An X-Band Luneburg Lens Antenna Fabricated by Rapid Prototyping Technology

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Abstract — **In this paper, a 3-D Luneburg Lens has been designed, fabricated and characterized. Refractive index control of the lens is based on the mixing ratio of air voids and a polymer. The 12 cm ($4\lambda_0$ at 10 GHz) diameter lens is designed to work at X-band. The effective permittivity of the unit cell is estimated by effective medium theory and calculated by the finite-element simulation software Ansoft HFSS. Fabrication is implemented by a polymer jetting rapid prototyping method. In the measurement, the lens antenna is fed by an X-band waveguide. The half-power beam width of the antenna is 14 degrees and no obvious side lobe is found in the measurement above the noise floor.**

Index Terms — **Luneburg Lens, Lens Antenna, Gradient Index, Rapid Prototyping.**

INTRODUCTION

A Luneburg Lens is a well-known device for wide angle radiation scanning because of its broadband behavior, high gain and the ability to form multiple beams. Every point on the surface of an ideal Luneburg Lens is the focal point of a plane wave incident from the opposite side. Usually the permittivity distribution of a spherical Luneburg Lens is given by Equation (1):

$$\varepsilon_r = 2-(r/R)^2 \qquad (1)$$

where R is the radius of the lens and r is the distance from the point to the center of the sphere. In reality, to realize the gradient permittivity, the inhomogeneous lens is usually divided into a finite number of concentric shells, with each shell fabricated using a homogeneous material and then assembled together [1-2]. Other methods of building the Luneburg lens using materials with variable effective dielectric constant have also been reported, including drilling holes and changing the thickness [3], using complementary metamaterials [4], and controlling the pattern on a printed circuit board [5]. However, these methods are mostly used for building 2-D Luneburg Lens because of either intrinsic or fabrication limitations. Moreover, the conventional method for building a spherical Luneburg Lens are time consuming because each part needs to be fabricated separately and assembled carefully.

In this paper, a continuous 3-D Luneburg Lens is designed, fabricated and characterized for X-band operation. The gradient permittivity is realized by the filling ratio of a polymer used in a polymer-jetting rapid prototyping technique. The effective permittivity of each unit cell is designed independently based on its distance to the center of the sphere. The fabrication process using this polymer jetting rapid prototyping technique is convenient, fast and inexpensive. Measurement shows that the half-power beam width of the $4\lambda_0$ diameter lens is 14 degrees at 10 GHz, which agrees with design simulation well.

II. POLYMER JETTING RAPID PROTOTYPING

The polymer jetting rapid prototyping technique used here allows fast fabrication of polymer components with arbitrary shapes and complexity [6]. A commercial rapid prototyping machine Objet Eden 350 is employed to fabricate the Luneburg Lens. With this machine, the fabrication process is relatively straightforward. First, we design and analyze the desired Luneburg Lens structure in an electromagnetic simulation program such as HFSS or CST. After the design is finished, the resulting 3-D structure is exported into a CAD program and converted into a series of layered slices, with each slice representing a 16 μm thick region of the designed model. The slice description is composed of two different materials, the model material and the support material. The model material is assigned to regions that are actually the desired objects, and the support material is to provide a surface on which the next slice is constructed and can be eliminated later to provide air voids. The data describing the slices are sent to the prototyping machine one by one. Once the data for each slice is received, a series of print heads, just like the print head of an ink-jet printer, deposits a thin layer of polymer made of two different ultraviolet-curable materials onto the construction stage. The model material regions of the slice receive an uncured acrylic polymer while the support material regions receive an uncured water-soluble polymer. Then both of the materials are immediately cured by the ultraviolet lamps on the print head. After one layer is completed, the construction stage is lowered by 16 μm, and then the next layer is printed on top. After the entire structure is finished, the water-soluble support material is washed away using a high pressure water spray leaving just the model material in the designed region. Construction of this Luneburg lens structure using this system is fast and inexpensive.

978-1-61284-757-3/11/$26.00 C2011 IEEE

III. LUNEBURG LENS DESIGN

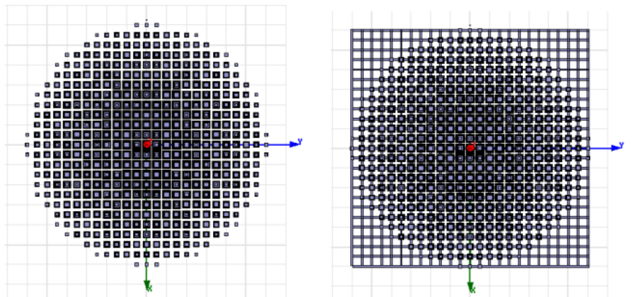


Fig. 1. The front view of the Luneburg Lens design. Left picture is the discrete polymer cubes with different size used to control the dielectric constant of the lens. Right picture includes the thin rods used to support the whole structure together with the cubes.

The Luneburg Lens is designed to be composed of discrete polymer cubes with different size as shown in Fig. 1. This figure is the front view of the lens. The whole structure is mechanically supported by thin rods that go through each of the unit cell and connect all the discrete cubes together. The dimension of these rods is very small so that they have negligible impact on the EM properties of the lens structure. The variable dielectric constant is controlled by the filling ratio of polymer in each unit cell. To achieve the permittivity distribution given by Equation (1), the filling ratio should be maximal at the center of the lens, gradually decreasing with the radius and finally reaches zero at the surface of the lens. The relative permittivity of the polymer used in the prototyping machine is measured to be 2.7. So it is easy to realize the desired variable relative dielectric constant from 2 to1 by changing the filling ratio.

This lens is designed with a 12 cm ($4\lambda_0$ for 10 GHz) diameter to work at X-band. The discrete unit cell size is 5 x 5 x 5 mm^3, which is 1/6 of the wavelength in free space at 10 GHz. Each unit cell is a polymer box in the center with air voids around it. Because the effective permittivity of the unit cell is not perfect linear with the filling ratio as the simple effective medium theory would predict, we cannot just use the approximated average permittivity as the effective permittivity to design the Luneburg Lens. In order to determine a more accurate relationship between the effective permittivity and the box size (or, the filling ratio) in the unit cell, finite-element simulation software Ansoft HFSS is applied to simulate the unit cell and optimize the design.

The effective permittivity simulation setup is shown in Fig. 2. A polymer slice made up of 12 x 12 x 6 unit cells is placed in a waveguide. All the unit cells have the same box size of 5 mm. From the S parameter of the waveguide, we can extract the effective permittivity of the unit cell at different box size from 0 to 5 mm. The results are shown in Table I.

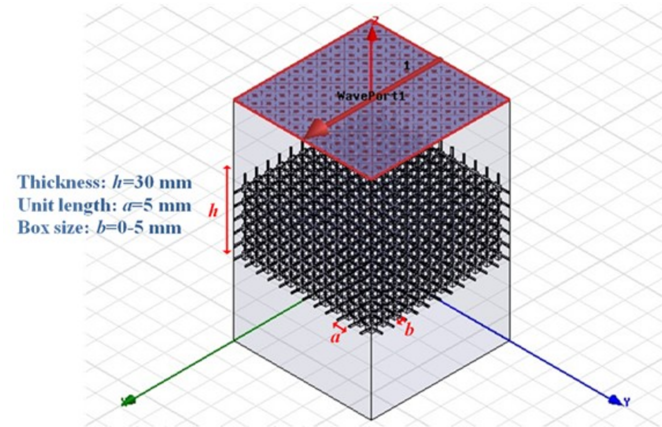


Fig. 2. The effective permittivity simulation setup, in which h is the thickness of the unit cell slice, a is the length of a unit cell, b is the size of box.

Also, the approximate effective permittivity is calculated using the filling ratio from Equation (2):

$$\varepsilon_r = \varepsilon_p \cdot (f) + \varepsilon_0 \cdot (1 - f) \qquad (2)$$

in which ε_p is the permittivity of the polymer box and f is the filling ratio. It can be seen that the permittivity extracted from the HFSS simulation and calculated from the filling ratio agree well when the box size is less than 2 mm, but differs for larger values. This is because the effective permittivity of the unit cell is not strictly linear in the filling ratio. In order to calculate the required box size for any desired permittivity, an exponential fit was applied. In Fig. 3, the black curve is the extracted permittivity from HFSS simulation; the red curve is the exponential fitting of the extracted results; the blue curve is the permittivity calculated by Equation (2). Then in the lens design, the box size can be calculated to obtain desired permittivity using fitted function:

TABLE I

COMPARISON OF DIELECTRIC CONSTANT (ANALYSIS VS. SIMULATION)

Box size (mm)	0.5	2	2.5	3	3.5	4	4.25	4.5	4.75	5
ε_r(extraction)	1.013	1.103	1.1735	1.274	1.473	1.752	1.9	2.1	2.37	2.7
Tanδ	0.003	0.004	0.006	0.009	0.013	0.0176	0.02	0.022	0.0261	0.03
Filling ratio	0.001	0.0588	0.1148	0.1984	0.343	0.512	0.6141	0.729	0.8574	1
ε_r(filling ratio)	1.0017	1.1	1.1952	1.3372	1.5831	1.8704	2.044	2.239	2.4575	2.7

$$b = 5.5593 - 590974e^{-\varepsilon_r/0.07958} - 9.54823e^{-\varepsilon_r/0.95537} \quad (3)$$

in which b is the box size and ε_r is the desired permittivity.

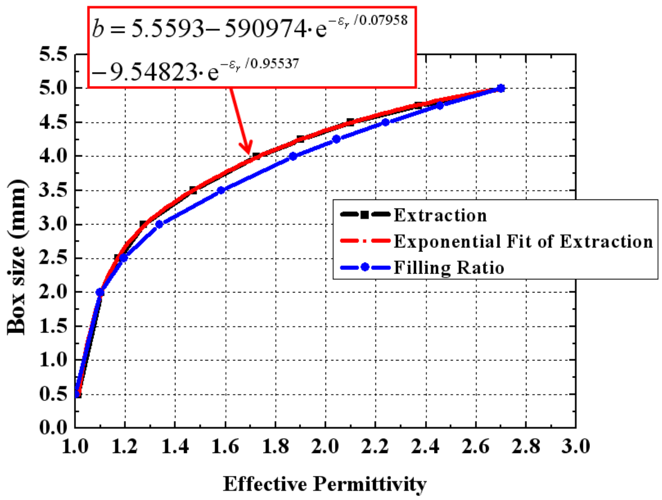


Fig. 3. The effective permittivity of unit cell with different box size. The black curve is the extracted data from HFSS simulation, the red curve is the exponential fit of the extraction data. The blue curve is the approximate permittivity calculated from the filling ratio.

IV. HFSS Simulation of Luneburg Lens

After the unit cell design is completed using the fitting curve in Fig. 3, a Luneburg lens is input into the HFSS software with the effective permittivity determined by its distance to the center using Equation (1). The 12 cm diameter lens is composed of 7497 boxes (or unit cells) with different sizes. The structure of the lens is shown in Fig. 4. The permittivity of the model region is set to 2.7, and the loss tangent is set to be 0.03. A dipole antenna is placed on the surface of the lens as the excitation; the H plane is the XY plane. The simulated far field pattern in the XY plane is shown in Fig. 5.

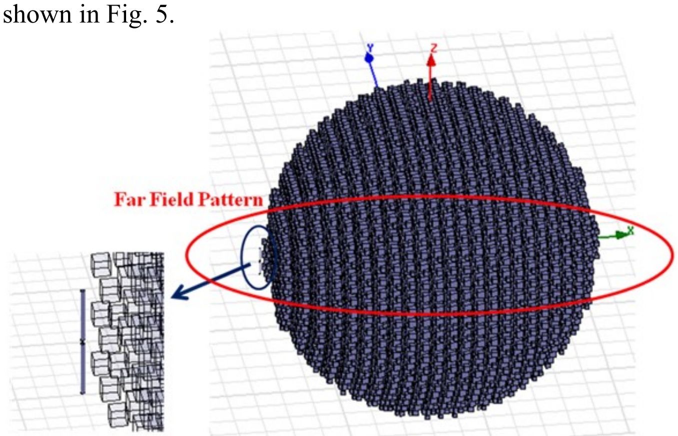


Fig. 4. Simulation setup of the Luneburg Lens in HFSS. The excitation is a dipole antenna placed on the surface of the lens (see inset).From Fig. 5, we can see that the simulated gain of our Luneburg Lens antenna is 17.1 dB and the H-plane half-power beam width of the antenna is 13 degrees.

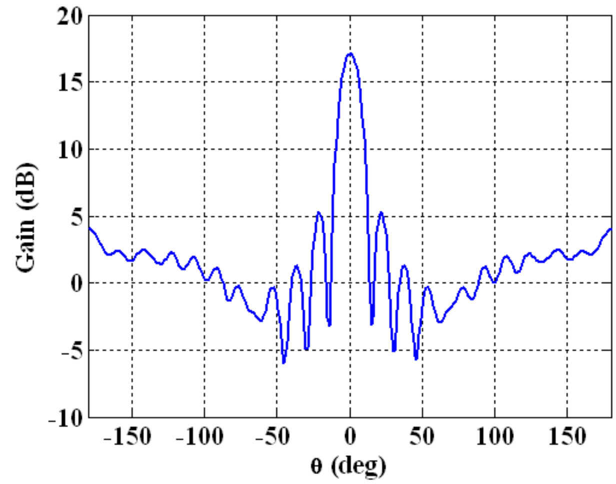
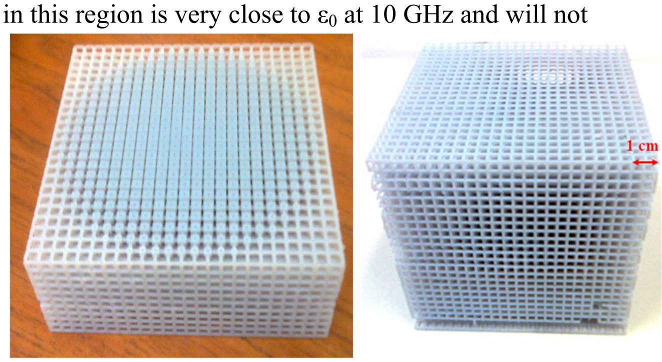


Fig. 5. Simulated the H-plane far field pattern of the Luneburg Lens in Fig. 4 at 10 GHz.

V. Fabrication And Experiment

The Luneburg Lens is fabricated using the polymer jetting rapid prototyping technique described previously. The lens is printed slice by slice with model material and support material. The model material region includes all the cubes and the thin rods used to support the whole structure, and the support material region is all the rest space around the model material. After the structure is finished, a high pressure water spray is used to wash the water-soluble support material away and just leaving the model material in the designed region.

The photo of the fabricated lens is shown in Fig. 6. Left picture is the cross-section cut through the center of the lens. It can be seen that the box size is larger in the center and decreases to zero at the surface of the lens. The posts outside the lens are just for the convenience of mounting the lens on the measurement stage. As their volumes are very small compared to the unit cell size, the effective dielectric constant in this region is very close to ε_0 at 10 GHz and will not



(a) (b)

Fig. 6. The photo of the Luneburg lens: (a) cross-section cut from the center of the lens. (b) the entire lens.

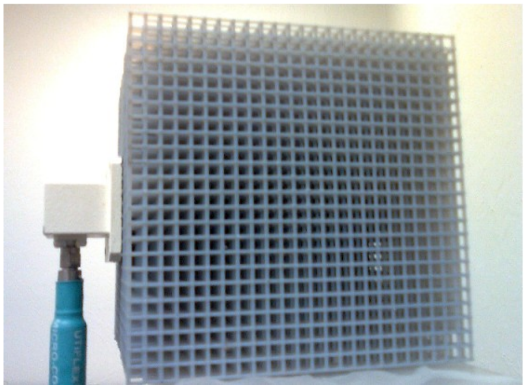


Fig. 7. Experiment setup, the Luneburg lens is fed by an X band waveguide mounted adjacent to the surface of the Luneburg lens.

significantly influence the electromagnetic properties of the lens.

To feed the Luneburg lens, an X band waveguide is mounted adjacent to the surface of the lens as shown in Fig. 7. The lens antenna radiation patterns are measured using a vector network analyzer. A standard gain horn antenna is used to calibrate the Luneburg lens gain. The measured far field pattern of the antenna at 10 GHz is show in Fig. 8. The gain of the Luneburg Lens is 18 dB and the half-power beam width is 14 degrees, agreeing very well with simulation results. No obvious side lobe is observed above the noise floor.

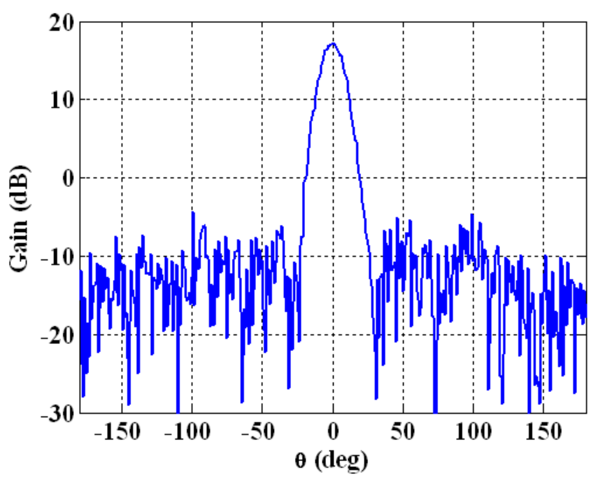


Fig. 8. Measured radiation pattern of the Luneburg lens at 10 GHz.

IV. Conclusion

In this paper, an efficient way to design and fabricate a spherical lens with continuous Luneburg index distribution was proposed and demonstrated. The diameter of the lens is 12 cm ($4\lambda_0$ at 10 GHz), with a unit cell size of 5 mm. Measurement show that the gain of this lens antenna is 18 dB, half-power beam width is 14 degrees and no obvious side lobe is found above the noise floor. Compared to traditional Luneburg lens, this 3-D Luneburg lens can be fabricated with lower cost and the fabrication process is more convenient and faster using the rapid prototyping technique.

Acknowledgement

This work was supported in part by the National Science Foundation under Awards 0823864 and 0925220, and the state of Arizona under TRIF.

References

[1] L. C. Gunderson and G. T. Holmes, "Microwave Luneburg Lens," Applied Optics, vol. 7, no. 5, pp. 801-804, May 1958.

[2] B. Fuchs, O. Lafond, S. Palud, L. Le Coq, M. Himdi, M. C. Buck, and S. Rondineau, "Comparative Design and Analysis of Luneburg and Half Maxwell Fish-Eye Lens Antennas," IEEE Trans. Antennas & Propagation, vol. 56, no. 9, pp. 3058-3062, September 2008.

[3] L. Xue and V.F. Fusco, "24 GHz automotive radar planar Luneburg lens," IET Microw. Antennas Propag., vol. 1, no. 3, pp. 624–628, 2007

[4] Q. Cheng, H. F. Ma, and T. J. Cui, "Broadband planar Luneburg lens based on complementary metamaterials," Appl. Phys. Lett., 95, 2009

[5] C. Pfeiffer and A. Grbic, "A Printed, Broadband Luneburg Lens Antenna," IEEE Trans. Antennas & Propagation, vol. 58, no. 9, pp. 3055-3059, September 2010.

[6] Z. Wu, J. Kinast, M. E. Gehm, and H. Xin, "Rapid and inexpensive fabrication of terahertz electromagnetic bandgap structures," Optics Express, vol. 16, no. 21, pp. 16442-16451, Oct. 2008