Highly directive antennas based on a slim Luneburg lens

C. Mateo-Segura[1], A. Demetriadou[1,2], Y. Hao[1]

[1]Queen Mary, University of London, Mile End Road, E1 4NS, London, UK
email: c.mateo@ieee.org; email: yang.hao@eecs.qmul.ac.uk
[2] Blackett Laboratory, Imperial College London, SW7 2AZ, London UK
email: a.demetriadou06@imperial.ac.uk

Abstract

Transformation optics has emerged as a useful tool to control the behaviour of electromagnetic fields and thus offers potential for designing novel antenna structures. In this contribution, a new antenna system based on a slim flat Luneburg lens located above a radiating source printed on a ground plane is proposed. The permittivity map of the transformed lens able to convert the non-directive beam radiated by a single source to a highly-directive beam with low side-lobe level is calculated. Numerical simulations based on CST Microwave Studio are performed to illustrate the proposed antenna system performance in comparison with a common Fabry-Perot cavity antenna. Results confirm the high-directivity, low side-lobe level and steering capability of the proposed antenna.

1. Introduction

Achieving highly-directive antennas have always been a pursued design goal and the subject of extensive studies [1-4]. Various geometries have been proposed in the past few decades to significantly increase the directivity of a single radiating source and minimise the side-lobe level (SLL). The most common example is the Fabry-Perot cavity antenna which can be realized by a single or stack of dielectric layers [1, 2] or by employing a Partially Reflective Surface (PRS), with suitable frequency selective properties, placed at a distance of half-wavelength from a perfect electric ground plane [3, 4]. The directivity enhancement, however, will only be achieved at a single frequency independently of the matching condition. This is a major drawback in modern wireless communication systems where broadband performance is required. On the other hand, for many scanning applications having an antenna with steering capability is a main advantage. Although different approaches have been reported to overcome both broadband and steering capability issues, all the proposed antenna designs are rather complex or have drawbacks in either the frequency bandwidth, the side-lobe level or their steerability.

The advent of transformation optics as a way to control the electromagnetic field trajectories by means of specifying the required electromagnetic properties of a material has opened a myriad of novel devices for conventional electromagnetic applications [5, 6]. In this sense, here we proposed a simple approach that overcomes the aforementioned problems by means of using a lens as a superstrate. The main concept is based on using a transformation lens to control the radiated beam from a source, Fig 1a. The transformation lens consists of a slimmer flat design of the Luneburg lens so its dimensions are more suitable for antenna systems. By applying the appropriate transformation, the permittivity map in the slim lens will enforce the antenna system to produce a high-directive beam with very low levels of side-lobes. Furthermore, the proposed antenna system is steerable, maintaining both high-directivity and low side lobe level for relatively wide angle range.

2. Transformation Lens

A coordinate transformation of the Luneburg lens which creates a slim “discussed-shaped” lens has been recently proposed in [7]. The aim of reshaping the Luneburg lens was to significantly reduce its total spherical volume to accommodate it for antenna applications. However, the proposed slim lens results in a very complex system for manufacturing purposes. In order to overcome the fabrication complexity of such lens here we propose an all-dielectric flat slim lens whose permittivity map after assuming some simplifications [5, 6] is given in Fig. 1a. The permittivity map was discretized for an operating frequency of 10 GHz to further ease the manufacturing process.

Using CST MWS, a 3-D study of the lens performance in the presence of a radiating source located at a distance *b* (Fig. 1a) has been carried out at 10 GHz. The lens dimensions were optimised to account for the non-ideal spherical wavefront of the radiating source, here assumed a square patch antenna. The slim flat lens was proved to behave as the original Luneburg lens when at the frequency of operation the width of the lens is above the diffraction limit ($\Delta z' > \lambda/2$ in Fig. 1a). However, for the purpose of reducing the antenna system size the lens width is below the diffraction limit. In this case, the source should be placed at a certain distance away from the lens so that the lens can still compensate the wavefront curvature of the source [7]. Fig. 1b-c shows how the transformed lens with the permittivity map shown in Fig. 1a is capable of converting the wavefront of a square patch antenna into a plane wave on the other side of the lens (in a similar fashion as the Luneburg lens). This has been confirmed for two different positions of the radiating source along the ZY-plane, in particular at (λ, 0) Fig. 1b and (λ, λ /2) Fig. 1c, which confirms the steering capability of the lens. Moreover, our simulations showed that the directivity performance is dependant on *b* (i.e. distance between the lens and the antenna source) and in this case the optimum directivity enhancement is achieved at b ~λ.

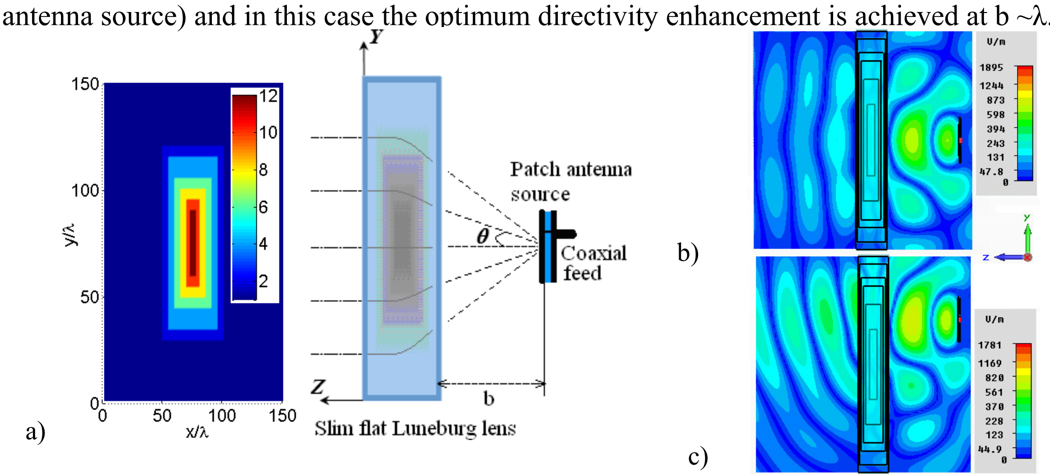
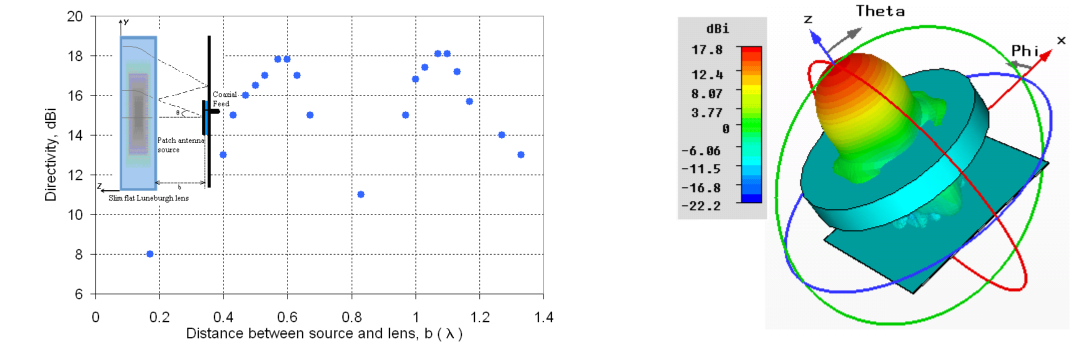


Fig. 1: a) Slim Flat Luneburg lens' permittivity map and cross-section of the antenna system set-up and E-field for the slim flat Luneburg lens for a point source excited at b) (λ,0) and c) (λ, λ /2).

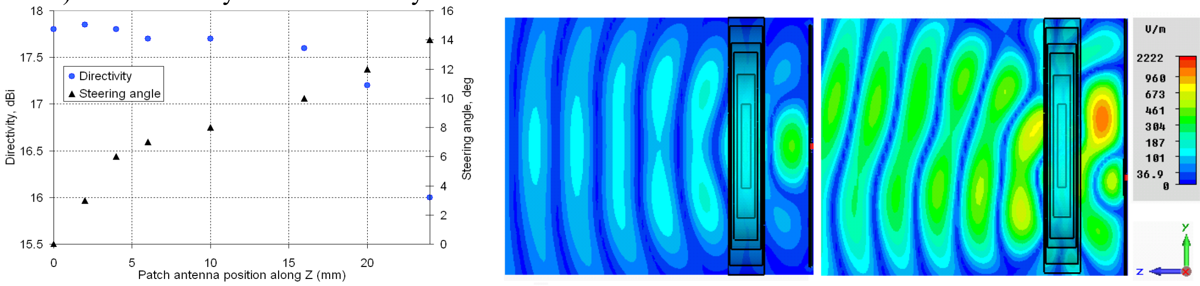
3. Antenna system performance in the presence of a ground plane

In this section the performance of the lens is studied in the context of a radiating source printed on a large ground plane (1.5 λ x 1.5 λ). The introduction of the ground plane gives rise to multiple reflections which prompts the reduction of the overall antenna system thickness. Although the lens has been designed without accounting for a ground plane, the new system still preserves the directivity enhancement and steering capabilities with low SLL. The directivity of the antenna system depicted in Fig. 2a is studied by tuning the distance between the lens and the antenna source, *b.* It was found that the value of the directivity presents two maximums at $b = \lambda$ (as in section 2) and also at $b \sim \lambda/2$ (as common Fabry-Perot cavity antennas), Fig. 2a. Consequently, a thinner antenna than the one in section 2 is obtained. Since the dielectric blocks that composed the lens are homogeneous and non-dispersive, the lens is expected to behave as a broadband device. Limitations to the broadband performance are however imposed by the bandwidth of the square patch antenna source. The 3-D directivity pattern of the antenna system at 10 GHz and at b~λ/2 was calculated using the 3-D electromagnetic simulator CST MWS and is presented in Fig. 2b. The maximum directivity at broadside is 17.8dBi. In order to study the steering capability of the proposed system, the patch antenna is considered at different positions over the ground plane. In Fig. 3 the E-field emerging from the lens is presented when the patch is placed at (λ/2, 0) and (λ/2, λ/4), where good agreement with the previous case is observed. The maximum directivity at θ, where θ represents the steering angle was carefully studied and proved that the antenna system is steerable for ±14^{o} preserving the directivity in the range 17.8 – 16dBi. The directivity bandwidth at b= λ/2 and the first SLL at φ=0º, where φ is the angle from the x-axis, are also estimated and compared with a Fabry Perot cavity antenna composed of a PRS array of rods 15 mm long and periodicity 6 and 2 mm along x and y respectively which produces the same directivity at boresight. A 3-D directivity bandwidth improvement of 5% is observed. The bandwidth can be significantly improved by employing a broadband source. The first SLL is maintained to lower values than the Fabry-Perot antenna employed as an example (10dB less) along the frequency band.



a) b)

Fig. 2: a) Directivity of the antenna system for varying distance between the lens and the radiating source, *b* and b) 3-D directivity of the antenna system.



a) b)

Fig. 3: a) Main lobe steering angle and directivity for different positions of the patch antenna over the ground plane, b) E-field pattern for the slim flat Luneburg lens for a point source excited at (λ/2,0) and (λ/2, - λ/4).

4. Conclusion

A transformed slim flat Luneburg lens has been designed and applied in an antenna system. Several assumptions were taken to simplify the design and manufacturing process without significantly affecting the lens performance. The all dielectric discretized lens was placed above a radiating source on a ground plane and the performance of the whole system was studied. A new broadband, highly-directive with low SLL design has been obtained. Moreover, its steering capabilities for a wide angle range were also shown. The proposed design is simple and outperforms similar superstrate antennas.

5. Acknowledgement

The authors would like to thank Office of Naval Research Global for the financial support (Grant No. N00014-09-1-1013)

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