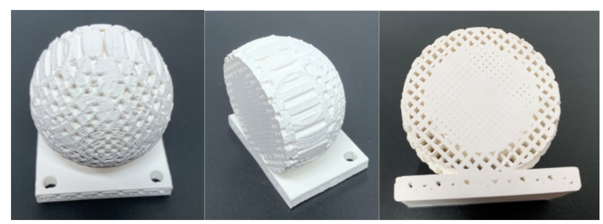

Fig. 5. 3D printed metamaterial Luneburg Lens

design. Using the Preperm [6] filaments ABS550, ABS400 and standard ABS (with ε_r = 5.5, 4 and 2.7 respectively) the two lenses were printed (the metamaterial lens uses only ABS550 filament). Fig. 5 shows the fabricated metamaterial lens.

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