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Additively Manufactured Metamaterial Luneburg Lens for X-band

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Abstract

This paper presents the design, simulation and fabrication of metamaterial based Luneburg lens for X-band through additive manufacturing using stereolithography (SLA) technique. SLA offers a fast and cost effective solution for prototyping of dielectric metamaterial structures. It also has better resolution as compared to fused deposition modelling and digital light processing method. A comparison has been drawn between the metamaterial lens and ideal gradient refractive index (GRIN) design for better understanding of lens operation, where it has been found that the non-ideal GRIN profile leads to some performance gaps. The performance of the fabricated structure has been tested at 10 GHz.

1. Introduction

Luneburg Lens is a gradient refractive index (GRIN) lens which was first proposed by R. K. Luneburg [1,2]. The refractive index of ideal Luneburg lens varies continuously. It has spherical symmetry and the incident wave should focus on opposite side of lens. The fabrication of continuously varying refractive index is not feasible. Conventionally, Luneburg lens has been manufactured by utilising finite dielectric shells, arranged in onion like configurations in such a manner that refractive index varies from 1 to 1.41 in steps, from surface to center. This is an expensive and time consuming process. With increase in number of dielectric shells, the performance of lens improves but it also becomes bulkier which proves to be a constraint for certain applications especially airborne systems [3]. For the optimal functioning of Luneburg lens, there should be precise alignment of dielectric shells with no to minimum air gaps between adjacent dielectric shells, as there presence can result in deteriorating response.

Metamaterials are engineered composite structures that show properties not naturally realisable and have opened a new arena for system realization with improved performance in terms of cost, size, weight and repeatability. Realization of spatially varying anisotropic electromagnetic material is one such application [4]. Metamaterial based GRIN lens design can mitigate electromagnetic scattering and tackles weight issues inherent in conventional lenses. It has given freedom to manipulate the electromagnetic waves while maintaining overall good performance. But metamaterial based designs are limited by available fabrication techniques.

Some methods of lens fabrication are printing pattern on PCB [5], changing the dielectric plate thickness or drilling hole on the dielectric plate in a waveguide [6], etc.

Additive manufacturing has received considerable attention in recent years in microwave [9] and will be ubiquitous in coming years. It is particularly advantageous for prototyping due to easy and cost effective fabrication. Stereolithography (SLA) is one of method used in 3D printing. It has better resolution than fused deposition modelling and is generally used in prototype fabrication.

In recent years, there is a lot of interest in Luneburg lens due to its application as retroreflectors where they are used to enhance the radar cross-section (RCS) of target so as to improve its visibility on radar [7] and has a wide application ranging from military to civil fields [8]. Also they are used in navigation of ships and Ball Lens In The Space (BLITS) satellite antenna (due to its high gain, directivity and beam scanning), road markers for self-driving cars, for target tracking in assistance with radar capture system and in radio frequency identification (RFID), etc. [10-12].

The paper presents design, simulation and fabrication of metamaterial based Luneburg lens for X-band using SLA technique. The paper is organized as follows; section II contains Luneburg lens design and fabrication, section III discusses the simulation with experimental setup. Finally, the conclusion is given in section IV.

2. Design and fabrication

Refractive index of an ideal Luneburg lens is as follows [1]

$$n(r) = \sqrt{2 - (r/R)^2}$$
(1)

Where R is the radius of designed lens, r is radial distance from origin. The refractive index profile is varied in step and realized by unit cell. The discrete refractive index profile ranging from 1 to 1.41 is formed within the lens. The air unit cell consists of polymer cubes of different sizes to achieve required refractive index profile. As nonmagnetic material is used in the fabrication, the effective permeability is taken as one. The effective permittivity is calculated by Burgmann effective medium theory (2).

$$\varepsilon_r = \varepsilon_P . (f) + \varepsilon_o(1-f) \qquad (2)$$

Where $\varepsilon_r$is the effective permittivity, ε_P is permittivity of polymer material and f is the polymer filling ratio.

The unit cell of dimension 5mm×5 mm×5mm is selected for design and the acrylonitrile butadiene styrene (ABS) is used as material. Polymer cubes are inserted in the air with thin support of ABS rods. The diameter of lens is 12 cm which is around 4.6 times of the wavelength and unit cell is 1/6 of wavelength for 10 GHz. A total of seven layers are used in the design and polymer cubes are placed in circle rings. At the center, polymer cube size is maximum (4.5mm), while it is minimum at the surface of the lens as shown in figure1.

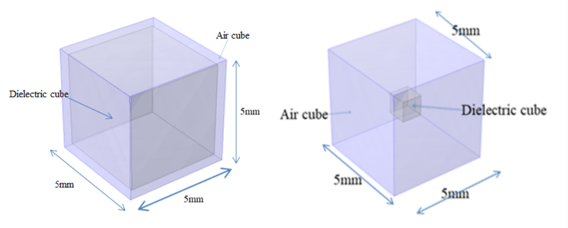


Figure 1.Unit cell dimensions, where grey part represents dielectric cube inserted in air box.

CAD model and fabricated lens is shown in the figure 2.

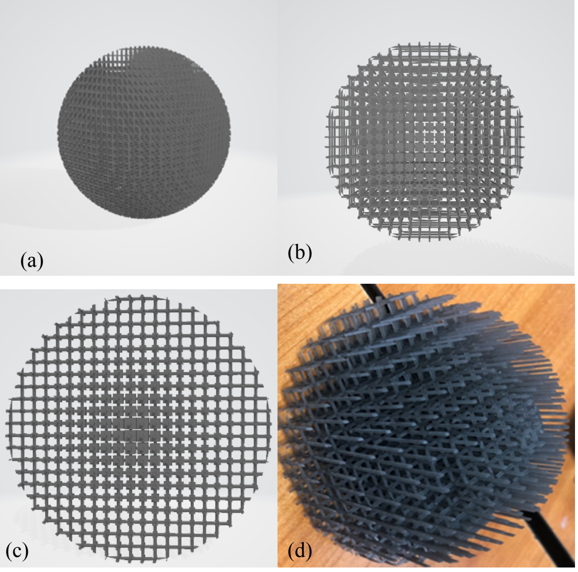


Figure 2. (a) 3D model of design lens, (b) Top view of model (c) sliced layer of model and (d) fabricated half of lens.

The dimension of support is such that its effective permittivity is around 1. Stereolithography (SLA) 3D printer Form1+ is used for fabrication of prototype and selected material is ABS. The dielectric constant and loss tangent of ABS is taken as 2.7 and 0.02 respectively from literature for X-band. The PreForm slicing software is used. Resolution of printer is around 25 microns. Two hemispheres are fabricated and later combined for achieving full lens.

3. Simulation studies and Experimental setup

The ray tracing of half lens with metal background is done by OSLO software and is shown in figure 3(a) . The ray tracing of ideal and metamaterial Luneburg lens is done on COMSOL multiphysics and is shown in figure 3(b) and figure 3(c) respectively. To understand the design parameters and evaluate the performance of the Luneburg lens, the 2D full wave simulation of model is done on COMSOL Multiphysics for frequency range 6 GHz to 14 GHz. The electric field distribution of incident wave is shown in comparison with ideal lens in figure 4 (a-b) at 10 GHz.

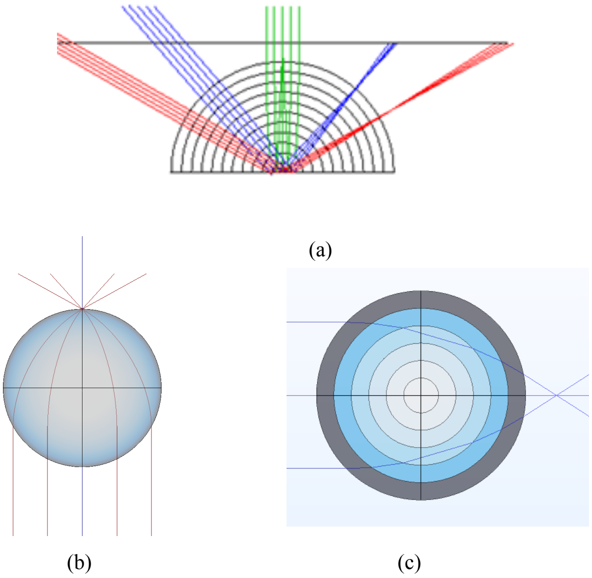


Figure 3 (a). Ray tracing of half of Luneburg lens with metal backing (b) ray tracing simulation of ideal lens , (c) .ray tracing simulation of metamaterial Luneburg lens.

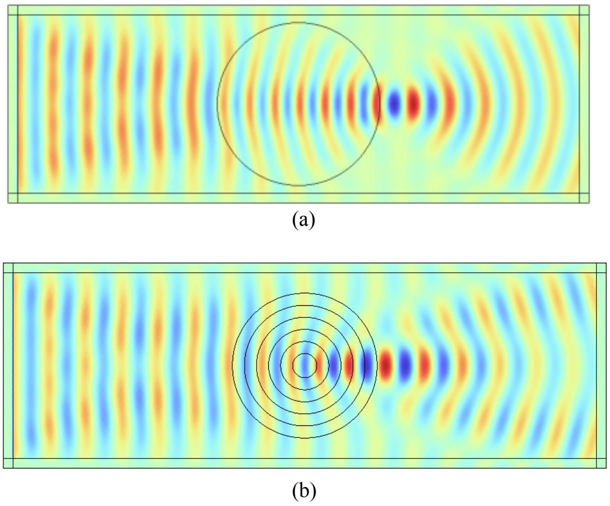
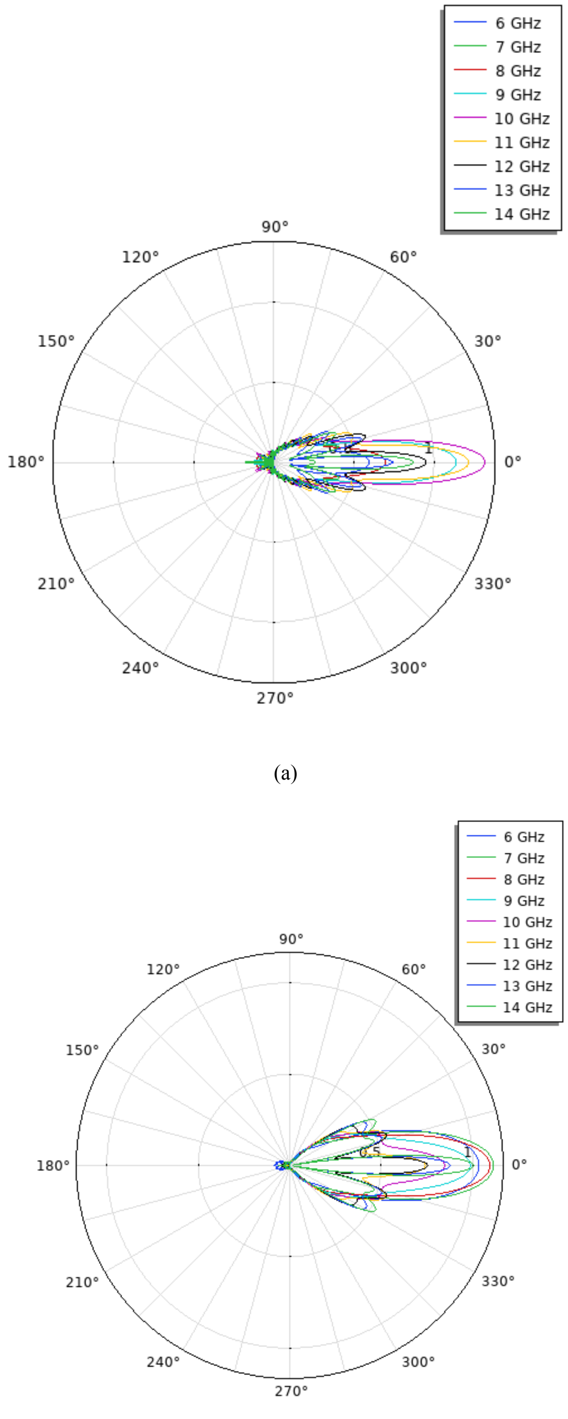


Figure 4. (a) The electric field response of ideal Luneburg lens.(b) The electric field response of metamaterial based Luneburg lens.

The results show that the incident plane wave passing through the device is focused into a finite spot instead of a geometrical point and the convergence of spherical wave-front is satisfactorily achieved by designed lens. There is no geometrical aberration in ideal Luneburg lens. The far field response is shown in figure 5.

From Fig.5, it is observed that a slight but noticeable difference is present between the far-field simulated profiles of ideal and metamaterial Luneburg lens. This difference can be attributed to the non-ideal GRIN profile of the metamaterial lens.



(a)

(b)

Figure 5. (a-b) Far-field pattern of simulated ideal and metamaterial Luneburg lens respectively.

For the experiment, Luneburg lens placed between X-band waveguide adaptor. The distance between waveguide adapters and lens surface is adjusted for impedance matching and is assessed to be 9 cm from lens surface. The lens antenna radiation pattern is measured at 10 GHz using a vector network analyzer. The experimental results show 5 dB gains. The measured values are lower than simulated one that may be due to absence of anechoic chamber and material losses.

4. Conclusion

Metamaterials based 3D Luneburg lens has been designed in this paper. The effective medium theory has been utilised to derive the constitutive parameters for the Luneburg lens. Lens with diameter of 12 cm has been taken and simulated for 6 to 14 GHz. The electric field response is recorded and compared with ideal GRIN lens . The designed lens show good response for X-band. In addition, ray tracing simulation for the analysis of lens performance has been done. By employing SLA technique the design has been fabricated.

6. References

1. R. K. Lilneburg, The Mathematical Theory of Optics, Los Angeles, CA, Univ. California Press, 1944.
2. P. Bantavis, C. Garcia Gonzalez, R. Sauleau, G. Goussetis, S. Tubau, and H. Legay,"Broadband graded index Gutman lens with a wide field of view utilizing artificial dielectrics: a design methodology," *Opt. Express* 28, 11, May 2020, pp.14648-14661, doi:10.1364/OE.389887.
3. A. J. Emerson and A. J. Cuming, "Stepped-index Luneburg lenses: antennas and reflective devices," Electron. Design, 1960.
4. N. Engheta, R. W. Ziolkowski, “Electromagnetic Metamaterials: Physics and Engineering Explorations,” *Wiley IEEE Press*, 2006.
5. L. Xue and V. F. Fusco, “Printed holey plate Luneburg lens,” *Microw. Opt. Technol. Lett*., 50, 20, December, 2007, pp.378–380, doi:10.1002/mop.23087.
6. K. Sato and H. Ujiie, “A plate luneberg lens with the permittivity distribution controlled by hole density,” *Electro. Commun. Jpn*., 85, 23, April, 2002, pp. 1–12, doi:10.1002/ecja.1120.
7. GUO Jie, YIN Hongcheng, MAN Liang”Review of controllable method of electromagnetic scattering characteristics of passive scattering elements”, *Systems Engineering and Electronics,* 41, 4, April, 2019, pp.716-723, doi:10.3969/j.issn.1001-506X.2019.04.03.
8. UO Jie, FENG Xuejian, YIN Hongcheng, LI Xin,” RCS Frequency Response Analysis of Luneberg Lens Reflector Based on Dielectric Loss*”, Procedia*

Computer Science, 187, 12, June, 2021,pp. 353-358,doi:10.1016/j.procs.2021.04.073.

9. M. D'Auria, W. J. Otter, J. Hazell, B. T. W. Gillatt, C. Long-Collins, N. M. Ridler, and S. Lucyszyn, "3-D printed metal-pipe rectangular waveguides," *IEEE Trans. Compon., Packag. Manuf. Technol.*, 5, 9, September, 2015, pp. 1339–1349,doi:10.1109/ TCPMT.2015.2462130.

10. M. Liang, W. Ng, K. Chang, K. Gbele, M. E. Gehm and H. Xin, "A 3-D Luneburg Lens Antenna Fabricated by Polymer Jetting Rapid Prototyping," *IEEE Transactions on Antennas and Propagation*, 62, 4, April 2014, pp. 1799-1807, doi: 10.1109/ TAP.2013.2297165.

11. C. Fan, et al, "A Wideband and Low-Profile Discrete Dielectric Lens Using 3-D Printing Technology," IEEE *Trans. Antennas Propag.*, 66, 10, October, 2018, pp. 5160–5169, doi: 10.1109/ TAP.2018.2862358.

12. B. Fuchs, R.Golubovic, A.K. Skrivervik, and Juan R. Mosig, "Spherical lens antenna designs with particle swarm optimization," *Microwave and Optical Techn. Lett.*, 52,7, July, 2010, pp. 1655–1659, doi: 10.1002/ mop.