Experimental verification of a broadband planar focusing antenna based on transformation optics

Zhong Lei Mei$^{1,2,3}$, Jing Bai$^1$ and Tie Jun Cui$^{2,3}$

1 School of Information Science and Engineering, Lanzhou University, Lanzhou 730000, People’s Republic of China
2 State Key Laboratory of Millimeter Waves, Department of Radio Engineering, Southeast University, Nanjing 210096, People’s Republic of China
E-mail: meizl@lzu.edu.cn and tjcui@seu.edu.cn

New Journal of Physics 13 (2011) 063028 (10pp)
Received 22 February 2011
Published 17 June 2011
Online at http://www.njp.org/
doi:10.1088/1367-2630/13/6/063028

Abstract. It is experimentally verified that a two-dimensional planar focusing antenna based on gradient-index metamaterials has a similar performance as that of its parabolic counterpart. The antenna is designed using quasi-conformal transformation optics, and is realized with non-resonant I-shaped metamaterial unit cells. It is shown that the antenna has a broad bandwidth and very low loss. Near-field distributions of the antenna are measured and far-field radiation patterns are calculated from the measured data, which have good agreement with the full-wave simulations. Using all-dielectric metamaterials, the design can be scaled down to find applications at optical frequencies.

Contents

1. Introduction 2
2. Antenna design 2
3. Results and discussions 5
4. Conclusions 9
Acknowledgments 9
References 10

$^3$ Authors to whom any correspondence should be addressed.
1. Introduction

In recent years, metamaterials have attracted considerable attention due to their interesting properties [1–3]. They are composed of periodic or pseudoperiodic sub-wavelength structures with electric and/or magnetic responses. The electromagnetic (EM) parameters of metamaterials can be artificially tailored with different unit-cell geometries and dimensions, rather than their intrinsically chemical components. Owing to such properties, they have a number of fantastic potential applications. The most remarkable example of these applications is invisibility cloaks designed with transformation optics (TO) [4–8], and other novel devices are possible too [9–14].

TO theory, together with metamaterial technology, has also been used in antenna design. Luo et al [15] designed a highly directive antenna, which can transform a large antenna into an equivalent one with a much smaller aperture. The transformation for a radiating source was also applied by Allen et al [16], and their design can achieve various antenna structures with good performances. Similar antennas were presented by Jiang et al [17] recently. One problem associated with general TO theory is that the resulting materials are always inhomogeneous and anisotropic (except for the cases with conformal mapping [18]), and may have singular-valued material parameters [19, 20]. The antenna designed will thus encounter some difficulties in practical implementation. To address the problem, TO theory based on quasi-conformal mapping (QCTO) was also proposed and successfully applied in various designs [6, 11, 14, 21, 22]. It was also been applied to plasmonic systems and satisfactory results were obtained [23–26].

In our previous work, a novel planar focusing antenna was designed with QCTO, which has a similar performance as that of a parabolic reflector and can be realized using PEC-backed GRIN materials [27]. A similar structure was also introduced by Tang et al [28] and was verified using the finite-difference time-domain method. The antenna is broadband in nature and can be scaled down to optical frequencies. In this paper, a prototype of the antenna is fabricated with I-shaped metamaterial unit cells. The near fields of the antenna are first measured in a two-dimensional (2D) near-field scanning apparatus and then the far-field radiation patterns are presented from the measured data. All the results are in good agreement with the numerical simulations.

2. Antenna design

Figure 1 shows the virtual (a) and physical (b) spaces concerning the antenna design. In the virtual space, the curved boundary represents a 2D parabolic reflector, expressed as \( \eta = 2.5(\xi - 0.2)^2 - 0.025 \). The aperture of the antenna is 0.2 m and the focal length is 0.075 m. Using a quasi-conformal mapping with slipping boundary conditions [6, 11, 13, 14, 21, 22], the quasi-rectangular region is transformed into a standard rectangle in the physical space. From the TO theory, we know that the resulting device, a PEC-backed metamaterial with a rectangular shape, will have the same electrical performance as that of the original parabolic reflector. For the detailed numerical calculation, see [27, 28]. In our design, TE mode (electric field normal to the transformation plane) is assumed; however, the same process also applies to TM mode. As we use QCTO, the anisotropy of the resulting materials is minimized; the anisotropy factor (a ratio reflecting the anisotropy, with 1 representing isotropic
Figure 1. Quasi-conformal mapping between the virtual (a) and the physical space (b). Green (horizontal) and red (vertical) lines show the corresponding mapping between the two spaces. (c) The refractive index distribution of the complete planar antenna region in which some material parameters are less than 1. Region II enclosed by the dashed box refers to the final antenna region. (d) The refractive index distribution for the final antenna, in which the refractive indices below one are all set to 1.

materials) is 0.9578 in our design. Therefore, these materials can be treated as isotropic and the proposed device can be easily implemented using GRIN material. The approximation will definitely lead to performance deterioration in the design, which is negligible in our experiment.

Figure 1(c) illustrates the refractive index distribution in the physical space. It is clearly observed that the refractive index is relatively large in the region flattened from the parabolic part. In contrast, it is less than 1 near the intersection parts between the parabolic curve and the bottom line. In most parts of the device (region I in the figure), the refractive index is close to 1. Although a refractive index below 1 can be realized with metamaterials, it always involves resonances at a particular working band, so in our design, we set all the material parameters below 1 to 1. This method is also adopted in [7, 8, 11, 14]. Moreover, region I can be excluded from the final design and then the antenna size is reduced to region II. The refractive index distribution of the final antenna (region II) is shown in figure 1(d), in which the refractive index varies from 1 to 1.47. Size reduction and parameter modification (set all parameters above one) will inevitably lead to performance degradation and are considered to be two major factors for the discrepancy between the measured data and theoretical prediction. Another solution is to put the antenna in a dielectric environment with permittivity larger than 1, so the refractive index inside the device is amplified by a factor of $\sqrt{\varepsilon_r}$, and this has proved useful in certain situations [21, 22].

We decided to design a planar antenna in the X band using metamaterials. The antenna is first divided into 4 mm × 4 mm square grids, where the refractive index is given by numerical
Figure 2. Geometry of the I-shaped unit cell (a) and its effective refractive index for $a$ varying from 0.8 to 3.5 mm (b). The blue solid line represents the real part of the parameters, while the red dashed line denotes the imaginary part.

calculation in the grid center. Due to the broadband and low-loss properties, I-shaped unit cells are employed in our design [21], as illustrated in figure 2(a), where the simulation setup is also shown. F4B is chosen as the PCB substrate, whose permittivity is 2.65 with the loss tangent 0.001 at 10 GHz. The substrate thickness is 0.25 mm. The I-shaped copper pattern lies on one side of the substrate, with a thickness of 0.038 mm. The second step is to map the refractive index at each point to metamaterial unit cells with different geometrical sizes. This mapping process contains three stages. Firstly, the commercial software Ansoft HFSS is utilized to calculate the $S$ scattering parameters for a single cell with a variable arm length $a$ (see figure 2(a)). In the simulation setup, periodic boundary conditions are imposed around the unit cell to mimic an infinite slab with a depth of $d = 4$ mm. Secondly, the well-accepted retrieval method is used to get the effective constitutive parameters corresponding to different $a$ [29]. As a consequence, the polynomial expression for the effective refractive index versus variable $a$ is determined using the curve-fitting technique. Finally, the cell geometry for each grid is found based on the above polynomial expression using a root-finding algorithm.

Figure 2(b) demonstrates the retrieved EM parameters for different arm lengths at 10 GHz. It can be seen that the refractive index varies from 1.06 to 2.08 when $a$ changes from 0.8 to 3.5 mm. Therefore the I-shaped unit cells are sufficient for the realization of the planar antenna. Moreover, the imaginary part of the material parameters is zero, indicating very small loss. Note that in the simulation, we fix $p = 4$ mm and $w = 0.3$ mm (see figure 2(a)).

Figure 3 gives the corresponding arm lengths of the I-shaped unit cells for antenna realization, which is achieved according to the relationship between the refractive index profile (figure 1(d)) and the response of unit cells (figure 2(b)). In figure 3, the grid is drawn with $4 \times 4$ mm$^2$ small squares, and they correspond to positions of constitutive metamaterial unit cells. The calculated arm length for each metamaterial unit cell is represented by the pseudocolor, which ranges from 0.86 to 2.86 mm. As the refractive index of peripheral grids approaches 1 (white grids in the figure), these grids in practical implementation are neglected, and this simplification will not greatly affect the performance of the antenna. This will be confirmed by the measured results in the following section.
Figure 3. Calculated arm lengths ($a$ in figure 2(a)), expressed by the pseudocolor, of the non-resonant unit cells for the designed planar antenna. The square grid represents the positions of each unit cell, which is shown as the inset in the figure. The white regions are not filled with unit cells since material parameters are very close to 1.

Figure 4. (a) Photograph of the fabricated planar antenna. (b) Experimental setup for the near-field measurement.

3. Results and discussions

The fabricated planar antenna is shown in figure 4(a). It has a size of 200 $\times$ 80 mm$^2$ with a height of 12 mm (3 unit cells in the z-direction). Please note that the outer region of the antenna structure is not implemented with metamaterial unit cells since they are close to vacuum. See the white region in figure 3 for comparison. The PCB strips are fabricated using the lithography technology, and the supporting frame is a hand-made foam structure with permittivity close to one. To measure the performance of the designed antenna, a near-field scanning system (shown in figure 4(b)) is used to map the electric-field distribution within a planar waveguide. The height of the waveguide is about 13 mm, just enough to hold the planar antenna. The 2D line source is implemented using a probe on the bottom side. The planar antenna is placed on the bottom metal plate, and another probe located on the top plate scans the antenna’s top surface to get the near-field distribution.

New Journal of Physics 13 (2011) 063028 (http://www.njp.org/)
In order to compare the performance of the antenna, we first make full-wave simulations using the finite-element-based commercial software COMSOL MULTIPHYSICS. Five different antenna structures are simulated; they include, antenna I, a parabolic reflector; antenna II, a bulky planar antenna with (accurate) anisotropic material parameters; antenna III, a bulky planar antenna with isotropic material parameters, some of which are less than 1, as shown in figure 1(c); antenna IV, the same as antenna III but the material parameters are modified to be larger than 1; and antenna V, the fabricated antenna, a compact-sized one with material parameters larger than 1, as illustrated in figure 1(d). The near-field distributions for these five structures were obtained. Since all have similar field distributions, only representative results are given. The results are illustrated in figures 5(a)–(c) at 10 GHz, which show that a cylindrical wave impinges upon antenna I, the parabolic reflector; antenna III, the bulky isotropic-material-filled planar antenna with some parameters less than 1; and antenna V, the fabricated antenna, respectively. It is observed that all the antennas have a high directivity in the axial direction. Outside the antenna area, which is outlined in each figure, the electric-field distributions are very similar to each other. The major difference is inside the antenna. In the case of the designed antenna with bulky size and non-modified isotropic parameters (antenna III) and the compact-sized planar antenna with modified parameters (antenna V), as shown in figures 5(b) and (c), respectively, when the wave enters the antenna its wavefronts are flattened near the PEC plate and then reflected back in the reverse direction. These observations confirm qualitatively the correctness of our design.

To quantify these observations, the far-field radiation patterns have been calculated by using the simulated data. First, the near-field data are collected along a circle surrounding the antenna. Then, Huygens’ principle is used to get the far-field information. The same method has been utilized by other researchers and has proved effective in various situations [17, 30]. The results are demonstrated in figure 5(d), which gives normalized far-field patterns for the above five cases. It is evident that antennas I and II (black and blue solid curves) have almost the same far-field patterns, which is a direct consequence of the invariance of Maxwell’s equations. Since the anisotropy ratio in our design is very close to 1, the approximate treatment of anisotropic materials as isotropic ones does not lead to much performance degradation. Hence, the radiation pattern for antenna III (red dashed curve) almost coincides with those of antennas I and II. However, ignoring the material dispersion, i.e. setting the parameters below 1 to 1, does introduce obvious performance deterioration, which manifests itself in the widened main beam width and the raised side lobe levels (antenna IV: magenta dash-dotted curve). Similar effects are observed when the antenna size is reduced, as is shown by the cyan solid curve with star (antenna V, the fabricated antenna) in this plot. We remark that the above observations cannot exclude the application of the fabricated antenna. For one thing, the fabricated antenna is easier for implementation and experimental verification; for another, it has a similar performance to that of the parabolic reflector and has a broadband structure. Hence, in the experiment, we focus on the performance of antenna V with reference to antenna I.

The measurement results for the different antennas are illustrated in figure 6. For antenna I, the parabolic reflector, which is realized using a hand-made copper strip with the predefined shape function, the near-field distribution is given in figure 6(a). A comparison of this figure with the corresponding simulation result in figure 5(a) shows that they agree well with each other. The difference is mainly attributed to the geometrical deviation from the ideal parabolic function. Good agreement can also be observed for the fabricated antenna, i.e. antenna V. The difference between figures 6(b) and 5(c), where the working frequencies are both 10 GHz, is
Figure 5. Simulated near-electric-field distributions and far-field patterns for representative antenna structures at 10 GHz. (a) antenna I, the parabolic reflector; (b) antenna III, the bulky planar antenna with isotropic materials, some of which are less than 1. Corresponding material parameters are given in figure 1(c). (c) Antenna V, the compact-sized planar antenna with material parameters larger than 1. Corresponding material parameters are shown in figure 1(d) with a loss tangent of 0.002. Field distributions for antenna II, the planar antenna with accurate anisotropic materials, and antenna IV, the bulky antenna with all parameters larger than 1, are not shown since they look similar to the figures given. (d) Calculated far-field radiation patterns for the five antennas. Antenna I, black solid curve; antenna II, blue solid curve; antenna III, red dashed curve; antenna IV, magenta dash-dotted curve; and antenna V, the fabricated antenna, cyan solid curve with star.

negligible. The tiny difference comes from the non-ideal cell arrangement in the device and the hand-made foam structure, which will also generate some size deviation in the square grids. Since the effective refractive index of each cell is closely related to the geometrical size, the refractive index distribution of the planar antenna may not be strictly satisfied. This will lead to small changes in the field patterns. Taking these factors into consideration, we conclude that the measured results agree well with the corresponding numerical simulations. The measured data for antennas I and V also closely resemble each other, although some differences can be
Figure 6. Measured results for the parabolic reflector and planar antenna at different frequencies. (a–c) Measurement results using the 2D mapper for the parabolic reflector at 10 GHz, and for the fabricated antenna at 10 and 11.5 GHz, respectively. The unit is mm. (d) Normalized far-field radiation patterns for antennas at different frequencies. Magenta solid curve with diamond: the parabolic reflector; black solid curve: simulation data for the fabricated antenna at 10 GHz; green dash-dotted curve: measured result at 8.5 GHz; red solid curve with star: measured result at 10 GHz; blue dashed curve: measured result at 11.5 GHz. The near-field distribution for 8.5 GHz is not shown in the figure since it is similar to those given.

identified through careful observations. The discrepancy between them is mainly due to the size reduction and parameter modification, as is demonstrated in the simulation part. Note that the fabricated antenna is based on the refractive index distribution given in figure 1(d), not that of the ideal antenna, i.e. antenna III in figure 1(c); for the reason of easy implementation and broad bandwidth, this discrepancy should not be exaggerated. Moreover, the difference can be made smaller if a bulky size is chosen or the antenna is put into a background medium. The broad bandwidth of the antenna is illustrated by the field maps taken at 8.5 (not shown here for the sake of clarity) and 11.5 GHz (figure 6(c)) in the figure, which show similar performances as those of the map at 10 GHz.

To quantitatively investigate the measured antenna performance, the far-field radiation patterns have been calculated by using the measured data and the results are given in figure 6(d). As shown in figure 6(d), for the simulated and measured planar antennas at 10 GHz (antenna V,
black solid curve and red solid curve with star), the radiation patterns agree well in the peak radiation direction, and only small differences are found near the side lobes, which suggests the correctness of our fabrication technique. Relatively large differences can be found between the measured parabolic reflector (magenta solid curve with diamond) and the planar antennas. We note again that the difference between simulated and measured results mainly comes from the following approximations: parameter modification and size reduction. As mentioned earlier, these simplifications are considered as a shortcut for experimental verification and can be made as small as possible (e.g. to use a bulky size). This also suggests that one has to make tradeoffs between the antenna performance and its structure complexity in practical applications. The measured far-field radiation patterns at 8.5 (green dash-dotted curve) and 11.5 GHz (blue dashed curve) are also shown to confirm the broad bandwidth of the antenna, and both agree well with the curve for 10 GHz (red solid curve with star) and the simulation curve (black solid curve).

Through the measurements, we conclude that both the near-field distributions and far-field patterns are in good agreement, which demonstrates that the planar antenna has a similar performance to that of the parabolic reflector. The above results also confirm that the planar antenna can be realized using actual metamaterials with good directive behavior. The working frequency varies from 8.5 to 11.5 GHz with acceptable performance. It can be further expanded by carefully choosing the optimized unit-cell types and dimensions.

Finally, we comment on the improvement of the 2D planar antenna. In this design, we focus on verification of the planar antenna structure, but little effort is made on the impedance matching of the final device. Small reflections at the interface are generated because of the impedance mismatch. To reduce the reflection, we can choose modified I-shaped unit cells, which can provide impedance-matched gradient-index metamaterials and lead to better performances [30]. Besides, the 3D antenna can be designed also by rotating the 2D results around their axis [14]. In this context, the closed-square ring unit cells are good candidates owing to their isotropic properties inside each layer [31]. The feed source of the antenna can also be improved to achieve highly directive behavior. Due to the losses of metal inclusions in the structure, the present design cannot be scaled down to the optical frequency. In order to achieve broadband and low-loss performance at the optical frequency, the optical planar antenna can be implemented with all-dielectric metamaterials by drilling hole arrays in an ordinary dielectric [22].

4. Conclusions

In conclusion, we have fabricated and experimentally verified a novel planar antenna by using gradient index metamaterials, which has a high directivity like its parabolic counterpart. The I-shaped unit cells are utilized in the design because of their broadband and low-loss properties. The fabricated prototype has been tested using the 2D field-mapping device and the measured results show good agreement with numerical simulations. The antenna can be implemented with all-dielectric metamaterials at optical frequencies.

Acknowledgments

This work was supported in part by a Major Project of the National Science Foundation of China under grant numbers 60990320 and 60990324, in part by the 111 Project under grant number 111-2-05 and in part by the National Science Foundation of China under grant numbers
60871016, 60901011 and 60921063. ZLM acknowledges the Fundamental Research Funds for the Central Universities (no. LZUJBKY-2009-61) and the Open Research Program Funds of State Key Laboratory of Millimeter Waves (no. K201115).

References

[1] Shelby R A, Smith D R and Schultz S 2001 Science 292 77
[2] Smith D R, Mock J J, Starr A F and Schuring D 2005 Phys. Rev. E 71 036609
[3] Driscoll T, Basov D N, Starr A F, Rye P M, Nemat-Nasser S, Schuring D and Smith D R 2006 Appl. Phys. Lett. 88 081101
[4] Pendry J B, Schurig D and Smith D R 2006 Science 312 1780
[5] Schurig D, Mock J J, Justice B J, Cummer S A, Pendry J B, Starr A F and Smith D R 2006 Science 314 977
[6] Li J and Pendry J B 2008 Phys. Rev. Lett. 101 203901
[7] Ma H F and Cui T J 2010 Nat. Commun. 1 21
[8] Kallos E, Argyropoulos C and Hao Y 2009 Phys. Rev. A 79 063825
[9] Pendry J B 2000 Phys. Rev. Lett. 85 3966
[10] Enoch S, Tayeb G, Sabouroux P, Guérin N and Vincent P 2002 Phys. Rev. Lett. 89 213902
[11] Kundtz N and Smith D R 2009 Nat. Mater. 9 129
[12] Cheng Q, Cui T J, Jiang W X and Cai B G 2010 New J. Phys. 12 063006
[13] Ergin T, Stenger N, Brenner P, Pendry J B and Wegener M 2010 Science 328 337
[14] Ma H F and Cui T J 2010 Nat. Commun. 1 124
[15] Luo Y, Zhang J, Chen H, Huangfu J and Ran L 2009 Appl. Phys. Lett. 95 193506
[16] Allen J, Kundtz N, Roberts D A, Cummer S A and Smith D R 2009 Appl. Phys. Lett. 94 194101
[17] Jiang W X, Cui T J, Ma H F, Yang X M and Cheng Q 2008 Appl. Phys. Lett. 93 221906
[18] Leonhardt U 2006 Science 312 1777
[19] Leonhardt U and Philbin T G 2006 New J. Phys. 8 247
[20] Milton G W, Briane M and Willis J R 2006 New J. Phys. 8 248
[21] Liu R, Ji C, Mock J J, Chin J Y, Cui T J and Smith D R 2009 Science 323 366
[22] Valentine J, Li J, Zentgraf T, Bartal G and Zhang X 2009 Nat. Mater. 8 568
[23] Huidobro P A, Nesterov M L, Martín-Moreno L and García-Vidal F J 2010 Nano Lett. 10 1985
[24] Liu Y, Zentgraf T, Bartal G and Zhang X 2010 Nano Lett. 10 1991
[25] Aubry A, Lei D Y, Fernández-Domínguez A I, Sonnefraud Y, Maier S A and Pendry J B 2010 Nano Lett. 10 2574
[26] Renger J, Kadlec M, Dupont G, Aćimović S S, Guenneau S, Quident R and Enoch S 2010 Opt. Express 18 15757
[27] Mei Z L, Bai J, Niu T M and Cui T J 2010 Prog. Electromagn. Res. M 13 261
[28] Tang W X, Argyropoulos C, Kallos E, Song W and Hao Y 2010 IEEE Trans. Antennas Propag. 58 3795
[29] Smith D R, Schultz S, Markos P and Soukoulis C M 2002 Phys. Rev. B 65 195104
[30] Ma H F, Chen X, Xu H S, Yang X M, Jiang W X and Cui T J 2009 Appl. Phys. Lett. 95 094107
[31] Liu R, Cheng Q, Chin J Y, Mock J J, Cui T J and Smith D R 2009 Opt. Express 17 21030

New Journal of Physics 13 (2011) 063028 (http://www.njp.org/)