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Citation: Appl. Phys. Lett. 102, 074103 (2013); doi: 10.1063/1.4793206
View online: http://dx.doi.org/10.1063/1.4793206
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v102/i7
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Broadband flattened Luneburg lens with ultra-wide angle based on a liquid medium

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(Received 14 January 2013; accepted 7 February 2013; published online 19 February 2013)

A two-dimensional flattened Luneburg lens with an ultra-wide viewing angle has been realized based on a liquid medium approach in our present work. A field-of-view angle up to 180° is achieved over the microwave regime. The transformed lens is realized by using a low-loss liquid medium and a large variation of refractive index from 1 to 4.18 is achieved. The non-resonant property of the liquid ensures a broadband and low-loss performance of the lens from 12.4 GHz to 18 GHz. The high directivity and relatively low loss of the proposed lens were demonstrated by simulation and experimental results. © 2013 American Institute of Physics.

doi:10.1063/1.4793206

Since the Luneburg lens was put forward in 1944,1 it has been extensively studied.2–11 This magic aberration-free lens possesses a gradient index (GRIN) profile described by the equation

\[ n(r) = \left( \frac{2}{\epsilon_0} \frac{r^2}{R^2} \right)^{1/2}, \]

where \( r \) is the distance from the point inside the lens to the center of the lens and \( R \) is the radius of the sphere.2 The perfect focusing ability of the Luneburg lens has aroused particular interest in the field of antennas and telecommunication. However, the difficulty of manufacturing and its spherically focal surface, which cannot be well matched to the planar feeding source or detector array, has significant potential advantages over conventional lenses, it is far less prevalent in practical applications due to the difficulty of manufacturing and its spherically focal surface, which cannot be well matched to the planar feeding source or detector array.

In recent years, the development of transformation optics (TO) theory14–17 provides a means to modify the traditional Luneburg lens by flattening the spherical surface while keeping the nature of the lens unchanged.4,7,12 The flattened lens, possessing a plane surface, can focus the incoming collimated rays from different incident angles to its flattened back surface. Therefore, the practicality of the lens could be greatly improved. Nevertheless, the fabrication challenge of the required GRIN materials is still an important restriction of the Luneburg lens. Over the past few years, investigations have been carried out to realize GRIN profiles using artificial metamaterials, which could offer a wide range of material properties.18–21 Various implementation approaches have been investigated to realize the transformed Luneburg lens by using metamaterials.6,7,22 Recently, a three-dimensional (3D) transformed lens has been achieved by drilling holes in dielectric plates.6 However, the field-of-view of the previous proposed flattened lens is less than 180°, which cannot satisfy the needs in the telecommunication and antenna fields where a full field-of-view is pursued. A flattened Luneburg lens with extreme-angle was described by Kundtz and Smith.7 In that Letter, the lens was designed with metamaterials, which needed a complex implementation process and had serious limitation in bandwidth.13

In this letter, we presented a simple and effective way to realize flattened Luneburg lens with an ultra-wide field-of-view based on a liquid medium approach. The two-dimensional (2D) lens, realized with non-resonant liquid medium, showed a broadband and low-loss property from 12.4 GHz to 18 GHz (Ku-band). An extreme beam-deflection angle up to 90° was achieved. By adjusting the composition of the liquids, a wide range of refractive index from 1 to 4.18 was realized in the implementation of the lens. High directivity and low-loss performance of the lens was demonstrated by simulations and experiments.

The design of the flattened Luneburg lens7 was based on the TO theory and the recently developed quasi-conformal mapping (QCM) theory.23,24 It has been proved that the QCM technique may minimize the anisotropy in a 2D transformation,23 implying that the lens could be implemented with isotropic dielectric materials. This approach ensures a broadband property and is much easier to realize.6,7 To simplify the design process, the area where the refractive index was less than 1 was replaced with the free space, which possessed a refractive index equal to 1.7 The dielectric constant profile after the approximation is shown in Fig. 1(a). It shows that the dielectric constant of the transformed lens varies from 1 to 17.5. The relation between the refractive index and the dielectric constant for nonmagnetic materials is \( n = \sqrt{\varepsilon_r} \), where \( n \) and \( \varepsilon_r \) are the refractive index and the dielectric constant of the material, respectively. So the refractive index of the profile changes between 1 and 4.18. Discretization process has been applied to the profile to put the design into practice. To realize the large variation of refractive index, we have adopted a liquid medium approach.25 A framework with very small wall thickness has been introduced, which will be injected with liquid medium with different dielectric constants in its unit shells. Theoretically speaking, the thinner the wall of the framework and the more finely the profile is discretized, the better the performance of the lens. But considering the fabrication issue, we finally divided the lens

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into 17 unit shells and the wall thickness of the framework is 0.4 mm. The discretized profile is illustrated in Fig. 1(b). From the innermost shell to the second to the outermost shell, the dielectric constant varies from 17.5 to 2.5 with a decrement of 1. The outermost shell is empty to ensure the impedance match with air.

To study the performance of the proposed transformed Luneburg lens, simulation work was carried out at the microwave frequency from 12.4 GHz to 18 GHz using commercial software (MICROWAVE STUDIO, CST). A Ku-band rectangular waveguide (aperture size: 17 x 8.3 x 9.3 mm) was employed as a feeding source emitter which could be placed at different positions on the base plan of the lens. Near-field patterns of the scattering field were calculated when the emitter waveguide was located at three different positions at the frequency of 15 GHz and the results are plotted in Figs. 2(a)–2(c). The simulation results show that the electromagnetic (EM) point sources emitted from different positions of the back surface of the lens are turned into approximate plane waves propagating in different directions. A maximum deflection angle up to 90° was achieved when the emitting source was placed at the edge of the lens (x = −5 cm), as shown in Fig. 2(c). However, when the feed is placed at the edge of the lens, the performance of the lens is not as good as the previous 2 cases (shown in Fig. 2(a) and 2(b)) because the portion with refractive index less than 1 was replaced with the free space. This approximation could have a negative influence on the performance of the lens for the large incident angles. The small reflection and interference effect shown in the figures resulted from the wave impedance mismatch caused by the framework. Figures 2(d)–2(f) show the near-field patterns of the scattering field of the lens for the frequency of 12.4 GHz (Fig. 2(d)), 15 GHz (Fig. 2(e)), and 18 GHz (Fig. 2(f)) when the feed is placed at x = −2 cm. As shown in the figures, the lens performs approximately the same way when the frequency of the incident EM wave increases, which demonstrates the broadband property of the lens.

The framework of the lens was fabricated by Stereolithography (SPS450B, Shaanxi Hengtong Intelligent Machine Co., Ltd) using the photo-curable resin whose dielectric constant is 3. It has a wall thickness of 0.4 mm. The photograph of the fabricated framework is illustrated in Fig. 1(c). As the figure shows, the 2D lens has a height of h = 100 mm and a maximum aperture of d = 142 mm. It was fabricated with a grooved lid with a width of t = 16 mm to prevent the liquid spilling and to permit the injection of liquid. Figure 1(d) shows the internal structure of the framework. The thickness of the lens was uniformly 10 mm along the z axis.

**FIG. 1.** Quasi-conformal mapping of the 2D flattened lens and the fabricated lens. (a) The dielectric constant distribution of the transformed lens after the QCM transformation. (b) Discretization of the dielectric constant profile. (c) The photograph of the fabricated framework of the transformed lens, in which h = 100 mm, d = 142 mm, and t = 16 mm. The wall thickness of the framework is 0.4 mm. (d) The internal structure of the framework of the lens.

**FIG. 2.** Simulated near-field distribution of the transformed lens. (a)–(c) The scattering patterns at 15 GHz when the feed is placed at x = 0 cm, −2 cm and −5 cm, respectively. (d)–(f) The scattering patterns of the lens at 12.4 GHz, 15 GHz, and 18 GHz when the feed is placed at x = −2 cm.

**FIG. 3.** Relations between the dielectric constant of the liquid mixture and the composition of the acetonitrile at different frequencies, and the dielectric loss tangent of mixtures between 12 GHz and 18 GHz (inset).

**FIG. 4.** Photograph of the measurement system. The mats are made of absorbent materials to prevent the external EM interference.
The variation of the refractive index was achieved by mixing two liquids with low and high refractive indexes, respectively. The effective refractive index of the medium mixture was in the range of the low and high refractive index liquids. Two non-dispersive and low-loss liquids, benzene and acetonitrile, were chosen in the practical execution, which had a relatively large difference in dielectric constant. The dielectric constant and loss tangent of the liquids were measured using the coaxial probe technique with a dielectric probe kit (Agilent, 85070E) and a network analyzer (Agilent, E8363B). The relationship between the effective dielectric constant and the composition of the liquid medium was available according to the curves in Fig. 3. As shown in the figure, the available effective dielectric constant of the medium mixture ranges from 2.5 to 40 and keeps relatively stable over the microwave frequency. It means the refractive index could be precisely controlled between 1.58 and 6.32 and was sufficient to meet the requirement of the proposed lens. As shown in the inset of Fig. 3, the loss tangent of the liquid mixture increases slightly with the molar concentration of acetonitrile increasing, but it is considerably small (less than 0.1) in a frequency range of 12–18 GHz.

The liquid planar Luneburg lens was experimentally tested in a microwave anechoic chamber as shown in Fig. 4. A pair of Ku-band standard rectangular waveguides was used as the feed and receiver, which were connected to a vector network analyzer to measure the radiation field. The receiver waveguide could be moved to different azimuth angles and the emitter waveguide was placed on the base plan of the liquid lens. The upper and lower surfaces of the lens were covered by aluminum plates to ensure a correct mode of the EM wave. The $S_{21}$ parameter was recorded as a function of azimuth angle from 0° to 180° at the microwave frequency when the feed was placed at different positions along the $x$ axis. Figures 5(a)–5(d) indicate the measurement results for four different cases with the feeding waveguide located at 4 different places on the base plan of the lens. The figures show a high directivity property of the lens over a broad bandwidth from 12.4 GHz to 18 GHz. As shown in Fig. 5(a), when the feed is placed at the center axis of the lens, the EM wave is not deflected. Figure 5(d) shows that a maximum deflection angle of 180° is achieved when the feed is placed at the edge of the lens ($x = -5$ cm). But as shown in the figures, the beam-deflection angle is not exactly the same as that of the simulation. The reason is that the gradient index of each shell was fixed as a constant in the simulation, while the refractive index of the liquid medium used in the experiment fluctuated slightly with the frequency. The resin framework also had an effect on the performance of the lens as it might cause the wave impedance mismatch. Efforts will be made on further reducing the wall thickness of the lens.

Compared with the metamaterial implementation, which was presented by Kundtz and Smith, the liquid medium approach is more promising for practical applications. In the previous work, the particular implementation of the metamaterial approach was produced by periodic repetition of metallic inclusions, which limited the bandwidth of the lens. By contrast, the liquid medium approach proposed in this letter could ensure a broadband property as it adopted non-resonant liquid medium. What is more, the latter approach was much easier to realize than the former one.

Here, it should be noted that this study has been primarily concerned with the 2D case. Our future work would be focused on further improving the directivity of the liquid lens and putting the application of this design in the 3D case. The proposed liquid lens was implemented with non-magnetic liquid medium, which also introduced the reflection and interference. Magnetic fluid materials like ferrofluids are promising candidates to solve this problem by improving the impedance mismatch with free space.

In conclusion, we have realized a transformed lens in the microwave regime based on a liquid medium approach. An ultra-wide field-of-view up to 180° has been achieved over a broad bandwidth frequency from 12.4 GHz to 18 GHz. The 2D lens has a large refractive index variation from 1 to 4.18, which was achieved by mixing two low-loss organic liquids. The performance of the lens was demonstrated by both simulation and experimental results. As all
the materials needed in the process are cheap and easily accessible, this approach proves to be a feasible way to promote the practical applications of the flattened Luneburg lens.

This work was supported by National Natural Science Foundation of China (No. 51105300), Ph.D. Program Foundation of Ministry of Education of China (20110201120075), and the Fundamental Research Funds for the Central Universities of China.