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► **To cite this version:**

C. Bilitos, J. Ruiz-Garcia, R. Sauleau, E. Martini, S. Maci, et al.. Design of Broadband Reflecting Luneburg Lenses by Higher Symmetries. 15th International Congress on Artificial Materials for Novel Wave Phenomena, Metamaterials 2021, Sep 2021, New York, United States. pp.53-55, 10.1109/Metamaterials52332.2021.9577089 . hal-03468778

HAL Id: hal-03468778

<https://hal.science/hal-03468778>

Submitted on 26 Nov 2022

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Design of Broadband Reflecting Luneburg Lenses by Higher Symmetries

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Abstract – This work reports the application of higher symmetries to the design of a Reflecting Luneburg Lens (RLL) with broadband response. RLLs consist of two stacked parallel plate waveguides (PPW) of circular shape, where the bottom PPW is filled with an azimuthally symmetric graded index (GRIN) medium, so that the fields coupled to the top PPW take the form of a plane wave. In this work, the GRIN medium in the bottom PPW is implemented by unit-cells consisting of metallic inclusions with higher symmetry. This type of unit cell achieves the required equivalent refractive index profile with reduced frequency dispersion, thus increasing the operational bandwidth of the lens. The proposed architecture can be used as beam-former for complete azimuthal scanning in a wide frequency range, while benefiting from the robustness and low-losses of metal-only structures.

I. INTRODUCTION

Future wireless networks will demand higher data rates and, therefore, wider bandwidths (BWs). The need for BW has fostered the interest in mm-waves. However, the cost and complexity of mm-wave phased arrays may hinder their application in some scenarios. Multi-beam antennas based on quasi-optical systems in parallel plate waveguide (PPW) constitute a cheaper alternative also with a low profile. Among the most popular solutions, one finds Luneburg lenses (LLs) [1] and pillbox systems [2]. The former can generate fan beams with azimuthal scanning and they are only limited by the number of sources. In the latter, multiple pencil beams are obtained owing to the radiation of the top layer in a double-layered PPW structure; a 180° PPW bend with parabolic profile connects the bottom and top PPW, so the azimuthal scanning will be impaired by coma phase errors. An alternative quasi-optical beam-former is the Reflecting Luneburg lens (RLL) recently introduced in [3]. It consists of two stacked PPWs, like pillbox systems, but with circular shape. The bottom PPW is filled with a graded index (GRIN) medium to guide the rays launched by a source in the focal circumference along curvilinear paths. After reflection and coupling to the upper PPW, the rays emerge parallel in the azimuthal direction given by the source position.

RLLs mitigate the scanning limitations of classical pillbox systems, but one has to implement a GRIN medium stable in frequency with refractive index values larger than in LL. Therefore, an appropriate unit cell must be found. Next, we explore the use of unit cells with higher symmetries for implementing RLLs. The concept of mirroring and transposing the unit cell geometry was first introduced in the 60's [4, 5] and recently revisited in [6] for the implementation of conventional Luneburg lenses. Here, we apply higher symmetries to the design of broadband RLL.

II. REFLECTING LUNEBURG LENS IMPLEMENTATION

RLLs comprise two stacked PPWs that allow one to collimate the rays after reflection in a PEC boundary and coupling to the upper layer. Owing to the GRIN medium profile in the bottom layer, the rays launched by a source at the focal circumference will follow curvilinear paths (shown in Fig. 1(a)) that provide a plane-wave in the top

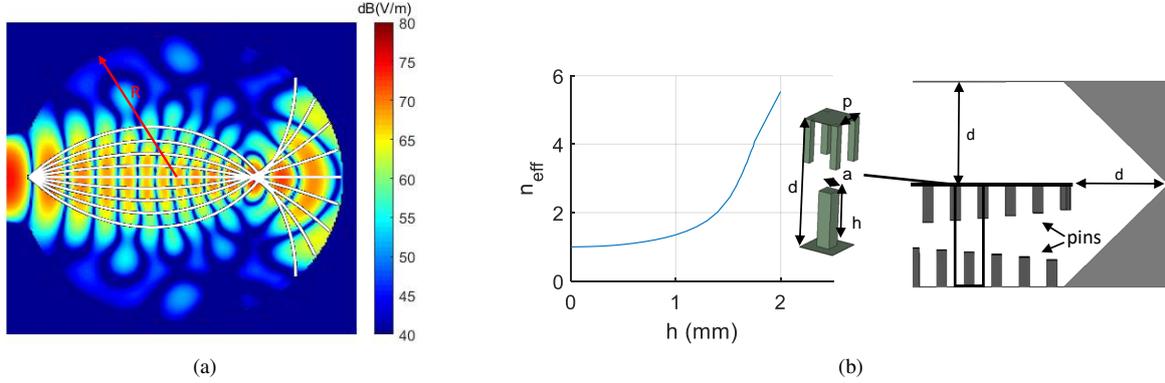


Fig. 1: (a) Real part of the vertical component of the electric field $Re(E_z)$ on the bottom PPW with $R = 2\lambda_0$ filled with the GRIN medium given by (1). (b) Left: local equivalent refractive index as a function of pin height at 30 GHz (pin dimensions are $a = 0.3$ mm, $p = 0.8$ mm, $d = 3$ mm). Right: side view of design of the corner reflector coupling to the upper PPW.

layer. The refractive index profile in the RLL bottom PPW [3], reads as:

$$n_{eq}(r) = n_0 \left(\frac{-1 + \sqrt{1 + 8(r/R)^2}}{2((r/R)^2)} \right)^{3/2} \quad (1)$$

where n_0 is the refractive index of free space, r is the radial distance and R is the radius of the lens. The wavefronts are shaped by the lens and then coupled to the upper PPW. An efficient coupling to the air-filled top PPW may be easily attained by a corner reflector, as the equivalent refractive index at the rim of the lens is equal to n_0 . For the sake of brevity, this study focuses on the realization of the lower layer GRIN medium and the coupling with the upper PPW.

The maximum refractive index value in the RLL profile calculated by (1) is $n_{max} = 2.8$, substantially increased with respect to other GRIN lenses such as the Luneburg Lens ($n_{max} = 1.4$) and the Maxwell Fisheye Lens ($n_{max} = 2$). This high variation acts as a limiting factor on the types of unit cell suitable to implement the RLL, especially if one desires to maintain an all-metal design. A bed of nails structure is a promising candidate to implement this large refractive index range. However, when realizing the RLL with a bed of nails, one has to deal with the frequency dispersion of this structure and a narrow stop band. This significantly limits the frequency range with unimodal propagation of the fundamental TM mode, crucial to avoid coupling to higher order modes. By employing unit cells with higher symmetries, one can mitigate the dispersive frequency behaviour on a wide frequency range, while achieving large variations of the effective refracting index. In practice, this is achieved by mirroring and transposing the unit cell, effectively increasing the structure's periodicity. Since one of our goals is to use a metal-only unit cell, two solutions seem most suitable: higher symmetric metallic posts and their complementary higher symmetric holey structures. Although the holey unit cell might appear as a more attractive solution due to its easy fabrication, acquiring the required refractive index range is a challenge without dielectric loading. Hence, we have concentrated our efforts on the metallic posts with higher symmetry.

The inset in Fig. 1(b) illustrates the proposed unit cell geometry along with the equivalent refractive index variation obtained at 30 GHz by modifying the pin height h . A variation of h between 0 and 2 mm suffices to implement $n_{eq}(r)$ in (1). The other dimensions of the metallic inclusion are $a = 0.3$ mm, $p = 0.8$ mm and $d = 3$ mm. Finally, the side view of the corner reflector and the unit cell are depicted on the right inset of the same figure.

III. NUMERICAL RESULTS AND CONCLUSION

As a proof of the concept, the proposed architecture was analyzed by a full-wave solver. The stacked circular PPWs comprising the design, have a radius of $R = 2\lambda_0$ where λ_0 is the free-space wavelength at 30 GHz. The two plates forming the bottom PPW are loaded with the periodic metallic unit cell showcased in Section II. The lens area is divided using a Cartesian lattice with periodicity equal to the unit cell side. Each cell is then filled with the post dimensions that match the local refractive index. The bottom and top PPWs present a height $d=3$ mm and

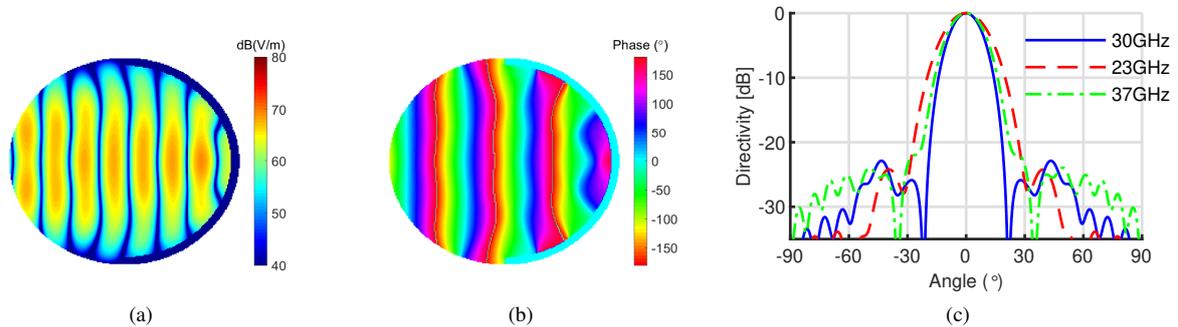


Fig. 2: (a) Real part of the vertical component of the electric field $Re(E_z)$ and (b) Phase distribution in degrees on the top PPW ($R = 2\lambda_0$). (c) Normalized H-plane directivity of the antenna backward broadside radiation for the central frequency $f_0 = 30$ GHz and the lower and upper limit of the operation band $f_l = 23$ GHz and $f_u = 37$ GHz

they are connected by the corner reflector in Fig. 1(b). The system is fed by an H-plane sectoral horn and radiates through an aperture situated on the top PPW.

At the central frequency, the electric field in the top PPW in Fig. 2(a) shows a propagating plane wave, also demonstrated by the flatness of the field's phase distribution (Fig. 2(b)). The bandwidth of the lens is assessed by calculating the far-field patterns corresponding to the power density distributions in Fig. 2(a) and (b). Fig. 2(c) shows the directivity patterns on the H-plane, which present a clear main lobe and side lobe levels (SLLs) below -20 dB throughout a frequency range from 23 GHz up to 37 GHz.

In conclusion, higher symmetries have been applied to the realization of RLLs at mm-waves. The proposed design has been validated by full-wave simulations, demonstrating sufficient broadband performance with a $BW \approx 47\%$. Therefore, this lens can be used as broadband beamformer at mm-waves. Furthermore, the structure is low-profile and completely metallic, thus maintaining reduced losses and structural robustness.

ACKNOWLEDGEMENT

This work has been supported by the Agence de l'Innovation de Défense (AID), and by the European Union through the European Regional Development Fund (ERDF), the French Region of Brittany, Ministry of Higher Education and Research, Rennes Métropole and Conseil Départemental 35, through the CPER Project STIC & Ondes.

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