WHITE PAPER

3D PRINTED DIELECTRIC LENSES INCREASE ANTENNA GAIN AND WIDEN BEAM SCANNING ANGLE

FORTIFY

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1
INTRODUCTION

There is a push in a majority of telecommunications and RF sensing markets toward higher performance wireless links and sensing technologies. To achieve these new regimes of throughput, latency, reliability, quantities of wirelessly connected devices, configurability, and sensing resolution there has been substantial industry investment, from cellular telecommunications to military radar applications, in using higher frequency portions of the spectrum. These efforts have required the development of more capable advanced/active antenna systems (AAS) for telecommunications and active electronically steered antenna arrays (AESA) for military/defense sensing and jamming technology. More sophisticated AAS are needed at higher frequencies to overcome the high atmospheric attenuation and alignment challenges associated with microwave and millimeter-wave communications and sensing. For the most part, electronically steerable phased array antennas have been the most explored solution for realizing AAS.

Phased array antenna technology presents several intrinsic design challenges and additional hardware requirements within the RF signal chain that scale with the desired performance of the AAS. There are other methods of creating electronically steerable antenna arrays, including the use of dielectric lenses with switched antenna elements, that provide better antenna gain/efficiency and wider beamsteering angle capability. However, the manufacturability and material requirements to achieve high performance dielectric lenses in production quantities has previously been inaccessible due to the complexity of the lens designs best suited to these applications - Gradient Refractive Index (GRIN) dielectric lenses.

A recently announced collaborative agreement between Rogers Corporation and Fortify has culminated in a novel approach to produce entirely custom and high resolution GRIN dielectric lenses that overcome the design and fabrication challenges that have essentially shelved this technology for decades. The collaboration has, to date, yielded material advancements in 3D printable filled photopolymer resin technology demonstrating wide dielectric constant performance of the material and fine resolution printing. Now, GRIN dielectric lenses that operate to as high as the ka band (~40 GHz) with complete geometric design freedom can be fabricated in a matter of hours.

This whitepaper discusses the trends in the RF/microwave industry driving the demand of AAS and some of the challenges associated with building AAS using traditional approaches. Furthermore, this paper details the benefits of using dielectric lenses and switched antenna array elements to achieve electronically steerable antenna arrays that can be lower cost, faster steering, higher gain, and with much wider beamsteering angle capability than with phased array antenna technology alone. Also included is a discussion of the use of dielectric lenses to augment phased array antenna performance; namely, maximum beam angle, gain, and sidelobe reduction. Additional details and discussion of GRIN dielectric lenses and the advantages of 3D printing Rogers Corp. new filled photopolymer resin technology is also provided. Lastly, a demonstration of a spherical GRIN lens fabricated with Fortify's digital light projection (DLP) printing technology and Rogers Corp. filled photopolymer resin is presented that clearly shows the gain, directivity, and antenna efficiency enhancements possible with GRIN dielectric lenses fabricated from this specialized material and method.

2

THE RISE OF ADVANCED / ACTIVE ANTENNA SYSTEMS & ELECTRONICALLY STEERED ANTENNA ARRAYS

In many RF applications there is a need to have a communication or sensing system that can be "steered" to point to another communication link or a target. Without the ability to steer the antenna pattern of a communication link or radar, for instance, either a fixed antenna array or omnidirectional antenna is required to cover all possible directions the system may need to transmit and receive from.

Mechanically steerable antennas were developed to replace the need for large omnidirectional antennas with extremely high power output and very sensitive receivers, or highly complex fixed antenna arrays. Advancements on mechanically steerable antennas involved the use of antenna arrays, which could be used to reach desired antenna gain/directivity performance without the need for a large parabolic antenna structure that posed many challenges for mechanical steering systems.

An antenna formed from multiple radiating elements transmitting the same signal is known as beamforming. Beamforming antennas can be designed to produce much higher gain/directivity antennas as a function of the number of radiating elements, or antenna elements. The greater number of elements in an antenna array, if designed with this in mind, can also mitigate the resulting, undesirable antenna pattern side-lobes.

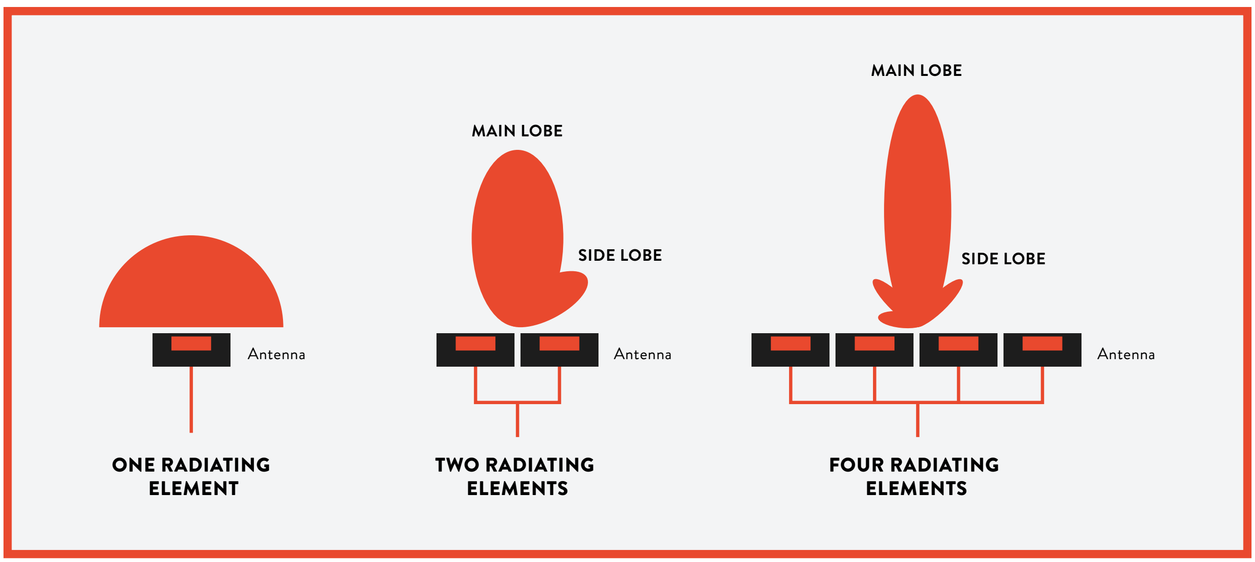

Figure 1: A depiction of beamforming antenna pattern behavior as a function of linear antenna elements

The next step forward was the development of antenna arrays that could be electronically controlled by manipulating the behavior of the individual antenna elements, essentially creating a virtual antenna with the desired antenna pattern. With the right electronics, the main lobe of this virtual antenna can be electronically steered, or have it's behavior electronically controlled, to perform a wide range of functions, including sweeps or targeting a specific point in 3D space with control over the gain and directivity of the electronically steered antenna array.

With this development, beamsteering was developed. One way of achieving beamsteering is to switch on and off certain elements of the array. Another way is to control the relative phase and amplitude of the signals from groups of array elements, or each individual element. With a large enough array antenna and sophisticated enough electronic control and feed system, beamsteering antennas can be made that direct the main lobe of the antenna anywhere to the maximum beam angle, relatively rapidly steer the beam, and even create multiple lobes that are independently steered.

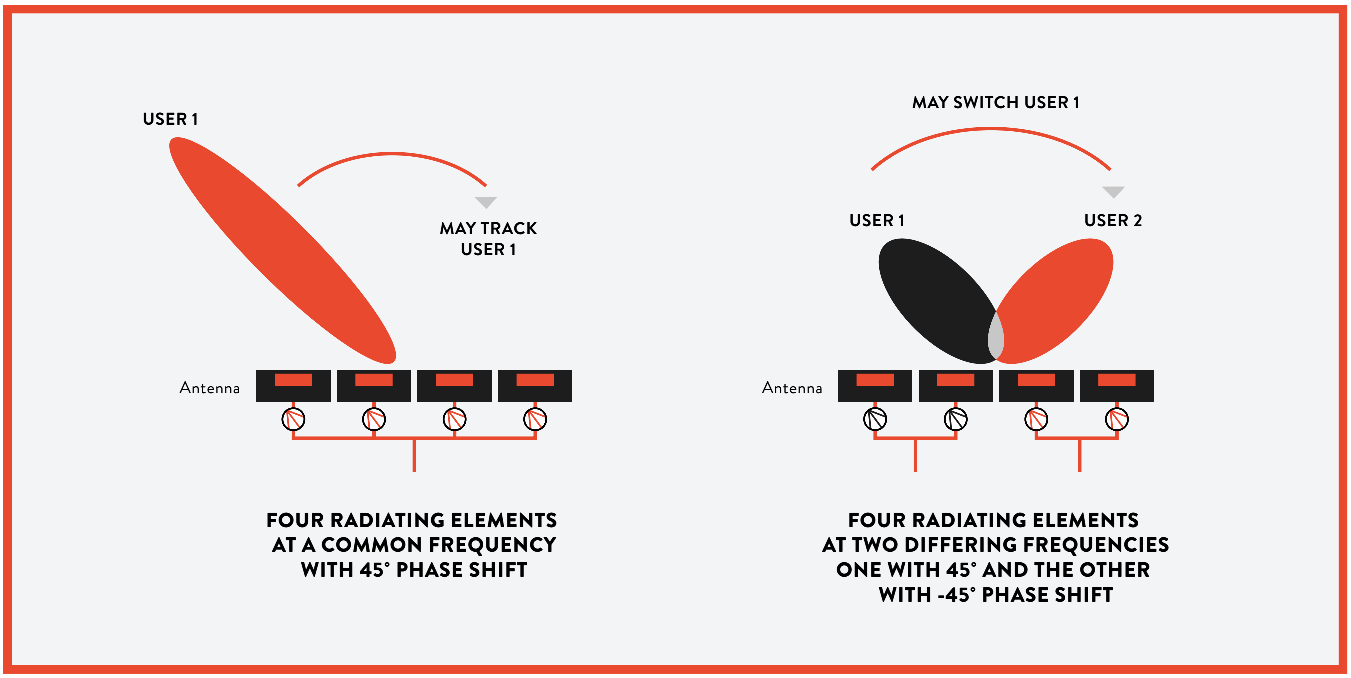

Figure 2: A beamsteering antenna

AAS USE CASES & SIGNIFICANCE FOR MILLIMETER-WAVE APPLICATIONS

Due to the complexity of beamsteering antennas systems, which require an array of transmitters, receivers, or transceivers with additional beamsteering control electronics to feed each element/element group, the cost for these systems tend to be relatively high and have historically only been used in defense, aerospace, and satellite communications applications. This has changed with the development and deployment of 5G cellular technology, which has created substantial interest in the use of frequency bands beyond 3 GHz for cellular applications and beyond 6 GHz for other wireless communications technologies.

3
CHALLENGES OF PHASED ARRAY ANTENNA AAS

The dominant type of AAS for mmWave communications has been phased array antennas built into a flat antenna panel. Phased array antenna systems have been developed that are compact, responsive, and meet the regulatory and performance requirements of the cellular telecommunications industry.

Figure 3: The main figures-of-merit (FOM) for AAS

HOW PHASED ARRAY ANTENNAS WORK

Phased array antennas work by adjusting the phase (time delay) of a signal sent through/received by an array of antenna elements in such a way that the spherical wave fronts emitted/captured by the radiating elements superimpose and form a plane wave in the desired direction. With a 2D array, the phased shifts at each element can be used to create a beam that can be scanned in either direction (azimuth), limited by the phase shifting hardware, antenna element style, and shape of the linear array. This is captured in the following image (Figure 5).

A 2D phased array with the right beamforming control system is able to generate a beam that can be scanned side-to-side (azimuth) and up-and-down (elevation). The gain of the antenna elements and the number of antenna elements dictates the gain of the array, as well as the directivity of each element. Generally, the optimum gain for a phased array antenna is at “broadside” or “boresight” which is directly perpendicular to the linear or flat panel phased array antenna. The gain drops as a cosine function of the angle from broadside. At 60 degrees from broadside a phased array antenna exhibits half the gain at broadside, and zero at endfire conditions (90 degrees).

To achieve a full 360 degree coverage with a phased array antenna typically requires four phased array antennas or a mechanically rotating antenna (gimbal system). Widening the antenna element spacing is a way of enhancing the beam scanning angle of a phased antenna array. However, there is a practical limitation to element spacing, as grating lobes generate ambiguity problems when the elements are spaced further than fraction of the smallest operating wavelength for a given antenna element design. At extreme angles for a given antenna element spacing, side lobes are also generated by phased arrays that are not negligible, and often variable attenuators are used to enhance sidelobe suppression performance. Additionally, pattern reconfigurable antenna (PRA) elements have been studied in order to overcome the limited scanning angles of phased array antennas, but come at the cost of additional complexity and having to drive extra switching elements [3.1]

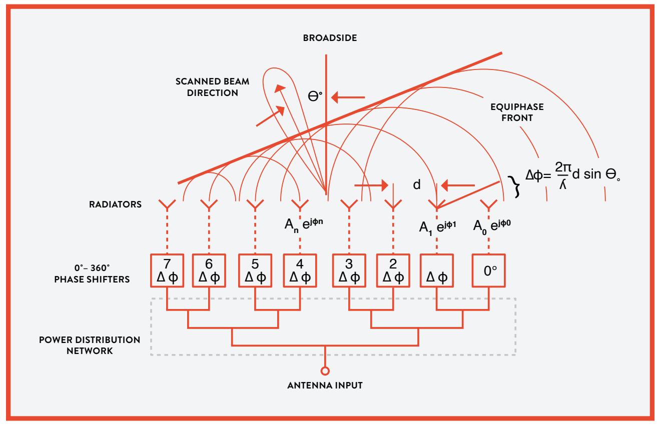

Figure 4: Linear phased antenna array during a scanning operation.

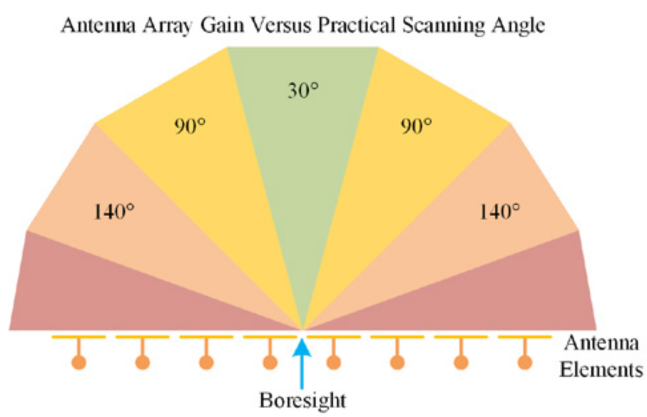

Figure 5: A depiction of a linear phased array’s gain performance at various angles away from the boresight with green being the highest and red being the lowest.

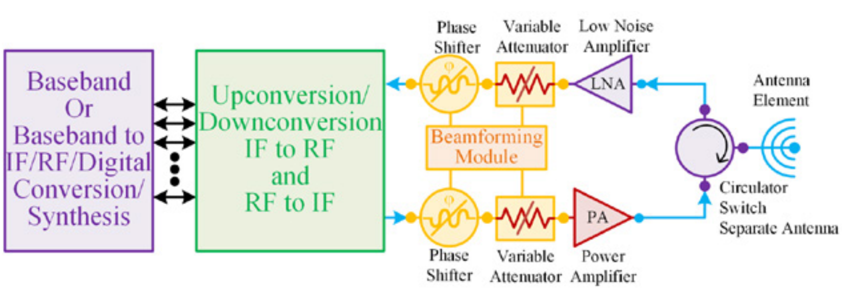

Figure 6: A simplified RF frontend (RFFE) for a phased array antenna element that is directly driven.

4

BEAMSTEERING ADVANTAGES WITH DIELECTRIC LENS ANTENNA ARRAYS

The earliest rollouts of mmWave 5G have already begun in the United States and other developed countries, where reception has been mixed. Though extremely fast throughput can be experienced with a user well positioned in reference to the mmWave 5G antenna, realizing the potential of this technology under dynamic use scenarios and delivering a seamless customer experience has been challenging.

One of the main challenges for mmWave AAS is achieving low scan loss (loss at angles outside of the broadside/boresight) for both azimuth and elevation with high scanning angle capability over a wide bandwidth. Accomplishing this is essential for delivering reliable high throughput enhanced mobile broadband (eMMB) services. It is currently a topic of interest in scientific literature to use metamaterials, frequency selective surfaces (FSS), and dielectric lenses to enhance the performance of AAS. Mainly these efforts aim to improve the gain and scanning angle capability, but also to minimize grating lobe generation and allow for greater design freedom [4.1, 4.2, 4.3, 4.4, 4.5]. Dielectric lenses are of particular interest as these structures are passive and can be designed as augments to existing phased antenna arrays or switched antenna arrays, but may also be used as the basis for an antenna or antenna array.

WHAT IS A DIELECTRIC LENS ANTENNA ARRAY

A dielectric lens antenna array employs dielectric lenses at the antenna array elements, or has the antenna elements configured in position around a dielectric lens. One of the uses of dielectric lenses paired with an antenna array element is to enhance the gain of each antenna element and minimize side-lobe levels, which results in an overall gain boost for the antenna array. Dielectric lenses may be specifically designed to transform radiating waves from an antenna to achieve a desired effect, depending on the application parameters. For instance, a "convex" dielectric lens can be used to increase the radiating aperture of an antenna, which enhances the antenna gain by transforming the spherical wave front into a planar wave. In this way an antenna with a dielectric lens can exhibit similar behavior to a reflector antenna without the need for a large reflector dish.

Using transformation optics techniques, an antenna or antenna array's radiation pattern can be manipulated to enhance an individual antenna's performance or an antenna array's maximum scanning angle, gain, side-lobe level, etc. The use of dielectric antennas provides increased design capability that can provide additional degrees of freedom to the electrical design of a radio's signal chain, including greater margins for link budget and receiver dynamic range.

In this way, a phased array antenna can be used to feed a dielectric lens, such as a luneburg lens or low-profile lens design, and experience wider scanning angle and gain with greater aperture efficiency. To otherwise achieve such high gain at such a wide scanning angle, PRA methods or a mechanical scanning system may be required, which would also lead to greater cost, complexity, and a larger antenna profile.

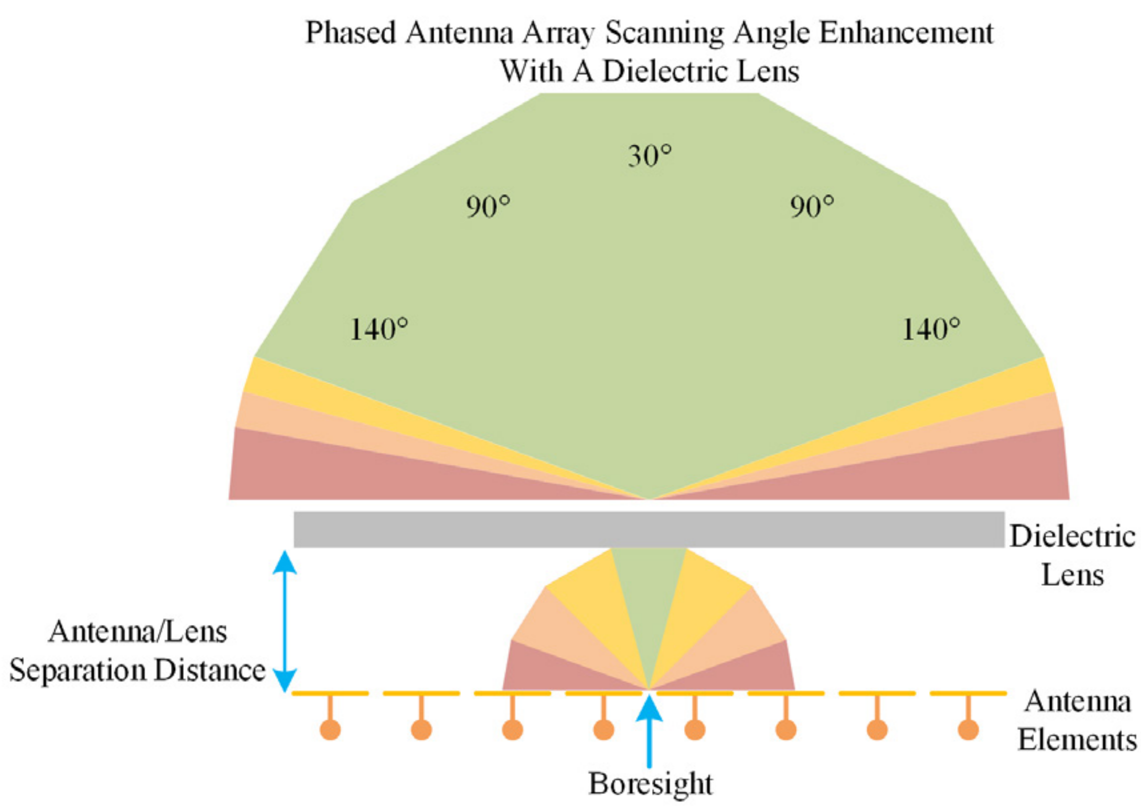

Figure 7: A phased array antenna augmented with a dielectric lens for enhanced scanning angle.

SWITCHED DIELECTRIC LENS ANTENNA ARRAYS VS. PHASED ARRAY ANTENNAS

Another method of realizing an electronically steerable antenna is to take advantage of transformation optics and employ a switched antenna feed system that directly illuminates a dielectric lens. A desired scanning angle for a switched dielectric lens antenna array can be achieved by appropriately designing the dielectric lens and positioning of the antenna elements.

Switched Dielectric Antenna Array With Spherical/Flat Luneburg Lens

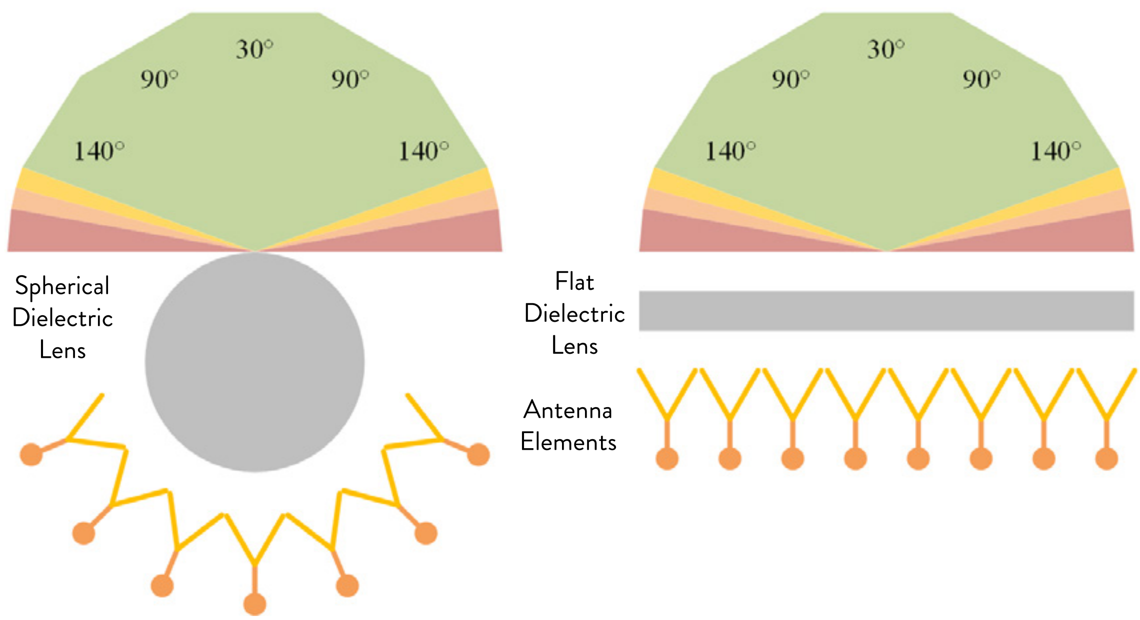

Figure 8: (left) A spherical dielectric lens with an array of feed antennas that can be operated as a switched antenna array with wide scanning angle. (right) A flat panel antenna array made using switched antenna feeds and a sophisticated dielectric lens.

SWITCHED DIELECTRIC LENS ANTENNA ARRAYS VS. PHASED ARRAY ANTENNAS CONT.

A switched antenna array requires a much simpler signal chain than a phased array antenna system, with a beamforming module only needing to control as many switches as there are array elements or subarrays. This removes the need for a phase shifter and an inline attenuator, as well as the processing needed to determine the exact phase and attenuation states for each array element. Depending on the components, this means that the switched antenna array signal chain may have lower intrinsic losses for both the transmit and receive signal chains. Lower cumulative insertion loss in a transmit signal chain leads to higher transmission efficiency and lower thermal management requirements. Less losses in the receive signal chain results in a higher dynamic range and possibly better added noise figure if lower amplifier gain can be used.

Though a switched antenna array is likely to have much simpler control and RF electronics, a switched antenna array also doesn't typically exhibit the degree or precision of beam angle that a phased array antenna system can achieve. The angle resolution for a dielectric lens switched antenna array is limited by the number of antenna elements and where they can be positioned in respect to the lens. Therefore, a phased array antenna may also be more compact than a dielectric lens switched antenna array depending on the design requirements and frequency range of operation.

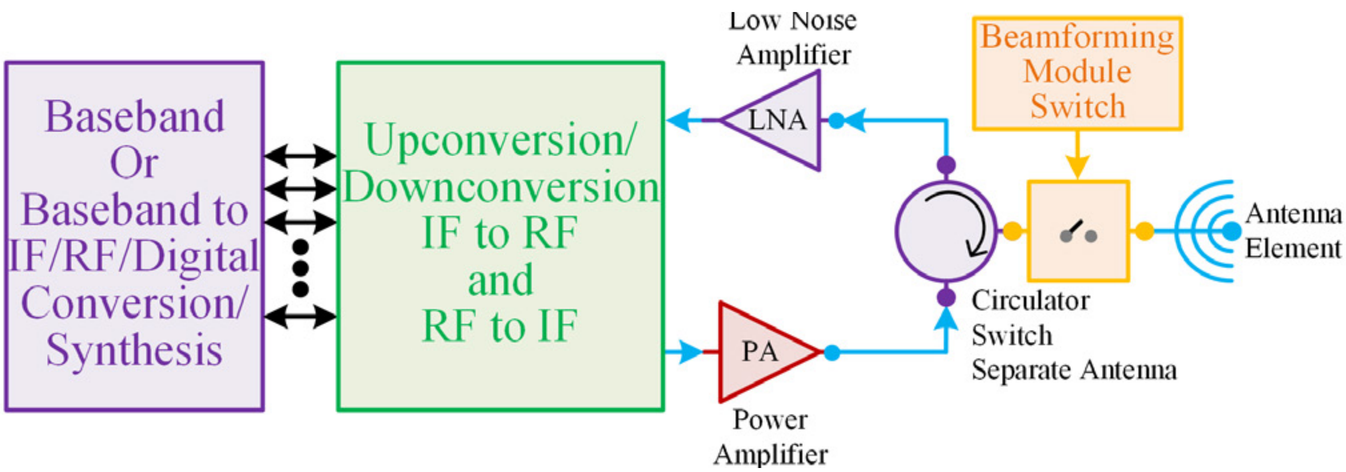

Figure 9: Example dielectric lens switched antenna array signal chain for a single element.

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WHY DIELECTRIC LENSES & WHY NOW?

Until now, there has also been another dominant limitation when implementing dielectric lenses for practical applications. Traditional manufacturing methods have limited the production quality or quantity of large and intricate dielectric lenses, such as gradient-refractive index (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.

The recent efforts to use mmWave spectrum for telecommunications, defense, and sensing applications eager to avoid spectrum congestion at lower frequencies, has also opened doors for the practical use of dielectric lenses for these applications. As the size of dielectric lenses also scales with the operating frequency, mmWave systems would require physically smaller dielectric lens structures, which can be more readily manufactured compared to the relative sizes needed for previous generations of cellular telecommunications or radar.

GRIN LENS PRIMER

Gradient refractive index (GRIN) dielectric lenses are electromagnetic structures with a continuous spatially graded index of refraction. As mentioned earlier, traditionally manufactured GRIN devices typically rely on discrete transitions from one dielectric material to another, and a continuous refractive index gradient can never truly be achieved. For GRIN devices manufactured via 3D printing, the lens can be manufactured by a single polymer dielectric material. GRIN dielectrics provide unprecedented design freedom for various applications where methods like transformation optics can be leveraged to create higher performance microwave devices.

The index of refraction of a GRIN lens, by way of relative dielectric permittivity, or dielectric constant (ε_r), is defined and controlled through the generation of a periodic lattice topology of varying volume fraction. By locally controlling the ratio of air and the dielectric material, it is possible to control the local volume fraction of dielectric material to air, and thus the effective permittivity at a region within the lattice. More simply put, printing thicker lattice struts creates regions with higher effective permittivity, while thinner struts results in lower effective permittivity.

In the case of the Luneburg-style lens, by changing the density of the lattice and effectively increasing the lattice air fraction from core to perimeter, a radially continuous spatially graded index of refraction can be realized. The mixing of dielectric material and air is used to control the designed effective permittivity, but it also introduces incredible advantages to the overall loss of a device.

The most common implementations of this technology are variations of a Luneburg lens, where there is a radially symmetric gradient dielectric constant. These lenses are designed to achieve high gain when fed at the focal point, which typically lies near the surface of the lens. When antennas are placed around the sphere, the lens allows the device to emit directive beams at any angle simply by switching between feeding positions around the lens because of the aperture and symmetry of the lens antenna. GRIN lenses also have higher operating bandwidth than constant dielectric lenses.

Since the phase center of most antennas differ relative to the ease of placing them radially around the lens, a variety of Luneburg-style lenses would be designed depending on the application and implementation. Hence, a GRIN lens could be designed to provide superior gain over steering angle performance for applications like mmWave 5G, where steering directive beams are required.

Other variations of GRIN lens technology exist to allow for feeding along a plane, such as with a traditional PCB antenna array. The design space of GRIN lenses includes cases where the focal point lies along a plane for various incident angles, and can even be used in conjunction with a phased array to take advantage of the benefits of an electronically steered antenna array with the aperture and gain-at-angle performance of an RF lens antenna.

Additionally, the ability to use methods like transformation optics in the RF regime is enabled by the additive manufacturing of GRIN devices for applications beyond lenses, like dielectric waveguides, radomes, volumetric circuits, superstrates, and other dielectric antennas.

HISTORICAL CHALLENGES OF PRACTICALLY MANUFACTUREING GRIN LENSES

There are many methods found in literature for manufacturing GRIN lenses, such as Luneburg lenses. One of the more common methods is to machine and assemble sheet stock of dielectric material in a jig-saw like manner. These individual pieces form the core-shell structure of the Luneberg lens and can be held together by RF adhesive. This method is an inherently manual process and requires extreme precision, as any gaps between the layers of jigsaw pieces will introduce areas of low dielectric constant in the middle of the lens, disrupting the gradient.

GRIN devices are relatively straightforward to manufacture via 3D printing. Using lattice design concepts, GRIN devices are created in a facile manner 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 is called Fused Filament Fabrication (FFF). In FFF, thermoplastic or thermoplastic composite material is melted and extruded through a fine nozzle, precisely depositing material as a thin bead. Due to widespread availability of low-cost FFF machines capable of processing electrically relevant 3D printable commodity thermoplastics, FFF has been the most cost effective method of fabrication of GRIN devices to date.

However, the FFF process is slow and feature sizes are limited by nozzle size, making FFF incapable of meeting the volumes needed for the 5G mmWave rollout or low earth orbit (LEO) SATCOM user terminal deployment.

Advances in photopolymers and photopolymer printing technologies represent a boon for the manufacturing of high-fidelity GRIN devices. As light is easier to control than a mechanical extrusion nozzle, parts produced through Digital Light Processing (DLP) printing processes can achieve higher feature resolution than FFF, easily meeting the requirements for high-frequency applications. DLP technology itself is known to scale, as the layer masking technology lends itself well to faster printing as well as the possibility for running multiple parts in parallel. Though DLP has many advantages, photopolymers themselves are inherently lossy, especially when compared to traditional low-loss materials commonly used in electronic devices. Common photopolymers are an order of magnitude more lossy than thermoplastics and require higher power to achieve the same gain when used in similar device designs.

As with any 3D printing process, there are practical limitations to the process that must be considered. In the case of the effective permittivity within the lens, the limitations are driven by the size of the individual struts of the lattice unit cell. Hence, the effective dielectric constant range between the dielectric material and air will be less than the real range due to processability constraints.

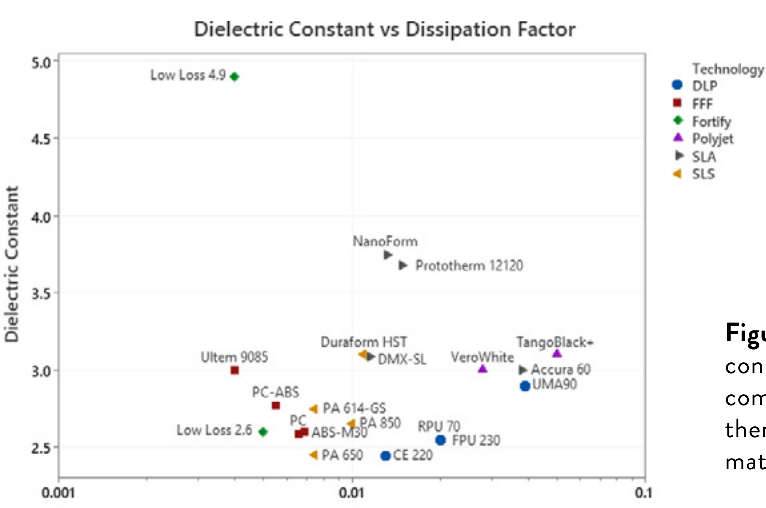


Figure 10: This chart plots the dielectric constant and loss tangent of several commercially available commodity thermoplastic and photopolymer 3D printing materials.

6

ROGERS & FORTIFY TEAM UP TO DEVELOP NOVEL FILLED PHOTOPOLYMER RESIN FOR 3D PRINTED GRIN DIELECTRIC LENS TECHNOLOGY

While interacting with customers, Rogers engineers noticed a general trend of attempts to employ traditional RF substrates, mainly printed circuit board (PCB) substrates, drilled, patterned, and stacked in thin layers to yield 3D dielectric GRIN structures. To enable a better solution, Rogers developed a filled photopolymer resin technology with a dielectric constant and loss tangent suitable for upper microwave and millimeter-wave applications.

Though the new filled photopolymer resin material's performance at mmWaves is excellent, tackling the manufacturability of the material proved challenging. Hence, Rogers' engineers sought out Fortify's 3D printing experts to take on the challenge and develop a capable and reliable manufacturing process for the new filled photopolymer resin material. The results are an exciting collaboration where extremely complex and fine resolution 3D dielectric structures with wide refractive index capability and low loss can now be designed and built within hours instead of weeks to months.

Fortify and Rogers Corporation designed a test case to demonstrate the real advantages of the 2.6 ε_r low loss polymer dielectric material and how it can be leveraged to design high performance GRIN devices for high frequency applications.

Due to the growing need for devices in the mmWave and Ka band bandwidths, the GRIN lens was designed for peak performance at 30 GHz. The design of the spherical Luneburg-style GRIN lens is shown below.

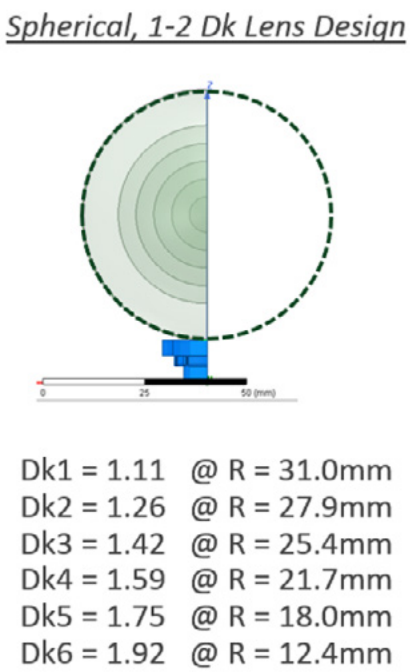


Figure 11: The design of the Luneburg-style GRIN lens with a dielectric constant designated for each shell of a given radius.

The performance of the device was simulated in ANSYS HFSS software with a WR-34 open-ended waveguide feed source at 30GHz as shown in the image below. The resulting simulation produces a symmetrical beam pattern with a peak directivity of 24dBi without losses considered in the fixturing and coax adapters.

It is expected that the loss of the polymer to significantly impact the performance of the lens and should be minimized, as it is approximately 6λ in diameter, where λ is the wavelength at 30GHz.
To bring this design from simulation to reality, Fortify and Rogers converted the desired dielectric constant of each shell of the Luneburg-style lens design to a relative volume fraction using a well characterized effective mixing approximation approach. From there, generative design tools were used to populate each dielectric constant permittivity map of the lens with a lattice of the appropriate volume fraction. The following image shows a cross-section of the device, demonstrating the radial change in volume fraction from the center to the surface of the device.

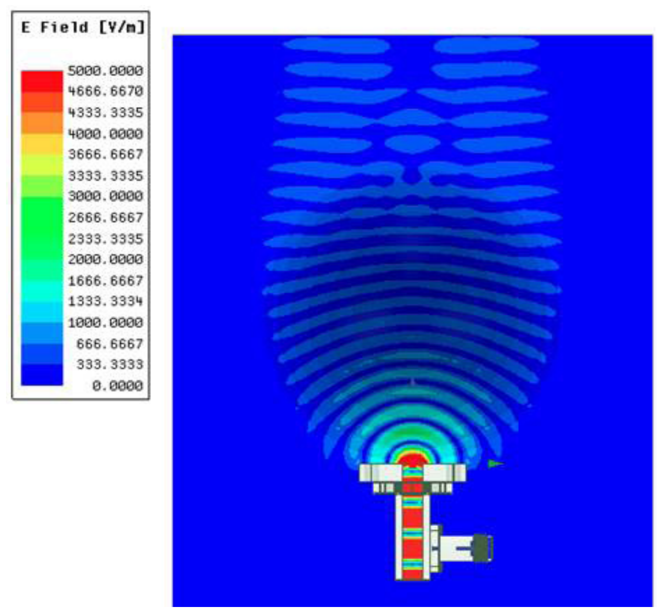


Figure 12: Lens design modeled in Ansys HFSS showing the electric field being focused by the GRIN structure.

DESIGN & SIMULATION CONT.

Using Fortify's Compass build preparation software, the part was supported and sliced, and a build file was generated. The Rogers Corp. 2.6 ε_r polymer dielectric low loss material was loaded into a Flux Core 3D printer, and Fortify's Continuous Kinetic Mixing (CKM) module was used to circulate, heat, and maintain the homogeneity of the particle-loaded dielectric polymer material. The build file was loaded to the Flux Core onboard computer, and the GRIN lens was printed. The image below on the left shows the lens attached to the build platform and support structures, while the image on the right shows the final part.

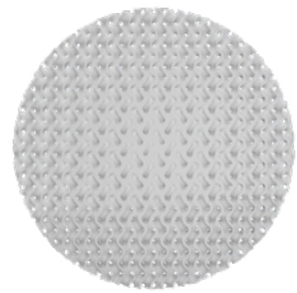


Figure 13: This device cross- section shows how the volume fraction of material reduces radially from the center of the sphere to the surface.

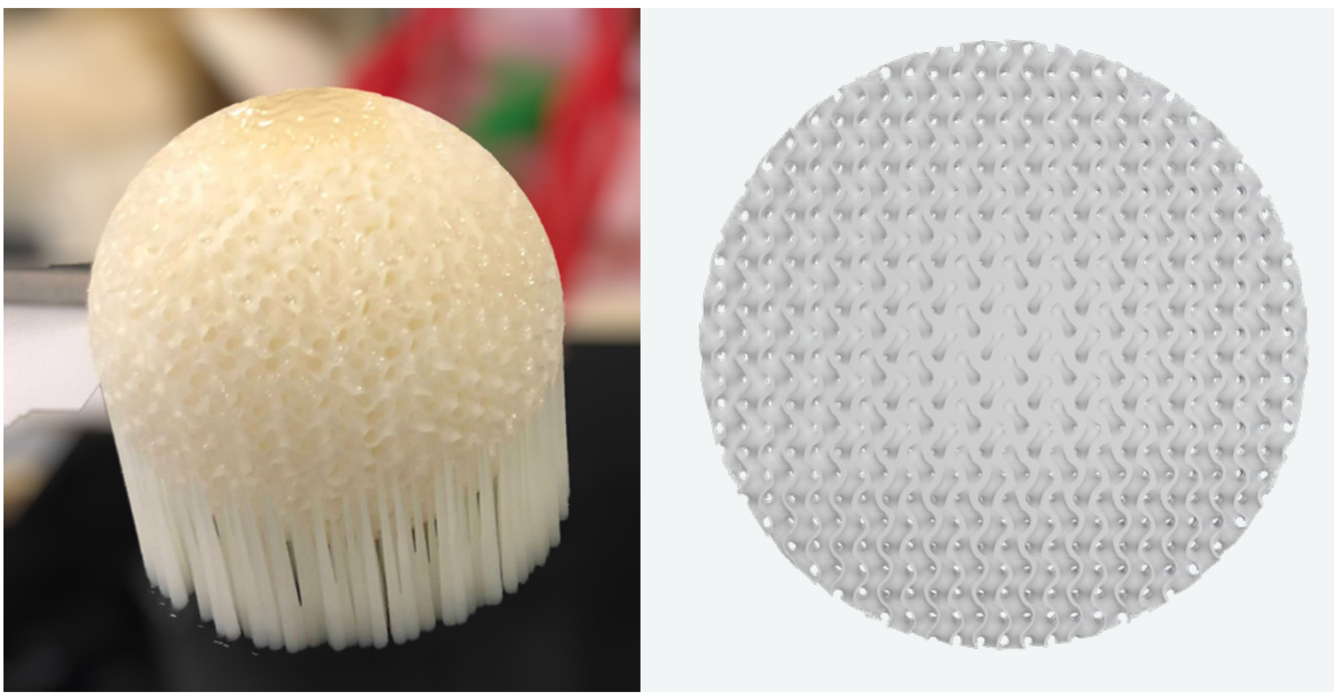


Figure 14: (Left) 3D printed lens on supports. (Right) The cleaned and cured lens

30 GHZ GRIN, LUNEBURG DIELECTRIC LENS IN ACTION

After some final processing steps, the lens was shipped to Rogers Corp. for RF performance evaluation in an anechoic testing range. The images below demonstrate how the lens was fitted and mounted its focal distance away from the open ended waveguide.

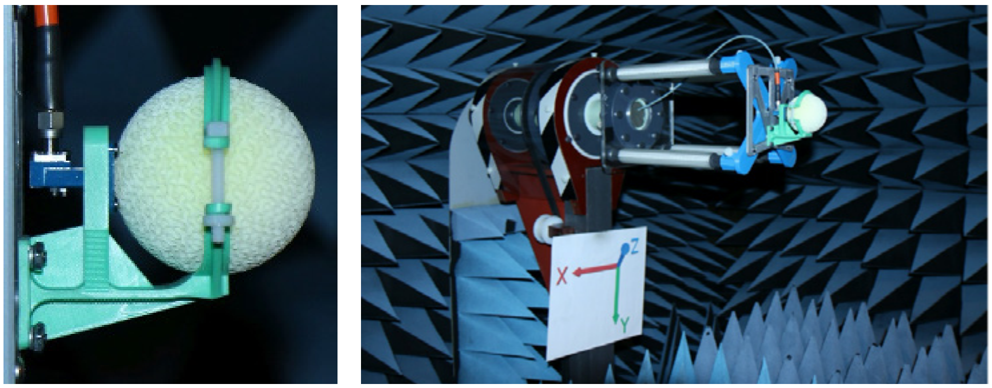


Figure 15: Left - The 3D printed GRIN lens mounted to the fixture in front of the open ended waveguide feed source. Right - The mounted lens affixed to the test rig in the anechoic test range.

The lens was tested in the Ka band with frequencies ranging from 24 GHz to 32 GHz.

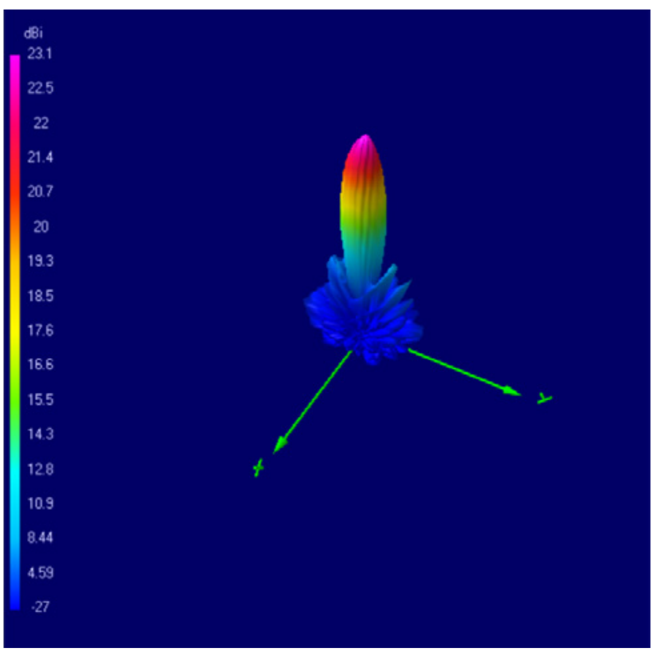


Figure 16: 3D antenna pattern of the printed Luneburg-style lens at 30 GHz.

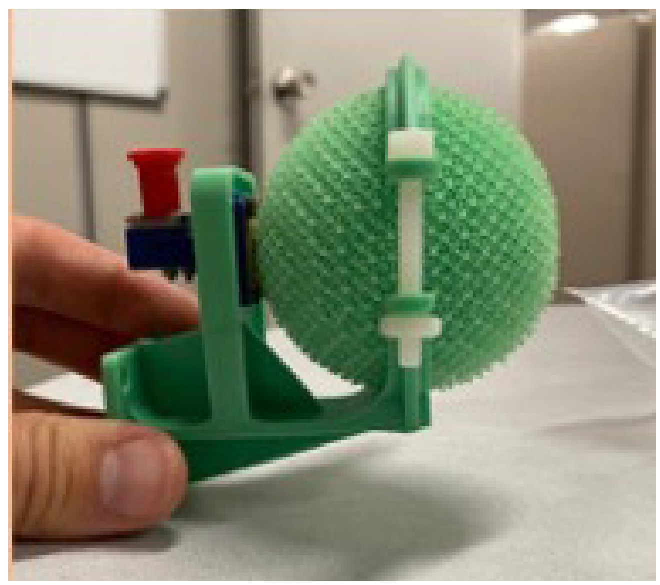


Figure 17: GRIN Luneburg lens built using conventional, commercially available photopolymer resin.

For a comparative test, a device of an equivalent design was prepared using a commercially available photopolymer with a 2.9 ε_r and a loss tangent of 0.039 @ 10Ghz. Images of that device and test setup are shown below.

30 GHZ GRIN, LUNEBURG DIELECTRIC LENS IN ACTION CONT.

The results of both the comparative lens and the 3D printed low loss polymer dielectric lens are shown in the radiation pattern charts below. The green curve shows the performance of the Rogers and Fortify printed lens, where the red curve shows the performance of the comparative commercially available photopolymer 3D printed lens.

As the radiation patterns show, the Rogers and Fortify printed lens exhibits a 4 dBi gain improvement over the comparative lens manufactured from conventional photopolymer material. Furthermore, the GRIN nature of the lens complements wide bandwidth applications. The GRIN lens shows an increase in gain as wavelength decreases due to growing aperture without breaking down, as the chart below demonstrates.

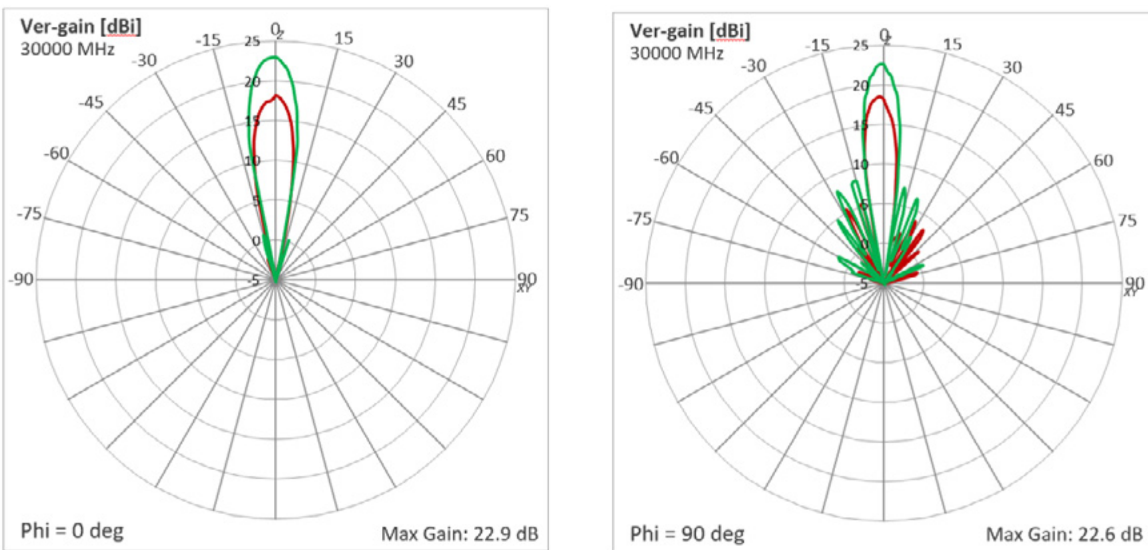


Figure 18: 30 GHz test results for the two lenses. In both charts, the green curve is the Rogers and Fortify printed lens, where the red curve is the comparative lens printed with commercially available photopolymer. Left chart - Phi = 0. Right chart - Phi = 90.

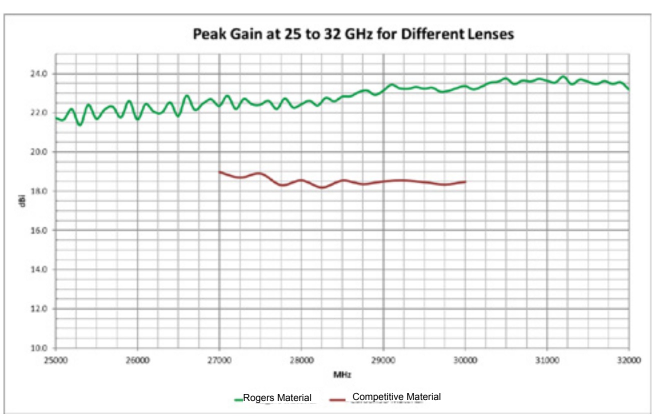


Figure 19: This chart shows the max axis gain and peak gain from any direction as a function of frequency. As frequency increases the gain increases, as the aperture size is larger relative to the wavelength. The green curve represents the Rogers and Fortify printed lens, where the red curve represents the comparative lens printed with commercially available photopolymer.

30 GHZ GRIN, LUNEBURG DIELECTRIC LENS IN ACTION CONT.

To confirm the consistency and steering capability of the Luneburg-style lens, the lens was rotated in the fixture 90 degrees in the azimuth and tested again. The results of the lens rotation experiment are in the table below, which show excellent performance of the lens regardless of feed position.

FREQUENCY	ROTATED 0°	ROTATED 90°
25 GHz	21.8 dBi	21.9 dBi
28 GHz	22.4 dBi	22.1 dBi
31 GHz	22.1 dBi	23.5 dBi

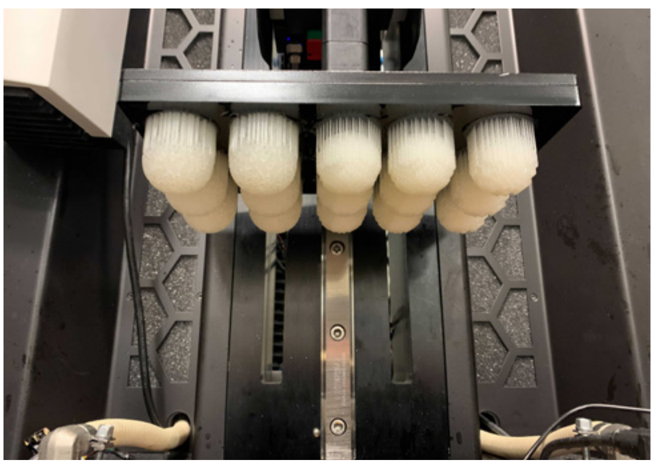


Figure 20: Image of a Luneburg-style lens printed on a Fortify Flux Core printer.

As the lens in this case study is roughly 78% air, the effective loss of the lens structure is considerably lower than the loss of an equivantly sized constant-K dielectric lens. For the 2.6 ε_r material, it would be ideal to leverage the entire effective permittivity range from 2.6 ε_r to the permittivity of air. In reality, due to processability considerations, this range is closer to 2 ε_r down to 1.15 ε_r. Fortify and Rogers continue to explore methods to widen the effective permittivity range of the 2.6 ε_r material in practical applications.

ADVANTAGES OF ROGERS' NEW FILLED PHOTOPOLYMER RESIN & FORTIFY'S MANUFACTURING PROCESS

GRIN lenses offer significant advantages over traditional solid dielectric lenses. It's a fairly straightforward activity to design and manufacture a solid Constant-K dielectric lens with comparable gain to the lens presented in this white paper - and in some cases may even be cheaper. Yet, it's necessary to look at a few key performance characteristics to fully understand the advantages of this new filled photopolymer resin and 3D printing approach.

WEIGHT

For design engineers who are concerned with SWAP (size, weight, and power), reducing the weight of a device can be a critical design priority. 3D printed GRIN lenses intentionally mix solid dielectric polymer material with air to recognize a desired effective permittivity. This introduces an added benefit of lowering the weight of the lens. For a 62 mm diameter spherical lens, the weight results are presented below.

Luneburg-style GRIN lens 3D Printed with Rogers' filled photopolymer resin: 34 grams
Spherical dielectric Rexolite lens: 131 grams

The results above show that a designer can achieve a nearly 75% weight reduction using this approach. It is important to note, that when using a GRIN lens in place of a comparable solid dielectric lens, the weight savings does not come at the cost of performance.

WIDEBAND PERFORMANCE

Consider a transmitting and receiving antenna device, where transmission (TX) and reception (RX) are operating at two different frequencies. Due to the narrowband nature of the solid dielectric lens, a distinct lens design is needed for each frequency to focus the signal. For a GRIN device, this is not the case. The wideband nature of the Luneburg-style lens is shown in the chart "Peak Gain at 25 to 32 GHz for Different Lenses", demonstrating substantial gain across a wide bandwidth. As a result, using a GRIN lens in place of a solid dielectric lens (or any other focusing device for that matter) will reduce the number of individual components in an antenna assembly and provide an opportunity for denser integration of components into an overall smaller form factor.

SPHERICAL SYMMETRY OF LUNEBURG-STYLE LENSES

A Luneburg-style lens is radially symmetric. These lenses are designed to achieve high gain when fed at the focal point, which is typically located at any point across or near the surface of the lens. When antennas are placed around the sphere, the lens allows the device to emit or receive directive beams at any angle simply by switching between feeding positions around the lens. As a result, one spherical luneburg-style lens can do the work of a multitude of solid dielectric lenses, reducing device complexity, decreasing device size, and enhancing performance.

ADVANTAGES OF ROGERS' NEW FILLED PHOTOPOLYMER RESIN & FORTIFY'S MANUFACTURING PROCESS CONT.

STOP FABRICATING AND START MANUFACTURING

As mentioned earlier, Fused Filament Fabrication (FFF) is as close to an incumbent additive manufacturing process as exists for GRIN devices at present. The thermoplastic materials available for FFF have great electrical properties, but the FFF process is stymied by either low throughput or poor minimum feature size. With Rogers printable dielectric photopolymer and Fortify's printing technology, it's possible to realize both small feature sizes and high manufacturing throughput. In the case of a 62 mm diameter lens, 5 individual devices can be printed on the same build platform at the same time on the Fortify Flux Core printer. Due to the inherent parallelization capabilities of the DLP print process, each layer of each device is cured at the same time, resulting in significant time and cost savings to the customer.

Compared to FFF, where manufacturing parallelization scales linearly with the number of extrusion nozzles (typically one per machine), the Fortify printing technology has the capability to dramatically outperform FFF while maintaining small feature sizes.

In the case of a 62 mm diameter lens designed for the Ka band, such as the one discussed in this white paper, Fortify's technology has a serious build speed advantage compared to FFF.

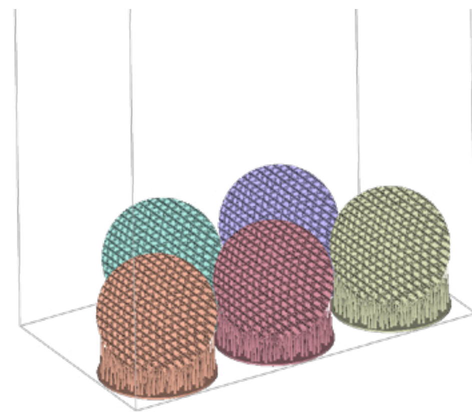


Figure 21: Isotropic view of a 5 lens build.

TECHNOLOGY	BUILD TIME	NUMBER OF PARTS	TIME PER PART
FFF	~12 hours	1	12 hours
Fortify	~15 hours	5	3 hours

Fortify's printing technology can reduce manufacturing times by as much as 400% when compared to FFF.

Unlike other manufacturing processes, such as using injection molds or traditional machining, DLP 3D printing systems can be configured to manufacture a supplied design in a matter of hours instead of days to weeks. The initialization for a DLP 3D printing processes is swift enough that a small batch of prototypes could be built from a print or submitted design requirements, a customer could have time for approval/analysis, and a full manufacturing run could begin in the time it takes for a mold to arrive or a shop to properly tool/fixture for a machining process.

ADVANTAGES OF ROGERS' NEW FILLED PHOTOPOLYMER RESIN & FORTIFY'S MANUFACTURING PROCESS CONT.

INNOVATION AND COLLABORATION

Fortify focuses on commercializing advanced DLP 3D printing systems capable of processing highly viscous filled resins. While traditional DLP platforms struggle printing at viscosities greater than 1000 centipoise (cPs), the Continuous Kinetic Mixing (CKM) technology employed on all Fortify Flux Series printers allow for the processing of advanced materials while maintaining filler homogeneity.

This technology is enabled by the collaborative efforts between the Fortify and Rogers Corporation technical teams. By combining Rogers' expertise in low-loss materials with Fortify's advanced composite processing capabilities, commercial production of high-fidelity, scalable, low-loss RF dielectrics is now possible

7
CONCLUSION

Realizing high performance AAS at mmWave frequencies that meets throughput, reliability, and user experience goals has proven a challenge to the industry. Complex, 3D printed dielectric structures, such as GRIN lenses, may be a powerful new tool for AAS designers to achieve higher gain and scanning angles than what was previously possible in production quantities. Fortify and Rogers are teamed up to bring low loss photopolymers to the greater industry, and together these organizations are focused on making this technology accessible and easy to use. The test results presented in this white paper demonstrate just one possibility in the wide range of possible applications for 3D printed dielectric structures and the presented GRIN design methodology.

RESOURCES

1. Introduction
    1.1.

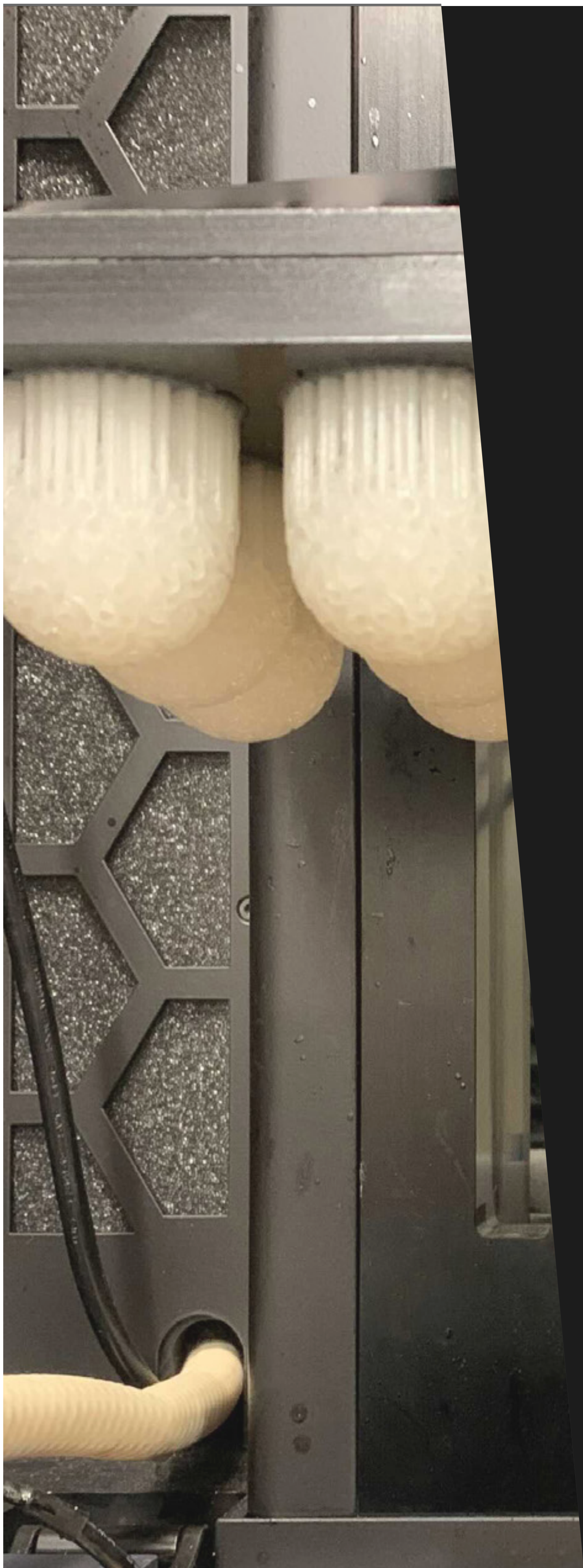
2. The Rise of Advanced/Active Antenna Systems & Electronically Steered Antenna Arrays
    2.1. A Review of Antenna Array Technologies for Point-to-Point and Point-to-Multipoint Wireless Communications at Millimeter-Wave Frequencies

3. Challenges Of Phased Array Antenna AAS
    3.1. Wide-Angle Scanning Phased Array Antenna using High Gain Pattern Reconfigurable Antenna Elements

4. Beamsteering Advantages With Dielectric Lenses
    4.1. Design of Cost-Effective Beam Steered Phased Array Antenna with Enhanced Gain using Metamaterial Lens
    4.2. Lens-enhanced phased array antenna system for high directivity beam-steering
    4.3. A Millimeter-Wave Phased Array Fed Biconvex Lens Antenna
    4.4. Practical Design Considerations for Compact Array-Fed Huygens' Dielectric Lens Antennas
    4.5. Grating Lobes Reduction Using a Multilayer Frequency Selective Surface on a Dual-Polarized Aperture Array Antenna in Ka-Band

5. Why GRIN & Why Now?
    5.1. DESIGN AND FABRICATION OF A RADIO FREQUENCY GRIN LENS USING 3D PRINTING TECHNOLOGY

6. Rogers & Fortify team up for novel filled photopolymer resin 3D printed GRIN technology
    6.1 Fortify RF & Microwave Technologies



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