Modified Luneburg Lens for THz Beam Steering Applications

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***Abstract*—This paper presents a modified Luneburg Lens based on Hamiltonian transformation optics, designed to demonstrate beam steering at terahertz frequencies. The modified Luneburg lens reported in this paper is a hemispherical lens manufactured using nano-composite ceramic technology. The lens is fed using a WR-03 waveguide probe, where the probe on its own has a gain of 8 dB in the boresight direction. Because of the high losses of the ceramic nano-composites at terahertz frequencies, no added gain is obtained by the lens. However, this initial prototype design is a demonstrator of a lens, manufactured using ceramic technology, attaining high directivity and beam steering at terahertz frequencies.**

Keywords—Transformation optics; Luneburg lens; Terahertz; Beam steering

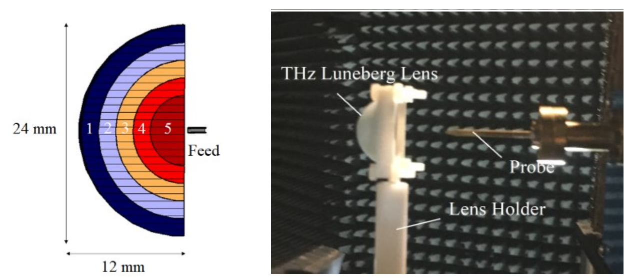
I. INTRODUCTION

A Luneburg (LL) lens essentially focuses an electromagnetic field approaching it to a focal point on its opposite surface. In other words, the lens is capable of transforming spherical waves into plane waves. Consequently, if any feed is positioned at the focal point on the surface of the lens, the lens is capable of generating plane waves from its opposite side. This guiding of electromagnetic waves inside the lens, without any aberrations, is achieved with the use of gradient index of refraction [1]. However, feeding a spherical structure is impractical because of its curved feeding plane. A flat feeding plane, on the other hand, provides accurate feeding for such lenses when fed by an open-ended waveguide.

The focal point on the surface of a conventional spherical LL can be modified by moving it inside the lens using Hamiltonian optics [2]. It has been demonstrated that with the appropriate dielectric constant distribution, a modified LL can perform beam steering just as a conventional spherical LL [3]. Experimental demonstration of such a concept has also been made using a metamaterial approach in [4]. Based on the dielectric constant distribution reported in [3] for a modified LL, a terahertz (THz) lens is designed and fabricated using nano-composite ceramic technology [5] in this work to attain high directivity and beam steering at THz frequencies. For the ease of manufacturing, the THz LL was fabricated as a hemisphere, instead of an extended hemispherical shape. The losses of the material were estimated based on a tangent loss (tanδ) analysis from the simulated results which is described in detail in Section III. With a 5-layered hemispherical LL a significant beam steer is observed when the feed is positioned at a maximum offset of 3mm.

TABLE I. PERMITTIVITY DISTRIBUTION FOR THE THZ LUNEBURG LENS

LAYER	PERMITTIVITY	INNER RADIUS (mm)	OUTER RADIUS (mm)
1	3	10	12
2	5	8	10
3	8	6	8
4	10	4	6
5	12	-	4 mm



a) b)

Fig. 1. a) Design of the THz Luneburg Lens (Layers 1-5 as per Table 1 are depicted with different colours in the design) b) Experimental setup of the THz Luneburg Lens fabricated using ceramic technology fed 1mm away by a WR-03 waveguide probe.

II. MODIFIED LUNEBURG LENS: DESIGN AND FABRICATION

In this work, the 8-layered modified LL reported in [3] has been scaled to smaller dimensions to operate at THz frequencies. The focal point of a conventional spherical LL is shifted inside to have a flat feeding plane. However, since an extended hemispherical shape is complicated to fabricate using ceramic technology, a hemispherical lens is manufactured to test its practical applicability. The design parameters for the LL is tabulated in Table 1. The smallest fabricable sphere (radius = 4 mm) corresponds to a maximum dielectric constant close to 12 and similarly the largest sphere (radius = 12 mm) corresponds to a low dielectric constant of ~ 2. According to the availability of the ceramic materials the outermost layer dielectric constant of the lens was chosen as 3. The design of the 5 distinct layers of the hemispherical LL are shown in Fig. 1a. Each composite layer (layers 1-4) is cast on top of the layer below it in hemispherical form after the first solid hemispherical (layer 5) base is formed.

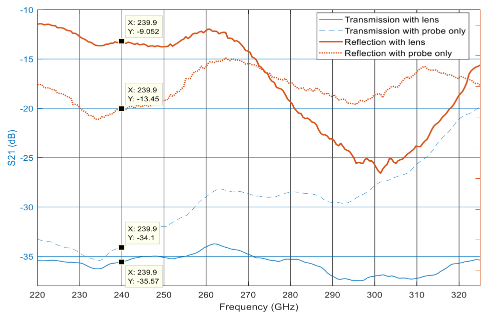


Fig. 2. Measured transmission and reflection response of the THz Luneburg lens and the WR-03 waveguide probe.

The hemispherical shape is attained via ceramic milling machining. The fabricated prototype of the THz LL is shown in Fig. 1b. The THz LL is also modelled using CST Studio Suite and its analytical performance evaluated.

III. Simulated and Measured Results

The transmission (S_{21}) and reflection (S_{11}) of the fabricated THz lens fed by a WR-03 waveguide probe is measured in the boresight direction. The measurements are taken using a PNA-X connected to THz-extender heads. On the receiving end, the THz extender head is connected to the probe followed by the fabricated THz LL (see Fig. 1b). The transmitter (a cylindrical horn connected to the other THz extender head) is positioned in the farfield of the THz LL and the transmission and reflection coefficients are measured as shown in Fig. 2. The operating frequency of the THz LL is considered as 0.24 THz, according to the project specification of this intended work. The THz LL is positioned 1 mm, which is the focal point of the lens, away from the probe. In transmission measurements a drop of 1.5 dB and in reflection measurements a rise of 4.5 dB at 0.24 THz is observed when the lens is positioned 1mm in front of the probe. There is a large discrepancy between the simulated gain and the measured transmission in the boresight. In the ideal simulated case (no losses), the boresight gain is estimated as 20 dB.

The gain of the probe, from the data sheet, is 8 dB at 0.24 THz. In the boresight, as a result, the THz LL is attaining a gain of 6.5 dB. However, considering the simulated results, the THz LL should have attained 20 dB gain on top of the gain of the probe. This 21.5 dB drop in gain is accounted for both reflection and absorption (ohmic losses). Since the measured reflection amounts to 4.5 dB, the rest 17 dB is safely assumed to be ohmic losses. An analysis is performed on the modelled THz LL using different values of loss tangents ($\tan \delta$) and the farfield radiation pattern is recorded as shown in Fig. 3. With $\tan\delta \sim 0.03$, the gain in the boresight falls from 20 dB to 3 dB (a drop of 17 dB). As a result it is estimated that the ceramic composite material used to fabricate the THz LL has a $\tan \delta$ of around 0.03 in the WR-03 band. Using $\tan \delta = 0.03$ in the modelled THz LL design, the feed is translated up to 2 mm off the axis of the lens to observe beam steer. Fig. 4 shows the simulated radiation pattern of the THz LL with a maximum beam steer of 34º off boresight. This shows that with low loss ceramic materials ($\tan \delta \leq 0.01$), it is possible to manufacture high-gain beam-steerable LL antennas operating in the WR-03 band.

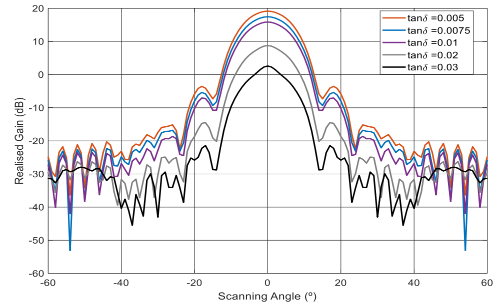


Fig. 3. Simulated Gain of the prototype THz Luneburg Lens with loss tangents ranging from 0.005 to 0.03 at 0.24 THz.

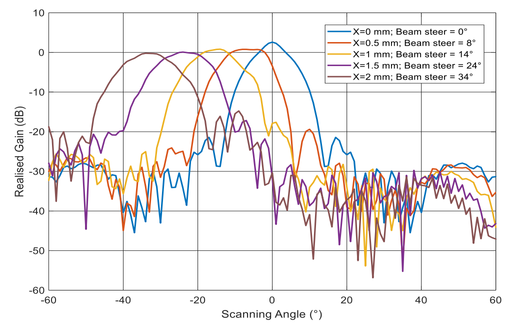


Fig. 4. Simulated radiation pattern of the THz Luneburg Lens, with loss tangent of the lens material being 0.03 at 0.24 THz, showing beam steering. X represents the distance the probe is translated off the axis of the lens.

IV. Conclusion

A modified Luneburg lens operating at 0.24 THz with beam steering capabilities is reported in this work. The losses of the material with which the lens is fabricated is estimated and is considered to be the reason for its degraded boresight gain. A maximum beam steer of 34º with low scan loss (up to 3 dB maximum) is observed from the simulated results.

Acknowledgment

The authors (YH and ASA) would like to acknowledge the support of European Research Council and Engineering and Physical Sciences Research Council (Grant no. EP/P016421/1)

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