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3D printed dielectric lens for the gain enhancement of a broadband antenna

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Abstract
A novel 3D printed dielectric lens to enhance antenna gain parameters is presented. The lens is fabricated using a fused deposition method (FDM) which is a cost-effective and an efficient 3D printing technique. Poly-methyl methacrylate (PMMA) is used as a dielectric material due to its good RF properties. The thickness of the dielectric lens is 14 mm and provides a gain enhancement of up to 6.9 dBi over a wide frequency range. The dielectric lens is designed and computationally analyzed to demonstrate refractive index value close to zero. It has been shown that impedance-matched near-zero refractive index lens geometry eliminates strong reflections, and consequently enhances the antenna gain. A correlation is established between the individually, stacked unit cell layers and near-zero refractive index cut-off frequencies. The claim is substantiated through measured results using a broadband Vivaldi antenna. A gain enhancement of up to 6.9 dBi is recorded for the bandwidth from 13.5 to 24 GHz. An excellent correlation is reported between the measured and simulated results.

KEYWORDS
3D printing, broadband gain enhancement, dielectric lens, fused deposition method, near-zero refractive index

1 | INTRODUCTION

Antenna characteristics enhancement has always been an active research area. Frequency selective surfaces (FSS), electromagnetic band gap (EBG), photonic band gap (PBG), metamaterial, and so forth are some of the commonly used techniques, employed to improve antenna return loss, bandwidth, radiation configurability, miniaturization, directivity, and gain.[1-3] The right choice of the technique comes often with the trade-off between conflicting requirements. These techniques are highly dependent on the choice of frequency, which often leads to limited operational bandwidth. Metamaterials emerge as an excellent choice to obtain negative and even near-zero refractive index superstrates, that can significantly enhance an antenna gain by taking advantage of ultra-refraction properties. However, the usability is again frequency specific, due to inherent limitation of sub-wavelength resonant ($< \lambda/10$) response and sets a limit on the use of metamaterials.[4,5] Apart from that, fabrication tolerances for metamaterials are also very stringent. The microwave lens employs concepts from optics and electromagnetic and appears as a decent solution when a broadband characteristics enhancement is needed. The microwave lens transforms the quasi-spherical wave emitted by the radiating source into near-plane wave.[6] The phenomena lead to gain enhancement that is relatively less frequency dependent. Near-zero metamaterials (NZM) have a permittivity (ε) near zero and a permeability (μ) close to unity, and results in near-zero refractive index ($n = \sqrt{\mu\varepsilon}$). However, the response of permittivity is highly dependent on the resonance behavior of the geometry. Besides, the permeability remains finite, and the impedance ($\eta = \sqrt{\mu/\varepsilon}$[7]) is mismatched from free space, resulting in large reflections at the interface, outside the narrow design bandwidth.[7]

Microwave dielectric lenses have been around as early as 1960,[8] however, due to their size at microwave frequencies and fabrication challenges they have been mainly limited to THz and optical applications.[9] Besides suitable electromagnetic properties of the material, the choice largely depends on the fabrication and machining process. This often excludes the use of harder materials for the lens fabrication.[10] Often these lenses come in a spherical shape, which is difficult to machine precisely and curvature results in increased size. Flat lenses such as Gradient Refractive Index (GRIN) lenses circumvent the need for spherical dome shape, however, as the name implies it requires using different materials to be stacked together to achieve the gradient refractive index properties. This can add to fabrication, machining complexity, and the choice of more than one suitable material with appropriate electromagnetic properties.

In this work, a relatively simple and cost-effective fabrication technique is proposed to obtain a homogeneous multi-layered flat dielectric lens that is 0.6 λ thick (at 13 GHz). The material used is poly-methyl methacrylate (PMMA), commercially known as plexiglas. It has the dielectric constant $\varepsilon_{r(L)} = 3.2$ and loss tangent $\tan\delta_L = 0.001$. The design is fabricated using 3D printing based on the fused deposition method (FDM) technique. 3D printing offers flexibility of design and geometries, reduced material wastage, rapid prototyping, and good duplicity of design, which in turn, can be translated into cost-effectiveness in comparison to micro-machining based fabrication processes.

In the next section, the design and the computational analysis of the lens geometry is elaborated. Section 3 explains the fabrication process using 3D printing

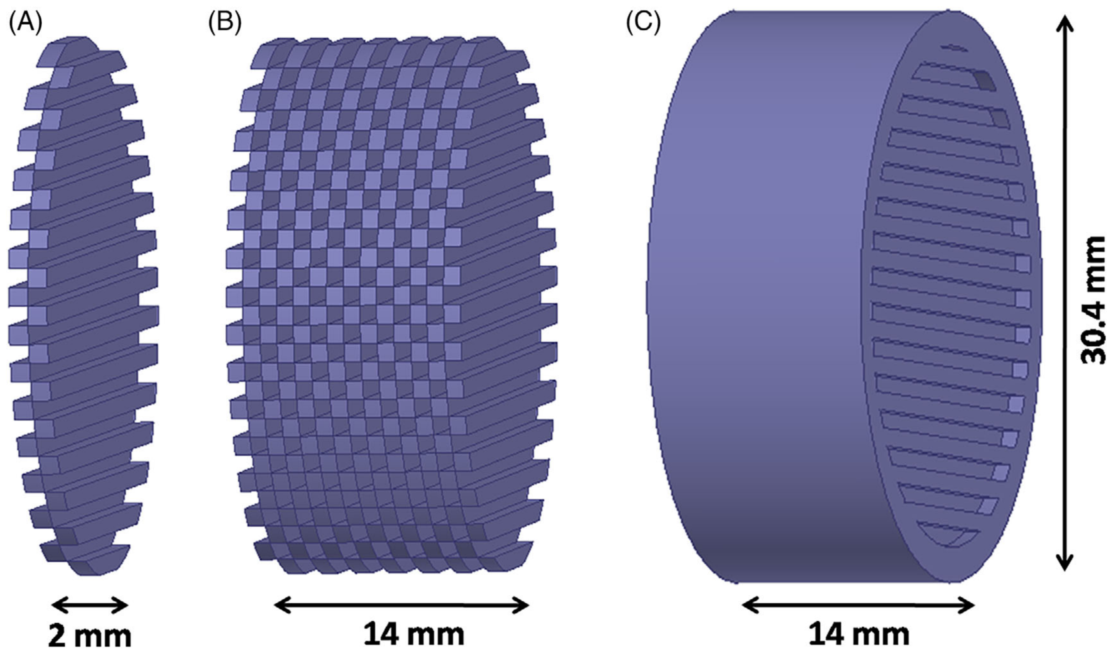

FIGURE 1 Individual unit cell, A, proposed design composed of seven unit cells, B, proposed design rim for structural reinforcement, C

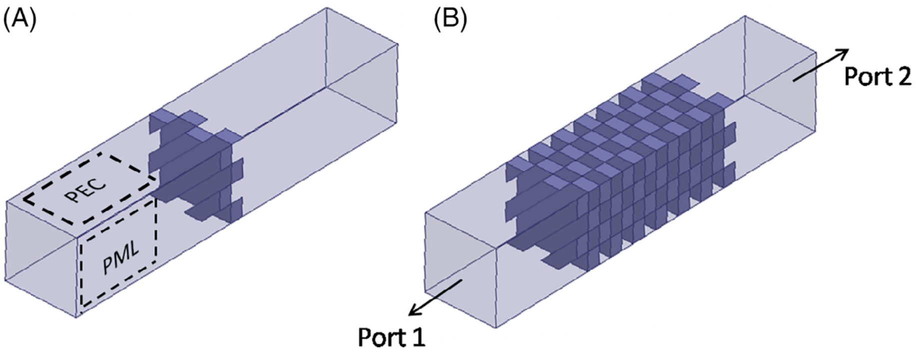

FIGURE 2 Unit cell analysis setup. A unit cell is placed in a rectangular waveguide, with top and bottom walls assigned as PEC and side walls assigned as PML, A, simulation setup for seven layered lens geometry, B

technique. The gain enhancement is simulated and experimentally verified in section 4.

2 | MICROWAVE LENS DESIGN AND ANALYSIS

A flat 14 mm thick lens is designed, using a spatially shifted periodic layered structure. A unit cell shown in Figure 1A has a thickness of 2 mm. An individual unit cell is composed of square shaped alternate rectangular pillars of area 1×1 mm^2, separated by air. The lens has 30° orientation angle with normal. The proposed design is made of seven unit cells stacked together as shown in Figure 1B. An outer rim of thickness 2 mm keeps the individual unit cells adhered to each other to maintain structural integrity, as shown in Figure 1C. The diameter of the lens is chosen such, that it corresponds to the antenna aperture for gain enhancement. The net diameter is 30.4 mm (including 2 mm outer rim) in this case.

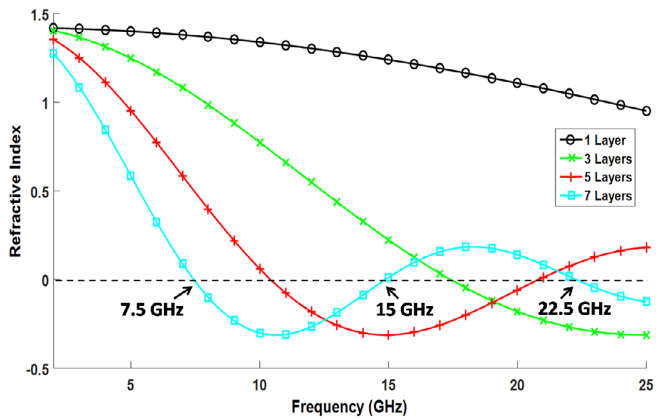

FIGURE 3 Lens with different number of unit cells (layers) and their effect on refractive index as a function of frequency

The design is simulated and analyzed in Ansys HFSS v15. A unit cell as shown in Figure 1A is enclosed in a rectangular waveguide. The opposite pair of boundary walls are assigned perfect magnetic layer (PML) boundary and perfect electric conductor (PEC) layer. The unit cell is placed at the center of the square waveguide geometry. The input and output ports were excited using waveports. Waveports are chosen due to their additive functionality of higher modes incorporation. It is important to mention that the two ports should be equi-distant from the lens, to suppress reflection artifacts caused by different path lengths. Different path lengths can introduce erroneous transmission and reflection coefficients. In addition, waveport provides de-embeding feature that enables runtime suppression of error in S_{11} and S_{12} parameters. The simulation setup for one unit cell analysis is shown in Figure 2A. The number of unit cells are incremented from 1 to 10 layers in our simulation model. Figure 2B shows simulation setup for seven layers.

Unit cells are analyzed and the refractive index (n) is extracted from S_{11} and S_{12} transmission and reflection coefficients, respectively. The refractive index extraction is based on Nicolson-Ross-Weir (NRW) approach and the extracted refractive index for different number of unit cell layers[11,12] is shown in Figure 3. The design is computationally analyzed to obtain an optimal number of layers that shows near-zero refractive index (NZRI) value. It can be seen that refractive index approaches close to zero, as the operational frequency goes higher. Conversely, NZRI can be achieved at the lower frequencies by stacking higher number of unit cells together.

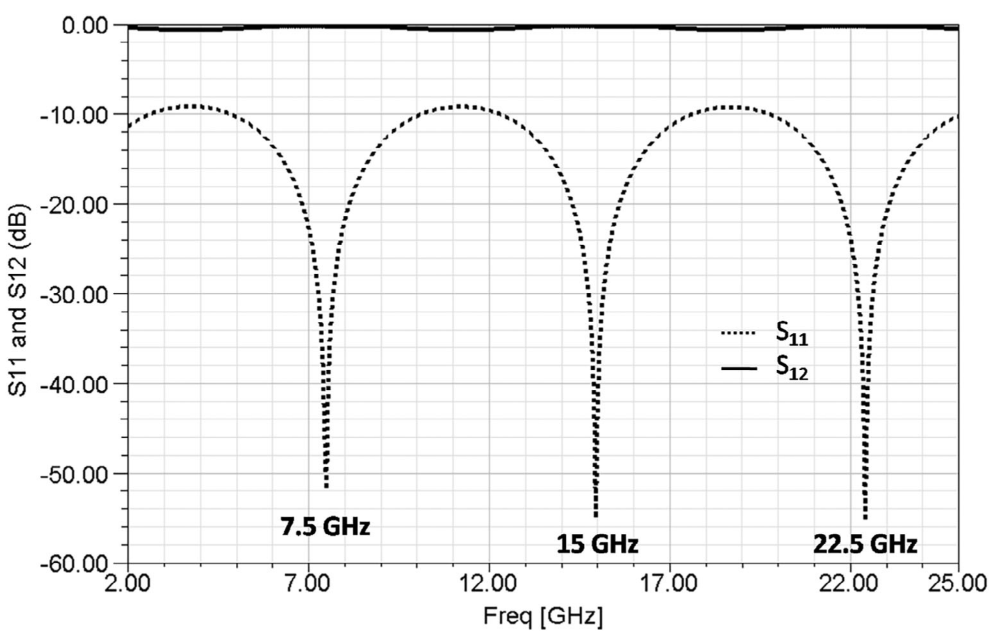

FIGURE 4 Transmission (S_{21}) and reflection coefficient (S_{11}) for a seven layered dielectric lens

The case with seven layers (seven unit cells stacked) is further elaborated for discussion and fabrication. The transmission coefficient (S_{21}) and the return loss (S_{11}) for seven layers dielectric lens is shown in Figure 4. It can be seen that there are periodic resonance peaks at 7.5, 15, and 22.5 GHz, in this given frequency sweep region (2-25 GHz), with periodicity of 7.5 GHz. At the resonance frequency, $S_{11}\cong 0$ and $S_{21}\cong 1$ and the slab is matched to free space impedance $\eta_0 = \sqrt{\mu_0/\varepsilon_0}$, where ε_0 and μ_0 are the free space permittivity and permeability, respectively. In Figure 3, it can be seen that at these frequency points the refractive index goes to zero. With a thicker lens geometry, not only the zero refractive index value shifts to lower frequency points, but also the zero refractive index points lie closer to each other in the frequency spectrum. This explains, why a large number of layers are a better choice for gain enhancement in a more stable manner, besides a good option when the gain enhancement is needed at a certain frequency band.

3 | FABRICATION OF LENS GEOMETRY

As a proof of concept, a dielectric lens composed of seven layers (seven unit cells stacked together) is fabricated using Renkforce RF500 3D printer. The 3D printer is based on FDM technology and can produce a feature size down to 0.4 mm. 3D printing is fairly economical and efficient in comparison to conventional micro-fabrication techniques.[13,14] It offers not only the realization of relatively complex geometries but also an ease of repeatability, rapid prototyping and enables control over the infill density.[15,16] PMMA is used as a printing material due to its optimal printing temperature (235°C to 255°C). In this case, the nozzle temperature is kept at 243°C, in order to keep the material flow consistent, since the flow inconsistencies can produce bubbling that translates into uneven surface printing.[17,18] The printing bed is medium heated (102°C) to prevent warping. The 3D printed design is shown in Figure 5.

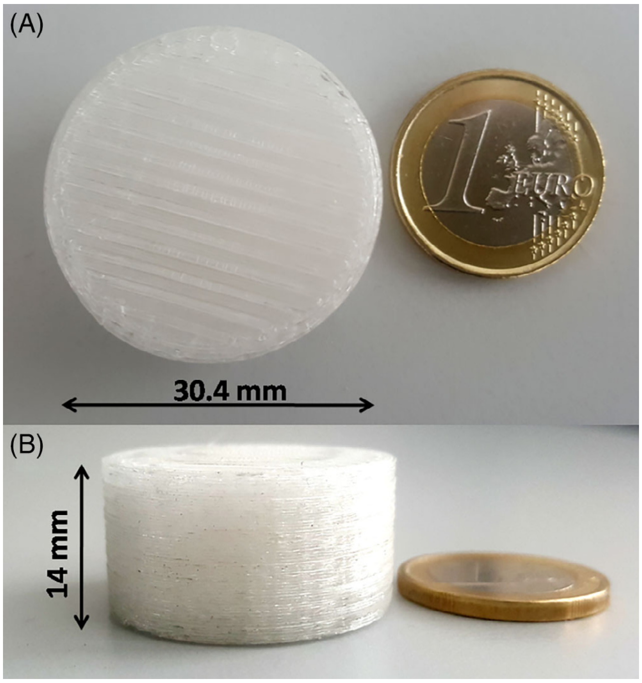

FIGURE 5 PMMA based dielectric microwave lens fabricated using 3D printing. Top view, A, Side view, B

4 | GAIN ENHANCEMENT

In order to verify the gain enhancement characteristics, the dielectric lens is simulated and measured with a

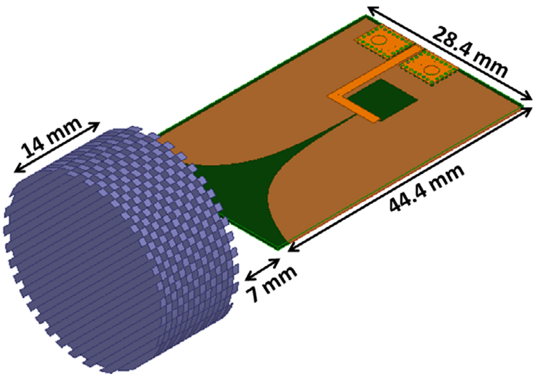

FIGURE 6 Design layout of a Vivaldi antenna with seven layers dielectric lens

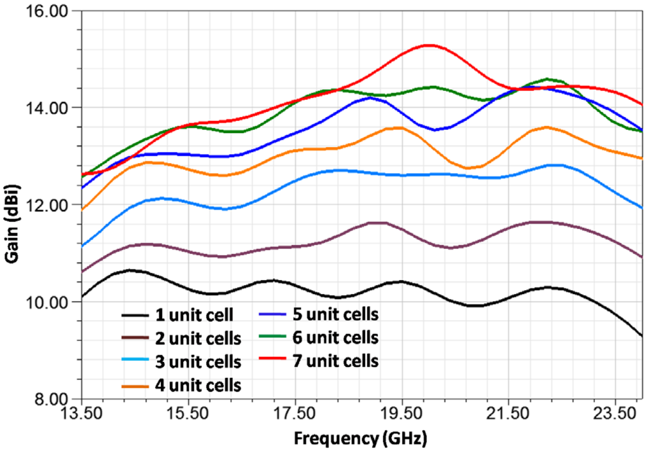

FIGURE 7 Parametric study on the lens geometric values (number of unit cells) and its effect on the antenna gain enhancement

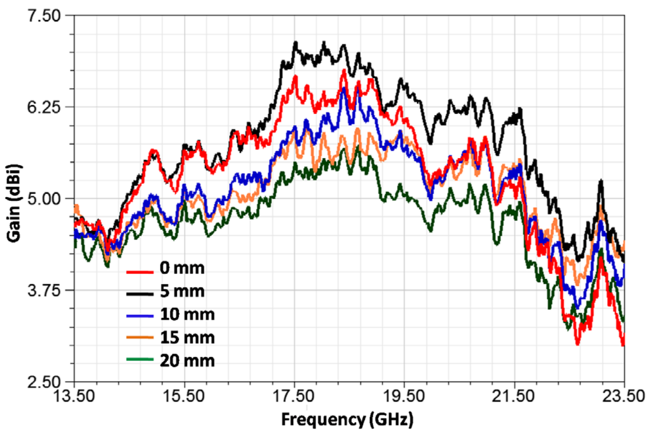

FIGURE 8 Gain enhancement measurement with dielectric lens mounted to the Vivaldi antenna, as a function of distance from the antenna

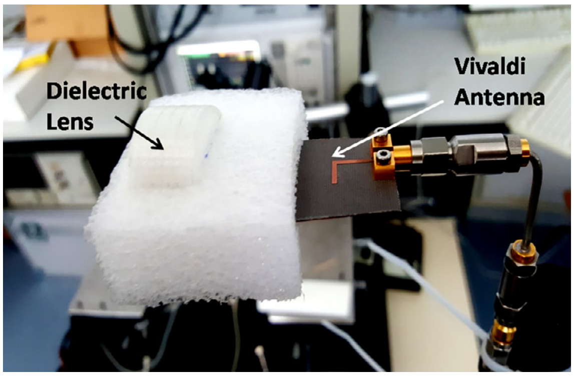

FIGURE 9 Gain enhancement measurement with dielectric lens mounted to the Vivaldi antenna

broadband Vivaldi antenna. Simulation and measurement setup are individually discussed in this section.

4.1 | Simulation setup

Simulation is carried out in Ansys HFSS v15. A broadband Vivaldi antenna is designed between 13 to 26.5 GHz.[19] The substrate material used is Roger's DiClad880 with dielectric constant $\varepsilon_{r(sub)}$ of 2.2 and loss tangent $\tan\delta_{sub}$ of 0.0009 at 10 GHz.[20] DiClad880 has an electro-deposited copper (Cu) cladding of t_{cu} = 35 μm thickness. The antenna has −10 dB bandwidth ranging from 12.5 to 25 GHz. The design layout is shown in Figure 6.

The antenna cavity is excited using a 50 Ω grounded coplanar waveguide (GCPW). The lens is placed at a distance of 7 mm from the antenna. The antenna and lens are enclosed in a radiation box that is at least quarter wave from the antenna, assigned at the lowest sweep frequency. A waveport excites the geometry and frequencies are swept from 12.5 to 26.5 GHz with a step size of 0.2 GHz, using discrete frequency sweep setup at the solution frequency of 28 GHz. A parametric study on the lens geometric values has been performed. The number of unit cells and its effect on the gain enhancement is shown in Figure 7. The gain enhancement shows more defined increments in the beginning as we progressively employ the unit cells, however, it starts to saturate (over the given bandwidth) for the dielectric lens constituted of six or higher number of unit cells.

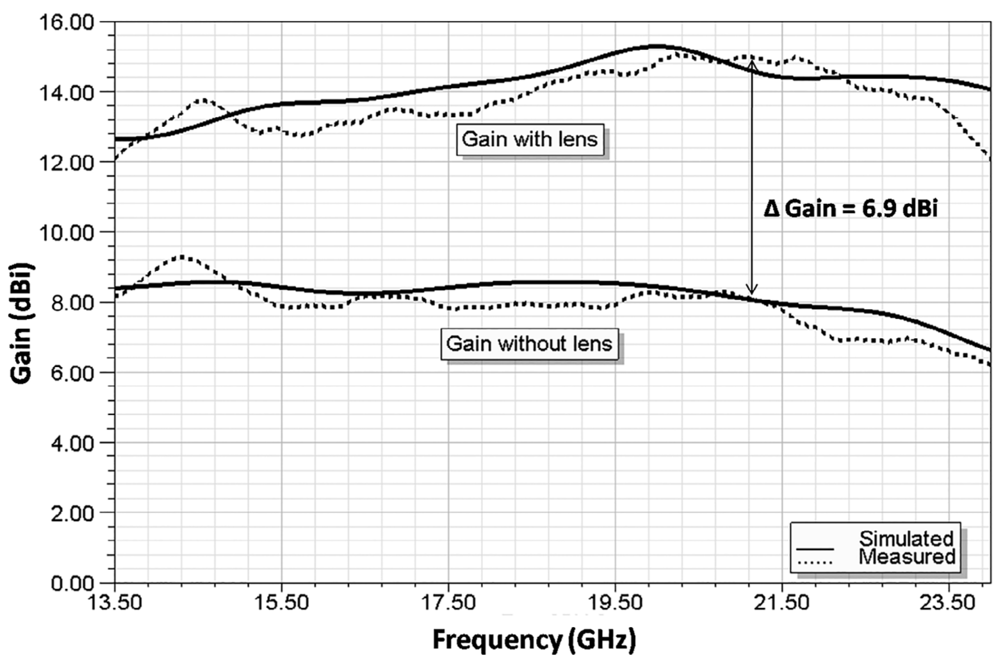

FIGURE 10 Simulation and measurement results for the Vivaldi antenna, with and without dielectric lens. Dotted line shows the measured results and solid line shows the simulated results

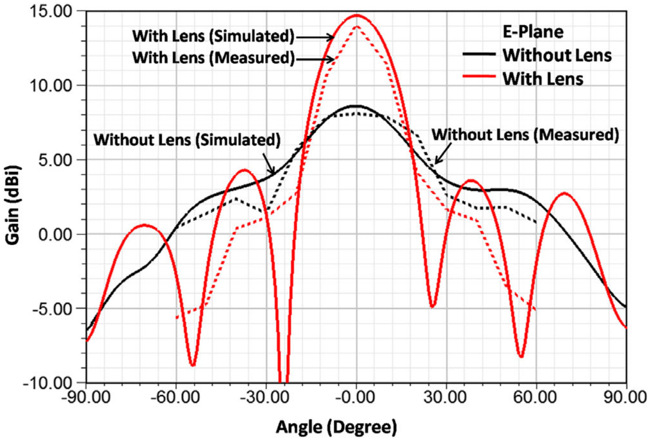

FIGURE 11 Simulated and measured radiation pattern (E-plane), including the side lobes, for the Vivaldi antenna, with and without dielectric lens. Dotted line shows the measured results and solid line shows the simulated results

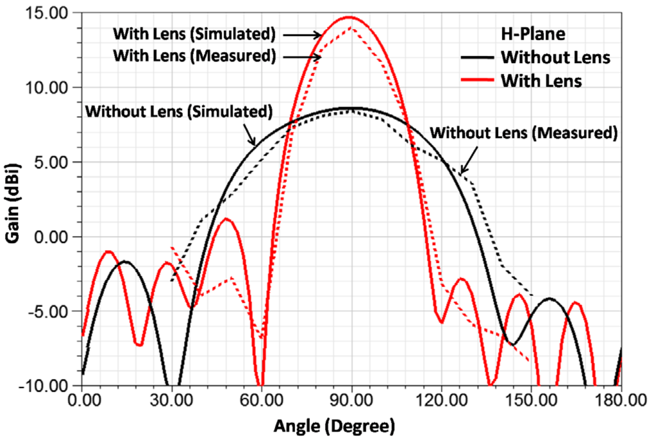

FIGURE 12 Simulated and measured radiation pattern (H-plane), including the side lobes, for the Vivaldi antenna, with and without dielectric lens. Dotted line shows the measured results and solid line shows the simulated results

4.2 | Measurement setup

The antenna return loss (S_{11}) is measured using Agilent Vector Network Analyzer PNA-X N5247A. Calibration is carried out using an electronic calibration kit ECal-module N4694A. Data smoothing and averaging of 2% is employed. Rosenberger 2.4 mm connector is used to couple RF energy into the antenna. The measurement could not be carried out in an ideally controlled environment, due to the non-availability of an anechoic chamber. Therefore, some of the factors influencing the measurement, could not be ruled out, completely. The measurements are performed by using the two-antenna method.[21] In this technique, two identical Vivaldi antennas are placed in their far-field region to obtain the reference gain of the Vivaldi antenna. In the second step, the measurements are obtained by introducing the dielectric lens. It is imperative to mention, that the distance between the dielectric lens and the antenna affects the net antenna gain. In order to provide a better insight into the effect of distance on the net gain, the measurements are performed at different distance values. The effect of gain enhancement as a function of distance is shown in Figure 8.

The lens is held in polyurethane foam at a distance of 7 mm from the antenna for optimal gain enhancement. The foam does not influence the measured results due to its very low dielectric value, which is comparable to the dielectric of air. The reported value of foam ranges from 1.03 to 1.11 at 10 GHz and decreases at higher frequencies.[22] The dielectric lens is mounted in front of Vivaldi antenna and as shown in Figure 9.

The simulation and measurement results for the antenna gain enhancement characteristics of dielectric lens are shown in Figure 10.

The radiation pattern, including the side lobes of the antenna, with and without dielectric lens is shown in Figures 11 and 12. E-plane radiation pattern is shown in Figure 11, and Figure 12 shows the H-plane radiation

TABLE 1 Comparison between lens dimensions and gain enhancement with other designs proposed in literature

References	Lens dimensions (mm) Width	Thickness	Measurement frequency (GHz)	Gain enhancement (dBi)
[23]	28.2	160	30	3.5
[24]	40 × 50*	1	7.5	1
[25]	25	41.42	20	4
[26]	100 × 100**	30	12	5
[27]	84 × 7.89***	20	12	5.5
[28]	80	53	8.8	4.6
[29]	87.5	0.635	28	6.5
Proposed design	30.4	14	21	6.9

*Hemispherical shaped; **Square shaped; ***Rectangular shaped.

pattern. It can be seen that there is a very good correlation between the measured and simulated results, over a very wide bandwidth. In addition, there has been a significant gain enhancement for a bandwidth of more than 10 GHz. A peak gain of 6.9 dBi was observed at 21 GHz.

Table 1, provides a comparative summary with literature studies to give a performance index, that employs a dielectric lens to achieve gain enhancement. It can be inferred that the proposed design shows superior functionality, in terms of size reduction and gain enhancement.

5 | CONCLUSION

In this work, a 3D printed dielectric lens that offers gain enhancement of up to 6.9 dBi over a wide frequency of range is demonstrated. The design is computationally analyzed and a correlation between unit cells, lens thickness, and near-zero refractive index is elaborated. The claim is substantiated using a broadband Vivaldi antenna. An excellent correlation is shown between the measured and simulated results. The lens can be used independently, in applications where high gain is required, such as imaging. The broadband gain enhancement makes the lens suitable and flexible for application where the frequency of operation cannot be discretely specified.

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Axel Bangert studied Electrical Engineering at the University of Kassel, Germany. He received his Bachelor's degree in 1987 and Master's degree in 1989. He worked as a research assistant at Fraunhofer Institute for Applied Solid State Physics in Freiburg, Germany, from 1989 until 1997. His research activities were on monolithic microwave integrated circuit design up to 100 GHz for different applications. In 1993, he received his Dr-Ing degree from the University of Kassel. After professorships at different Universities of Applied Sciences in Germany from 1997 until 2008, he became Head of the Microwave Electronics Lab at the University of Kassel. His current research work focuses on modeling and characterization of microwave semiconductor devices, RF MEMS, and design and realization of system components for microwave and millimeter-wave sensor systems like for example, radiometers and radars. He has authored or co-authored more than 50 publications in journals and conference proceedings.

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