HOW ADDITIVELY MANUFACTURING E-BAND DIELECTRIC LENSES IS CHANGING AUTOMOTIVE SENSING

CASE STUDY

I.

INTRODUCTION

As automotive, industrial, and satellite communication sectors trend towards higher frequency bands, the need for high directivity beamforming becomes essential.

This case study will review the device design and manufacturing process of a high-performance, low-loss 3D-printed GRIN lens for the E-Band. To validate the technology, a simple Luneburg-style, radially symmetric spherical lens was designed and printed using the FLUX CORE, a DLP 3D printer, and low-loss photopolymer dielectric material, Radix™. The lens was fed by E-band coaxe-to-waveguide transition and the performance was characterized from 60 GHz to 85 GHz

II.

THE CHALLENGE

Many industrial sectors, including automotive, robotics communication, and more are transitioning to higher frequency bands. These bands offer several advantages including higher data capacity and faster transmission. In the case of the V-band (40-75Ghz), some bands have been licensed for multi-gigabit wireless communications such as satellite constellations for business like Boeing, SpaceX, OneWeb, and Telestat [1]. Others are being leveraged for automotive radar and sensing applications like adaptive cruise control [2].

As the applicability of higher frequency bands becomes more relevant, the adoption of dielectric lenses is becoming more common, more practical, and more affordable. This is largely tied to device size – dielectric lens size scales with a device's operational wavelength. Therefore, higher frequency applications tend to be better suited for lenses – especially in the radio frequency and microwave spectrums.

GRIN (Gradient Refractive Index) lenses, such as Luneburg lenses, can offer higher operating bandwidth than constant dielectric lenses, while enabling the same or better-focusing capabilities. GRIN dielectrics provide unprecedented design freedom for various applications where methods like transformation optics can be leveraged to create higher performance microwave devices. However, traditional manufacturing methods have limited the production quality or quantity of large and intricate dielectric lenses, such as GRIN designs or other complex lens designs. This has limited the use of dielectric lenses to simple bulk lens designs, or "layered" lenses that don't exhibit the design freedom or performance of more sophisticated lens designs.

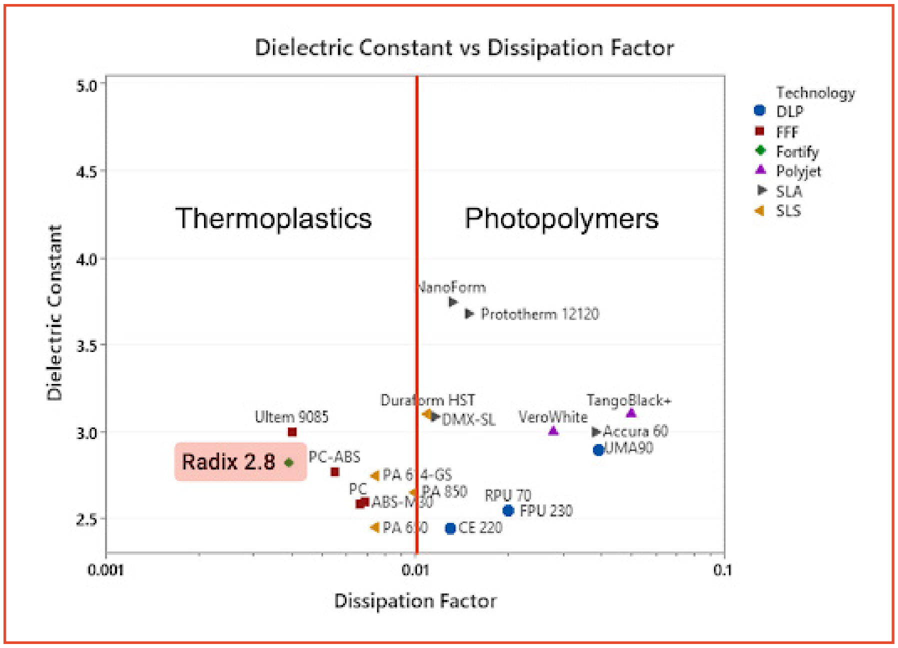
An approach that has been studied extensively in academia, and is starting to see some mainstream adoption, has been to utilize 3D printed GRIN lenses.

Using lattice design concepts, GRIN devices are easy to make and can vary dielectric constant by varying the density of the lattice itself. 3D printing is not limited by the same geometric constraints as traditional manufacturing, and intricate GRIN devices can be manufactured quickly and efficiently.

There is already commercial adoption of 3D printed GRIN devices, but market penetration is limited. The incumbent 3D printing technology Fused Filament Fabrication (FFF) is slow and feature sizes are limited by nozzle size. This makes FFF unable to meet the volume needs for the industrial sectors moving towards high frequency bands. Other competing technologies like Stereolithography and Polymer Jetting can achieve higher production rates and better surface finish than FFF, however, they are restricted to lower quality RF materials.

II.

The 3D printing industry had not invested heavily in the development of RF-specific materials, and materials have not been available that provide the throughput, resolution, surface finish, and performance needed for applications in the RF space.



This chart plots the dielectric constant and loss tangent of several commercially available commodity thermoplastic and photopolymer 3D printing materials.

III.

THE SOLUTION

Rogers Corporation recently developed a 3D printable low-loss photopolymer dielectric specifically tailored for RF and mmWave frequencies [3]. Fortify's FLUX CORE DLP 3D printer is built to run high viscosity and filled materials. Combined, the material and printer enable the fabrication of a quick-turn, high-performing, low-loss 3D printed graded dielectric lens.

IV.

THE PROCESS

GRADED-INDEX DEVICES

The Luneburg lens is an analytical lens design where the index of refraction has a continuous and radial transition from the core to the surface of a sphere. The lens material permittivity (the square of the index of refraction) for this device

$$\varepsilon_r(r) = 2 - (r/R)^2$$

is described by the equation:
where r is the distance from the lens center, R is the outer radius of the lens [3]. Achieving a gradient index of refraction is possible in 3D printing by using lattice structures and leveraging volumetric mixing of air and polymer dielectric solids to achieve an effective dielectric constant value [4].

The geometry that was used in this case study is the thin-walled gyroid. A gyroid is a Triply Periodic Minimal Surface (TPMS), which due to the surface-based nature of the structure offers practical robustness advantages over strut-and-node lattice types. As isotropy is a critical characteristic of a unit cell in this application, isotropy of the unit cell design was verified using an Ansys HFSS waveguide simulation and is described in detail by Rogers Corporation [4].

MIXING EQUATION AND DIELECTRIC RESIN

The relationship between the air volume fraction of this lattice geometry and the effective permittivity is determined using a Reverse Claussius-Mossotti model:

$$\varepsilon_{r,eff} = \varepsilon_{r,resin} \frac{1 + 2v_{air}\left(\frac{1-\varepsilon_{r,resin}}{1+2\varepsilon_{r,resin}}\right)}{1 - v_{air}\left(\frac{1-\varepsilon_{r,resin}}{1+2\varepsilon_{r,resin}}\right)}$$

where $\varepsilon_{r,eff}$ is the effective permittivity of the gyroid lattice region, υ_{air} is the volume fraction of air, and $\varepsilon_{r,resin}$ is the permittivity of the solid dielectric material used to form the lattice.
To calculate the air fraction for each region of the lens design, the cubic size of the gyroid unit cell is held constant while the wall thickness of the unit cell is varied. Since the operational frequency range of interest for this case study is the E-band (60 to 90 GHz) where the corresponding wavelength range is ~5 mm to ~3.3 mm, a unit cell size significantly smaller than ~3.3mm is optimal. However, due to practical manufacturing constraints, the cubic unit cell size selected for this design was 3 mm. The material used for this design is the Rogers Corporation Radix 3D-printable photopolymer dielectric with a dielectric constant of 2.8. This material was selected due to the very low-loss characteristics at higher frequencies, as well as its ability to be 3D printed with high feature resolution [3].

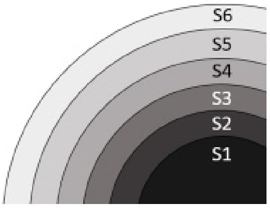
A relationship was established between the wall thickness of the gyroid, the relative air fraction, and the resulting calculated effective permittivity for the 3mm gyroid unit cell size.

IV.

DESIGN

The design of the lens tested in this work is presented in the right figure.

The core and shell design approach to the lens was selected over a continuous gradient to simplify the design and simulation. The conversion of the effective permittivity lens design to a 3D geometry was accomplished using nTopology.



Shell	Diam.(mm)	$\varepsilon_{r,eff}$
S1	4.93	1.96
S2	6.94	1.81
S3	8.54	1.66
S4	9.86	1.49
S5	11.02	1.38
S6	12.07	1.19

(Left) Section of the spherical lens design presented as a series of concentric shells of regions of effective permittivity. (Right) Table showing the effective permittivity and diameter for each shell in the design.

FABRICATION

The 24.14 mm diameter lens was 3D printed on a Fortify FLUX CORE DLP 3D printer [5]. The material used to print this device is the Rogers Corporation Radix 2.8dk 3D-printable photopolymer dielectric.

The 3D printed lens fabricated with the Rogers Corporation Radix 2.8dk printable polymer dielectric using the Fortify FLUX CORE DLP 3D printer.

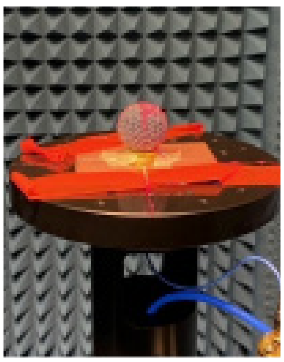
The Radix material consists of a unique low-loss photopolymer blended with specialty dielectric ceramic additives to create high-performance dielectric materials. The FLUX CORE leverages Continuous Kinetic Mixing™ (CKM), a module built onto the printer that circulates, heats, and mixes the loaded materials to maintain particle suspension and ensure even dispersion throughout the printing process.

The 3D printed lens fabricated with the Rogers Corporation Radix 2.8dk printable polymer dielectric using the Fortify FLUX CORE DLP 3D printer

V.

EXPERIMENT

The lens was mounted in a Rohde & Schwarz antenna test chamber and fed by a WR-12 coaxe to waveguide transition. The lens was held in place against the feed waveguide by a foam gasket throughout testing as presented below.

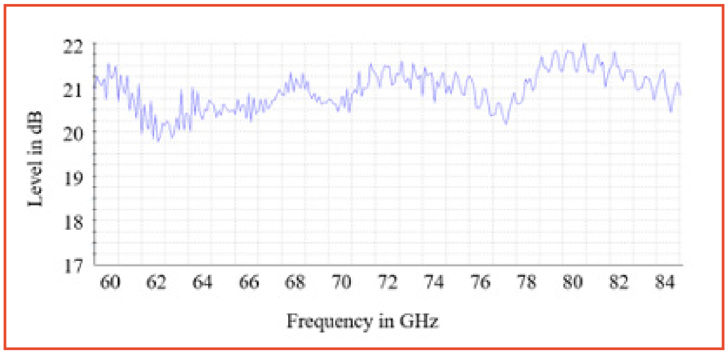


(Left) The lens was mounted on a test platform in the antenna test chamber and held in place with a foam gasket. (Right) The sensing antenna (top of image) captured data at 80-85 GHz.

VI.

RESULTS

The resulting lens antenna system measured realized gain between 20-22 dBi from 60-85 GHz at boresigh. The average gain measured is relatively constant throughout this band, with fluctuations believed to be due to calibration errors with the setup or slight fluctuation in peak gain angle.



Lens antenna realized gain at boresight in from 60-85GHz.

There are existing manufacturing technologies that might be used to create a device similar to the lens presented here. One such manner is the machining, perforation, and stacking of low-loss laminate boards. This concept can be found in academic literature but is not implemented in practice due to the high cost of raw material and extensive, precise machining. As a point of reference, the lens presented above can be printed and fully finished in a matter of hours, where a similar device manufactured through traditional methods may take several days of hands-on labor to machine and assemble.

VII.

CONCLUSION

The test results from the 3D printed lens demonstrates that a functional GRIN lens for E-band frequencies can be quickly and cheaply fabricated for automotive and industrial applications. The results show that a 6 shell, ~24 mm diameter Luneburg-style lens generated a beam pattern with a peak gain of approximately 22 dBi. With improvements in efficiency in the feed structure, and better calibration of the testing equipment, the authors expect an improvement in gain closer to 24 dBi.

These test results showcase the capabilities of low-loss 3D printed materials integrated with advanced 3D printing solutions can improve design and manufacturability of automotive sensing to meet demand as higher frequencies are becoming widely adopted in automotive and industrial applications.

ABOUT FORTIFY

Fortify is transforming the 3D printing industry with its patented DCM (Digital Composite Manufacturing) platform. DCM delivers new levels of additively manufactured part performance by introducing functional additives to photopolymers. By combining a deep understanding of material science with high performance mixing, magnetics, and polymer physics, Fortify is able to produce custom microstructures in high-resolution 3D printed parts.

The company is currently focused on applications ranging from injection mold tooling to high performance end-use parts with unique mechanical and electromagnetic properties. Founded in 2016 and based in Boston, Fortify technology enables material properties and components unattainable using other additive or traditional manufacturing processes. For more information, visit www.3dfortify.com.

FORTIFY

IX.

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