Metamaterial-Based 2D Multi-Beam Broadband Luneburg Lens Antenna

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Abstract

A metamaterial surface composed of non-resonant circular complementary closed ring resonators is designed to obey the refractive index of a Luneburg lens. An array of planar slot antennas placed at the periphery of the lens is used at wave launchers. A prototype of the lens associated with the feed structures has been fabricated using standard printed circuit board (PCB) technology. Measured far-field radiation patterns have shown directive beams in H-plane over the [8 GHz – 12 GHz] frequency range. Furthermore, this metasurface lens antenna has demonstrated beam-scanning with a coverage of up to 120°. Far-field measurements agree qualitatively with calculated near-field distributions.

1. Introduction

Due to their peculiar abilities to control and manipulate light, gradient index (GRIN) media [1] have been widely used to realize several microwave devices. Metamaterials have interesting physical properties that are well suited to realize such structures. GRIN lenses have been proposed as alternatives to conventional dielectric ones, where refractive index is varied throughout the lens instead of relying on the interfaces of the dielectric material to control light flow. It has been shown lately that a planar medium composed of metallic inclusions on a printed circuit board can satisfy the refractive index profile of a Luneburg lens [2-4] given by the relation $n(r)=\sqrt{2-\left(r/R\right)^2}$ $(0 \le r \le R)$ [5], where R is the radius of the lens and r is the distance from any point to the lens center. It has been reported that a point source on the surface of such planar 2D-lenses is transformed into a collimated beam on its diametrically opposite side. Experimental validation of such lenses was generally done by using horn antennas or coaxial to waveguide transitions as primary source to illuminate the lens. Such feed methods cause an increase in the profile of the Luneburg lens by the voluminous size of the feeding structure making in board integration of such devices very difficult. Also, the spherical locus of focal points of such lenses is inherently unsuitable for receiver arrays, which are generally planar.
Lately, we experimentally validated the combination of a compact low-profile Vivaldi antenna with substrate-integrated GRIN materials assimilating small electric size lenses [6-8]. The gradient index of the lenses was achieved through a two-dimensional array of waveguided units of complementary closed ring (CCR) resonators. The use of a planar feed in the overall low profile lens antenna presented a good matching to the spherical locus of focal points and an easy integration into inboard systems incorporating active devices.

In this present paper, we focus our attention on the combination of multiple planar antennas used as wave launchers to feed a metamaterial-based planar Luneburg lens in a parallel-plate waveguide. By switching between the feed antenna elements, beam scanning from -60° to +60° is successfully realized. The proposed lens antenna configuration offers advantages of compact, low profile, lightweight, and broadband features and also easy fabrication. Reported experimental far-field radiation patterns demonstrate broadband directive and steerable emissions, validating the good efficiency of the low-profile metamaterial-based GRIN lens antenna.

2. Lens antenna design

A broadband metamaterial-based Luneburg lens of radius R = 57.4 mm is designed to operate in the 8 GHz to 12 GHz frequency band. A circular non-resonant magnetic CCR resonator is used as the basic building block to design the gradient index (GRIN) lens. The circular closed ring resonators are etched on the copper-cladding of a 1.6 mm thick Rogers RT/duroid® 5880 substrate, (ε_r = 2.2 and tan δ = 0.0009). Such a complementary resonator operates in a quasi-TEM waveguide configuration as shown by the simulation setup in Fig. 1(a) and exhibits a magnetic resonance when the E-field is aligned perpendicularly to its plane. To obtain the desired effective index of the CCR units, the properties are characterized numerically using Maxwell's equations solver of CST Microwave Studio Suite. The gap g between the patterned circuit board and the top copper plate of the waveguide is fixed to 1 mm and the phase reference planes

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for the electromagnetic parameters retrieval are chosen such that the period a of the CCR unit cell is 4.1 mm. The variation of the refractive index consists in changing the CCR radius r, while keeping the other geometrical parameters fixed. In our design, the Luneburg lens is discretized into seven concentric regions, where each region composed of two cells corresponds to a specific refractive index.

Fig. 1(b) shows the real part of the effective index (n_{eff}) of the waveguided CCR metamaterials extracted from the complex reflection and transmission coefficients by the method described in [9]. They are used in their non-resonant frequency regime such that they present broadband material properties in the 8-12 GHz band. Indeed for frequencies well below resonance, the structure behaves as an effective medium. We can observe that the index presents low dispersion even for r = 1.9 mm in which case resonance is around 22 GHz.

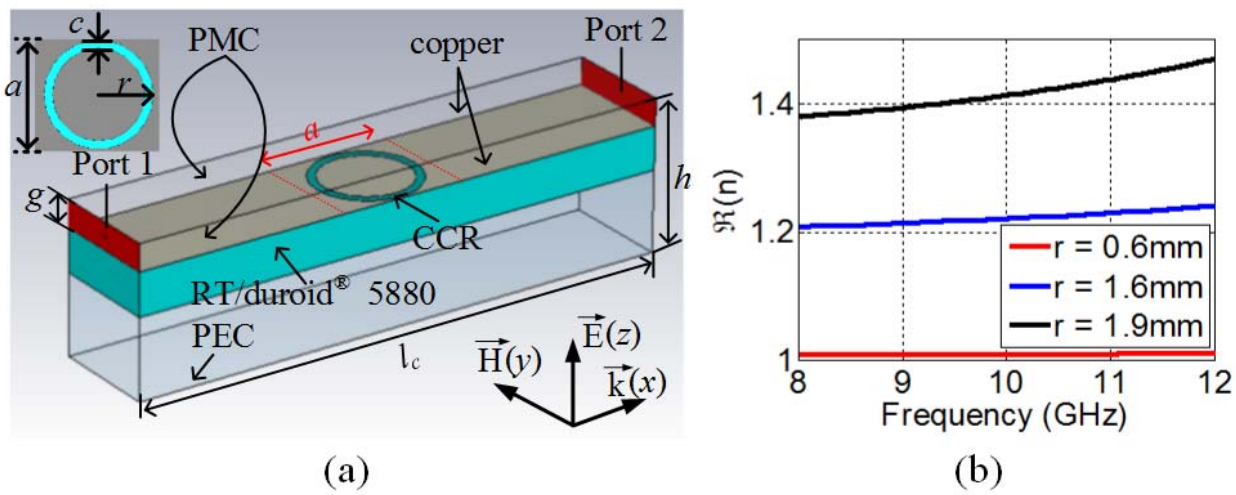

Fig. 1: (a) Simulation setup used to retrieve the effective constitutive parameters of the CCR cells. (b) Extracted effective index of the CCR structure structure with varying r values. The CCR cell is used in the non-resonant frequency regime such that it presents broadband features in the 8-12 GHz band (less than 7% variation over the whole band). The geometrical dimensions are l_c = 20 mm, h = 5.6 mm, g = 1 mm, a = 4.1 mm, and c = 0.3 mm.

The planar lens constructed from the waveguided CCR building blocks is inserted in a quasi-TEM waveguide consisting of two circular parallel copper plates spaced by h = 5.6 mm, consistent to the simulation setup of the CCR cell. As shown in Fig. 2(a), the GRIN slab is placed on a Rohacell® foam spacer, with a relative permittivity close to 1, to fill up the space between the lens and the bottom metallic plate. An arc array of five planar microstrip antennas partially inserted in the parallel-plate waveguide and placed at the periphery of the lens are used as primary feeds. As shown by the inset of Fig. 2(a), each antenna element is composed of square radiating slot milled on a similar substrate as the Luneburg lens. The slot is excited by a 50 Ω coplanar waveguide line ended with a radial stub. Two arc conducting lines are printed on the radiating slot in order to improve the impedance matching of the antenna element. It should be noted that only the radiating slot of the feed is inserted between the parallel plate waveguide. The coplanar waveguide line exciting the slot is kept outside the quasi-TEM waveguide. Such a configuration facilitates matching of the antenna element. The antenna elements with angular interval of 30° of the feeding array are positioned such that the phase center is situated at the lens periphery. The feeding structure is designed to provide an electric field parallel to the z-axis and perpendicular to the CCR plane. The dominant TEM mode is formed between the top metallic plate of the quasi-TEM waveguide and the CCR-based lens.

3. Experimental validation

To validate experimentally the concept, a prototype has been fabricated and tested. The impedance matching of the lens antenna is illustrated by the measured reflection coefficient shown in Fig. 2(b). A relatively good matching (< -9 dB) is observed experimentally in the [8 GHz – 12 GHz] frequency band. The coupling between the different feed elements is also given in the Fig. 2(b) and shows an average value of -20 dB over the whole frequency band, indicating a very good isolation.

To investigate the directive behavior and beam scanning performances of the integrated lens antenna, far-field radiation patterns have been measured in a full anechoic chamber. When the feeding elements “1”, “2” and “5” are independently excited, the measured radiations patterns at 8, 10 and 12 GHz are presented in Figs. 3(a)-(c). A highly directive radiated lobe is observed in the H-plane (plane containing H and k vectors) at all tested frequencies. By switching between the feeding sources, beam scanning can therefore be achieved from -60° to +60°. The measured half-power beam width is less than 18° in the whole operating frequency band and whole angle scanning coverage. The measured side lobes are around -6 dB for the worst case due to the relatively small radius of the lens (< $2\lambda_0$ at 10 GHz). A larger radius should lead to lower parasitic lobes. As presented in Fig. 3(d) for normal radiated beam when feed “1” is excited, a wide beam is radiated in the E-plane (plane containing E and k vectors), resulting in a three-dimensional fan-shaped beam of the lens antenna. The cross-polarization components measured show levels remaining below -29 dB over the whole [8 GHz – 12 GHz] frequency band.

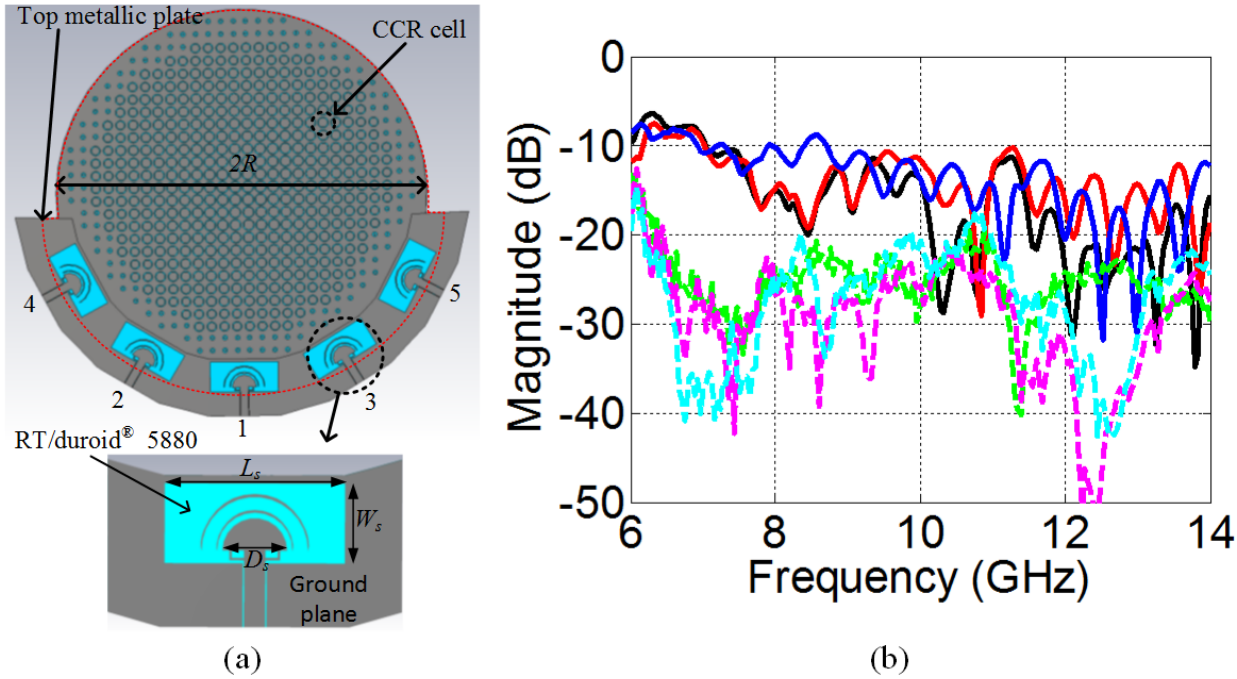

Fig. 2: (a) Schematic view of the lens antenna composed of the planar metamaterial-based GRIN lens and radiating slot elements placed in a quasi-TEM parallel-plate waveguide. The radius of the lens is R = 57.4 mm. (b) Measured S_{ij} parameters of the lens antenna showing good matching and high isolation.

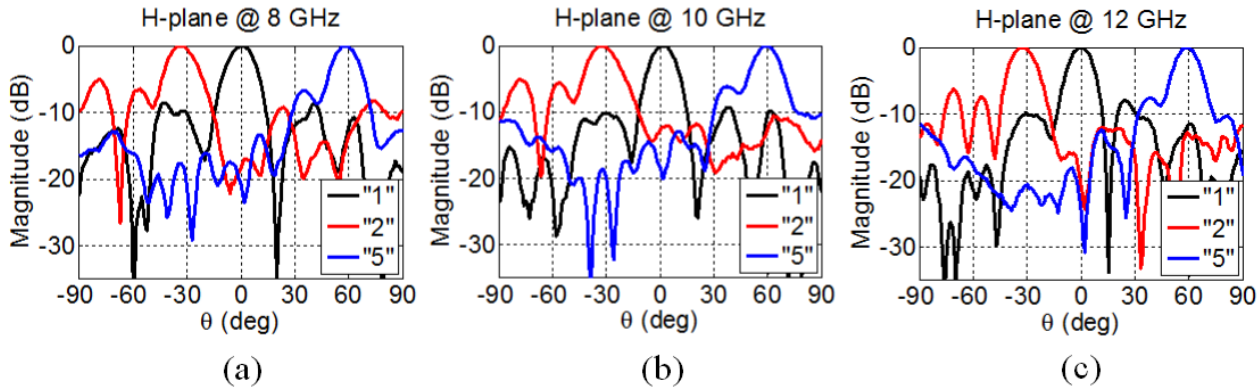

Fig. 3: Measured H-plane far-field radiation patterns at 8, 10 and 12 GHz when sources “1”, “2” and “5” are excited.

4. Conclusion

In this work, we have experimentally validated a low profile and substrate-integrated planar Luneburg lens that presents high beam-scanning performances with a coverage of up to 120° over a wide frequency range in the X-band.

The metamaterial-based structure is excited by an array of planar radiating slots placed on its periphery and is configured to operate in a quasi-TEM parallel-plate waveguide. The association between the feed structure and the metamaterial-based GRIN lens has shown a directive beam in the H-plane over a broadband frequency range from 8 GHz to 12 GHz.

6. Acknowledgments

This work was supported by the EADS Company Foundation through the METAQOPT project, contract No. 090-AO09-1006.

5. References

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