Broadband gradient refractive index planar lens based on a compound liquid medium

Haoxue Han, Lingling Wu, Xiaoyong Tian, Dichen Li, Ming Yin et al.

Citation: J. Appl. Phys. 112, 114913 (2012); doi: 10.1063/1.4769344
View online: http://dx.doi.org/10.1063/1.4769344
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v112/i11
Published by the American Institute of Physics.

Related Articles
Cylindrical Fresnel lenses based on carbon nanotube forests
Optical cavity efficacy and lasing of focused ion beam milled GaN/InGaN micropillars
Tunable-focus liquid crystal Fresnel zone lens based on harmonic diffraction
Amplifying mirrors for terahertz plasmons
Laser surface micro-/nano-structuring by a simple transportable micro-sphere lens array

Additional information on J. Appl. Phys.
Journal Homepage: http://jap.aip.org/
Journal Information: http://jap.aip.org/about/about_the_journal
Top downloads: http://jap.aip.org/features/most_downloaded
Information for Authors: http://jap.aip.org/authors
Broadband gradient refractive index planar lens based on a compound liquid medium

Haoxue Han,a) Lingling Wu,a) Xiaoyong Tian,b) Dichen Li, Ming Yin, and Yu Wang
State Key Laboratory for Manufacturing Systems Engineering, Xi’an Jiaotong University, Xi’an 710049, China

(Received 19 April 2012; accepted 12 November 2012; published online 13 December 2012)

We have proposed a new method to achieve gradient refractive-index (GRIN) optics via a compound liquid medium. By adjusting the composition of the liquid medium, the refractive index of the compound liquid was tuned in a very broad range from 1.58 to 5.15. The liquid medium also exhibited weak frequency dependence. Based on these properties, we designed a liquid GRIN planar lens and experimentally demonstrated the feasibility of this approach. The beam deflection of the lens was controlled by adjusting the distribution of the refractive-index of the lens. By changing the composition of the compound liquids in different cells of the lens framework, different spatially varied refractive index profiles have been achieved. The proposed liquid planar lens has shown a good directive property at different receiving angles and demonstrated a broadband performance between 12 GHz and 15 GHz. This method results in a rapid and flexible realization of gradient refractive index structures by using liquid medium. © 2012 American Institute of Physics.

I. INTRODUCTION

Elaborate optical devices like the Maxwell fish-eye lens, the Luneburg lens, and the Eaton lens are based on spatially variable refractive index structure.1,2 With bulk solid materials, the establishment of a gradient refractive index profile involves complex fabrication processes such as microcoated dipcoating, field-assisted ion-exchange,3 or vapor deposition4,5 and the functionalities cannot be changed after the fabrication. Natural transparent solids possess inherently small positive refraction indexes, except for a few semiconductors and insulators, such as lead sulphide or strontium titanate, which exhibits a relatively high peak refractive index at mid- and far-infrared frequencies.6 It is confirmed recently that a single-atomic-layered graphene can be used as a platform for planar gradient-index lens, which can be applied to modulate the propagation of Surface plasmon polariton (SPP) waves.7 However, the approach is only demonstrated by simulation, and the experiments are still under investigation. Variable indices of refraction have also been achieved with metamaterials by deploying arrays of sub-wavelength conductors and insulators, such as lead sulphide or strontium titanate, which exhibits a relatively high peak refractive index at mid- and far-infrared frequencies.6 It is confirmed recently that a single-atomic-layered graphene can be used as a platform for planar gradient-index lens, which can be applied to modulate the propagation of Surface plasmon polariton (SPP) waves.7 However, the approach is only demonstrated by simulation, and the experiments are still under investigation. Variable indices of refraction have also been achieved with metamaterials by deploying arrays of sub-wavelength metallic units to obtain a precise tailoring of the index distribution based on the effective medium approximation (EMA).8,9 Although the refractive index of metamaterial is precisely controllable, the small range of index limits its application on transformation optics devices that require drastic variation in the refractive indices.10,11 Recently, a transformation lens for directional emission at microwave frequencies was experimentally realized based on the conformal mapping, and a large refractive index variation has been achieved by drilling subwavelength holes inhomogeneously in several kinds of dielectrics.12 But it is hard to get high-quality and wide beam at specific frequency. A broadband terahertz metamaterial with a maximum refractive index of 38.6 was also achieved,13 nevertheless, as its predecessors, the refractive indexes of the metamaterials were sensitive to the frequency of the incident electromagnetic waves, so they worked well only in a relatively narrow frequency band.14–16 As with liquid materials, a GRIN profile can be achieved by the diffusion of solute17 or heat18 in a microfluidic system. However, the index profile was restricted to the diffusion process and it was unrealistic to sustain the refractive index profile.

In this paper, we proposed a facile and rapid method to realize broadband GRIN optics based on a flexible compound liquid medium with an ultra-wide range of refractive index. The variable refractive index was achieved by blending liquids with different dielectric constants. By carefully adjusting the composition of the liquid medium, the effective dielectric constant can be precisely controlled in a very broad range while maintaining low loss. Besides, once the device framework is properly designed, there should be no specific restrictions on the index profile, enabling more design flexibility for variable refractive index optics.

II. COMPOUND LIQUID APPROACH

The variation of the refractive index was achieved by mixing liquids of different dielectric constants \( \varepsilon_r \). For the medium mixed by two liquids with low and high dielectric constant \( \varepsilon_r^{\text{low}} \) and \( \varepsilon_r^{\text{high}} \), respectively, the effective dielectric constant \( \varepsilon_r^{\text{eff}} \) of the compound medium mixture will be in the range of \( \varepsilon_r^{\text{low}} \leq \varepsilon_r^{\text{eff}} \leq \varepsilon_r^{\text{high}} \). Therefore, the effective refractive index \( n_r^{\text{eff}} \) of the mixture medium will be in the range of \( n_r^{\text{low}} \leq n_r^{\text{eff}} \leq n_r^{\text{high}} \) according to the relation between the refractive index and the dielectric constant for nonmagnetic materials: \( n = \sqrt{\varepsilon_r} \), where \( n_r^{\text{high}} \) and \( n_r^{\text{low}} \) were the high and low refractive index of the medium, respectively. Certain organic solvents were taken into consideration for their

---

a)H. Han and L. Wu contributed equally to this paper.
b)Author to whom correspondence should be addressed. Electronic mail: leoxyt@mail.xjtu.edu.cn.
non-dispersive dielectric properties and low-loss nature at microwave frequency. Their advantages also included high chemical and temperature stability. To simplify the realization process, we chose only two liquids with a relatively large difference in dielectric constant. The dielectric constant and loss tangent of the liquids were measured using the coaxial probe technique\textsuperscript{19} with a dielectric probe kit (Agilent, 85070 E) and a network analyzer (Agilent, E8363B).

After substantial measurements of different liquids, benzene was taken as the low dielectric constant medium and acetonitrile as the high one. As shown in Fig. 1, the measured results in the frequency range of 12 to 18 GHz indicated that the dielectric constant of benzene kept stable around 2.5 and that of acetonitrile around 40. Their dielectric constants also exhibited a weak frequency dependence which was essential to the broadband performance of gradient refractive index devices. The frequency responses of the dielectric constant for the compound liquid with different concentration of acetonitrile were plotted in Fig. 1. The dielectric constant of the compound liquid increased with the concentration of acetonitrile improving. It can also be observed that the dielectric constant of compound liquids varied slightly as the external electric field frequency changed between 12 GHz and 18 GHz. The dielectric loss was also considerably small, which provided the basis of the broadband and low-loss property of the device achieved with the compound liquid.

III. LIQUID LENS DESIGN

The deflection of a microwave beam can be observed when the beam was normally incident on the liquid planar lens with a certain profile of gradient refractive index. The deflection angle depended on the lens geometry and the index gradient.\textsuperscript{8} The design of the liquid lens was illustrated in Fig. 2. Electromagnetic wave was incident at the feed end of a metallic horn and was deflected when propagated through the liquid lens. The lens aperture and width were \( t \) and \( 2a \), respectively. The EM wave source was placed at a normal distance of \( a \) away from the geometric center of the lens. The refractive index of the liquid lens was given by Ma et al.\textsuperscript{20} as

\[
n(\theta, x) = n_0 - (x \sin \theta + \sqrt{a^2 + x^2} - a) / t,
\]

where \( \theta \) is the deflection angle between the emissive direction of the beam and \( y \) direction, \( n_0 \) is the refractive index at \( x = 0 \) and can be chosen arbitrarily to facilitate the realization of the refractive index using liquid medium along the lens. The refractive index only changes along the \( x \) direction. The beam deflection angle of the liquid lens is in principle determined only by \( \theta \). It is noteworthy that the profile of \( n \) can be controlled by \( n_0 \). \( n_0 \) should be properly chosen so that the minimum of \( n \) exceeds the refractive index of benzene, which is the minimum index achievable with the compound liquid.

In practical realization, the lens was designed with dimension of \( a = 125.4 \) mm and \( t = 60.8 \) mm. The lens had a resin framework fabricated by stereolithography (SPS450B, Institute of Advanced Manufacturing Technology, Xi’an Jiaotong University). The framework possessed a thickness of 0.4 mm to ensure the required mechanical strength against deformation. There were two ribs across the lens to reinforce the boundaries of the cells. Along the \( x \) direction, the lens was equally divided into 33 unit cells that will be infiltrated with compound liquids of different refractive index. The horn was designed with detachable upper and lower parts to facilitate the installation of the planar slab lens, as shown by the inset in Fig. 2. The thickness of the lens was uniformly 10 mm along the \( z \) axis.

The distributed refractive index \( n_r(x) \) in the lens for \( \theta = 0^\circ, 30^\circ, \) and \( 60^\circ \) was illustrated in correspondence with the composition of the compound liquids in Fig. 3. Each of the discrete value was the effective refractive index of the compound liquid in the corresponding cell along the lens as shown in Fig. 2. Here, \( n_0 = 2.4 \) was chosen for \( \theta = 0^\circ \), \( n_0 = 3.5 \) for \( \theta = 30^\circ \), and \( n_0 = 4.2 \) for \( \theta = 60^\circ \). For all deflection angles between 0° and 60°, the calculated refractive index ranged from 1.58 to 5.15, which corresponded to a range of dielectric constant from 2.5 to 26.5.

The available effective dielectric constant of the compound liquids ranged from 2.5 to 40, so it is sufficient to meet the requirement of the previously designed GRIN lens.
Specifically, the wide index range was superior to the maximum birefringence $\Delta n = 0.5$ in nematic liquid crystals which found its application in tunable metamaterials.\textsuperscript{21,22} Thus, the compound liquid approach may have great application potential in tunable materials.

So far, the relationship between the effective dielectric constant and the composition of the liquid medium was available according to the curves in Fig. 1. Thus, different refractive index profiles for various beam deflection angles were realized by infiltrating proper compound liquids in the corresponding cells of the lens according to Fig. 3. But it should be pointed out that the proposed liquid lens is statically tunable, this means that we have to change the liquid medium to achieve different beam-deflection performance.

With the development of our research work, we believe that a real-time tunable lens antenna can be achieved by an automatic control system to fulfill the filling process in the future.

**IV. EXPERIMENTAL SCHEME AND MEASUREMENT RESULTS**

The performance of the GRIN lens antenna was characterized in a microwave anechoic chamber. Two Ku-band standard rectangular waveguides were used as the transmitter and receiver, which were linked to a vector network analyzer to measure the radiation field. The receiver waveguide can be moved to different azimuth angles as shown in Fig. 4. The transmitter waveguide was inserted into the feed end of the horn at azimuth angle $\varphi$ of 180°. The $S_{21}$ parameter was recorded as a function of azimuth angle from $-160^\circ$ to 160° throughout the whole Ku band. Fig. 4 indicated the measurement results for four different cases: horn without lens, lens antenna with designed emissive direction of $\theta =$ 0°, 30°, and 60°, respectively. As shown in Fig. 5(a), the EM wave emitted only by the metallic horn had an uniform amplitude distribution between $\varphi = -80^\circ$ $\sim$ $80^\circ$. The measured results for the deflection angle at $\theta =$ 0°, 30°, and 60° were illustrated in Figs. 5(b)–5(d), respectively. But as shown in the figure, the beam-deflection results were not very perfect because in theoretical analysis, the gradient index of this proposed lens should vary continuously; however, in the practical design, discrete indices should be used, which brought the inaccuracy of the experimental results.

At the frequency of 12 GHz, the measured mainlobe directions agreed well with the designed emissive beam direction and the sidelobe levels remained under $-10$ dB. This indicated that the designed liquid lens had a relatively good directivity. But in the case of $\theta =$ 0°, multiple reflection and interference effects occurred at the lens boundary because of the wave impedance mismatch between the air and the non-magnetic liquid material. To solve this problem, magnetic fluid materials like ferrofluids are promising candidates to improve the impedance mismatch with free space with the real part of the permeability greater than unity. Nevertheless, the large imaginary part of permeability usually results in a significant energy loss of electromagnetic waves transmitting in the material, and possible solutions are now under investigation.\textsuperscript{23}

Fig. 6 illustrated the field pattern of the lens antenna with an emissive direction of 60° at the frequency of 12 GHz, 15 GHz, and 18 GHz, respectively. The measured mainlobe directions were all close to the theoretical position, thus demonstrating a broadband performance. What should be noted is that at the frequency of 18 GHz, the sidelobe amplitude increased to $-2$ dB because at such a wavelength, the liquid lens can no longer be considered as a homogeneous effective material. This structural inhomogeneity can be overcome by further increasing the number of cells in the lens to scale down cells dimension and improving the material continuity perceived by the electromagnetic wave.

The experiment results verified the design of the GRIN lens achieved by the compound liquid approach. The liquid planar lens has shown a good directive property at different receiving angles by adjusting the composition of the liquid medium. The lens also demonstrated a broadband performance. What should be noted is that at the frequency of 18 GHz, the sidelobe amplitude increased to $-2$ dB because at such a wavelength, the liquid lens can no longer be considered as a homogeneous effective material. This structural inhomogeneity can be overcome by further increasing the number of cells in the lens to scale down cells dimension and improving the material continuity perceived by the electromagnetic wave.

The experiment results verified the design of the GRIN lens achieved by the compound liquid approach. The liquid planar lens has shown a good directive property at different receiving angles by adjusting the composition of the liquid medium. The lens also demonstrated a broadband performance between 12 GHz and 15 GHz. In the present research, non-magnetic liquids were taken as the phase shifting medium of the lens. Although the non-magnetic nature will cause reflections at the boundary between the lens and the background medium due to wave impedance mismatch, our
experiments indicated that the wave trajectory inside the lens kept unchanged. Our future work would be focused on further improving the directivity of the liquid lens and introducing magnetic permeability greater than 1 in the liquid medium while maintaining the low loss property.

V. CONCLUSION

In conclusion, a broadband GRIN planar slab lens based on compound liquid was designed and experimentally realized in the microwave regime. A wide range of refractive index from 1.58 to 5.15 was achieved by adjusting the composition of the liquid medium. The relationship between the effective refractive index of the compound liquid and the composition of liquids was determined by experiments. Apart from the wide refractive-index advantage, the liquids also show a weak frequency dependence in the microwave regime, which is very important to the broadband property of the lens. Based on these properties, a beam deflection angle up to 60° was achieved by the liquid lens. The proposed compound liquid approach provided a flexible and easy-to-fabricate way to obtain distributed refractive indices structures, which may greatly facilitate and simplify the traditional fabrication process of GRIN planar lens. And the idea of using the compound liquid medium to achieve the broad range of refractive index and the profile of GRIN lens has been emphasized.

ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation of China (Nos. 51105300 and 50835007), Ph.D. Program Foundation of Ministry of Education of China (20090201110038, 20110201120075), and the Fundamental Research Funds for the Central Universities of China.


FIG. 5. Electromagnetic wave amplitude distribution of the device without (a) the GRIN lens and with the GRIN lens for the deflection angle of (b) $\theta = 0^\circ$, (c) $\theta = 30^\circ$, and (d) $\theta = 60^\circ$.

FIG. 6. Electromagnetic wave amplitude patterns of the lens antenna with a deflection angle of 60° at the frequency of 12 GHz, 15 GHz, and 18 GHz, respectively.

20 A. Minovich, D. N. Neshev, D. A. Powell, I. V. Shadrivov, and Y. S. Kivshar, Appl. Phys. Lett. 96, 193103 (2010).