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Metamaterial-based LTCC Compressed Luneburg Lens Antenna at 60 GHz for Wireless Communications

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Abstract The paper presents a metamaterial based LTCC compressed Luneburg lens antenna for wireless communications. The antenna is designed at 60 GHz to utilize the unlicensed mm-wave spectrum available for short-range high-data-rate communications. The gradient index compressed Luneburg lens antenna is designed using the quasi-conformal transformation optics method. The design of the antenna is fully compliant with the standard LTCC process with a high-permittivity host material. The diameter of the antenna is 19 mm and the thickness is less than 2 mm. The peak antenna gain at 60 GHz of 16 dBi is demonstrated. Beam scanning capacity is demonstrated with 1 dB scan loss within ± 25 degree field of view.

Index Terms — metamaterials, antenna, lens, scattering.

I. INTRODUCTION

Modern wireless communications systems have put new demands on connection reliability and data throughput. To respond to these challenges, the wider use of mm-wave spectrum has been proposed as well as MIMO technologies. A particular interest presents an unlicensed spectrum around 60 GHz that enables high-data-rate communications for multiple consumer applications [1]. This in turn requires antenna engineers to propose multi-user high gain antenna designs to compensate for the path loss incurred at high frequencies [2].

Among the candidate antenna designs one can highlight active phased arrays with high functionality but high cost. Alternatively, reflector and lens antenna can provide high-gain multi-user performance at a lower cost. The Luneburg lens antenna has drawn the attention of researchers for theoretically enabling multibeam performance without scan loss within a wide field of view [3]. The antenna has been realised in a full spherical shape as well as in compressed form.

The compressed form lens uses transformation optics approach and has been realised in X-band with a set of ceramic shapes [4] as well as by an assembly of stacked multilayer printed circuit boards [5]. In this paper we employ the latter approach to design a compressed Luneburg lens antenna with low-temperature co-fired ceramics (LTCC) process for 60 GHz mm-wave spectrum.

II. COMPRESSED LUNEBURG LENS

The Luneburg lens is a gradient index lens with spherical symmetry with relative permittivity varying radially as

$$\epsilon_r(r) = 2 - (r/a)^2 \quad (1)$$

where a is the lens radius. The spherical gradient-index lens can be readily manufactured with different 3D printing techniques and various designs have been proposed in the literature.

In order to reduce the volume of the lens and make it better compatible with various feeding antennas and integrated electronics, the use of transformation optics method has been proposed and the lens was either partially or fully transformed to a cylindrical shape with a flat surface.

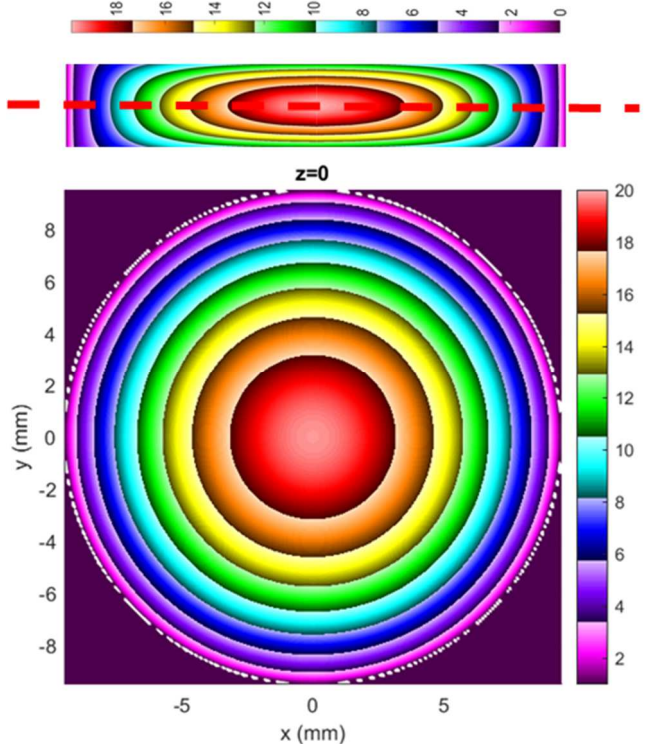


Fig. 1. 3D distribution of permittivity for the compressed Luneburg lens. Top: vertical cut of the permittivity, bottom: horizontal cut in the central plane.

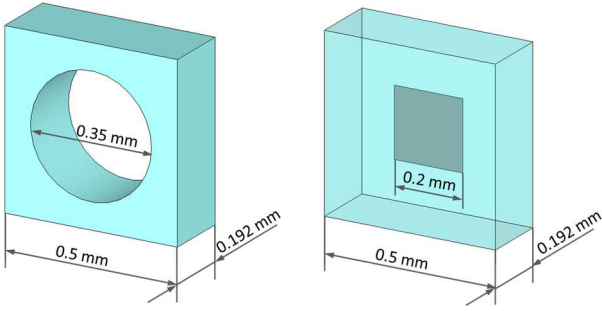


Fig. 2. Metamaterial unit cells.

By employing the following coordinate transformations

$$z' = \frac{\delta}{\sqrt{a^2 - y^2}} z, y' = y \quad (2)$$

and applying the equations of transformation optics one can calculate the permittivity and permeability distributions on of a flat Luneburg lens with radius a and height δ . The full set equations for the transformation can be found in [4], [6]. It has been shown in [4] that reducing the resultant anisotropic structure to the inhomogeneous isotropic distribution does not lead to significant discrepancies in the implementation.

The structure with a radius of 9.5 mm and a height of 1.92 mm has been simulated and the resultant permittivity is

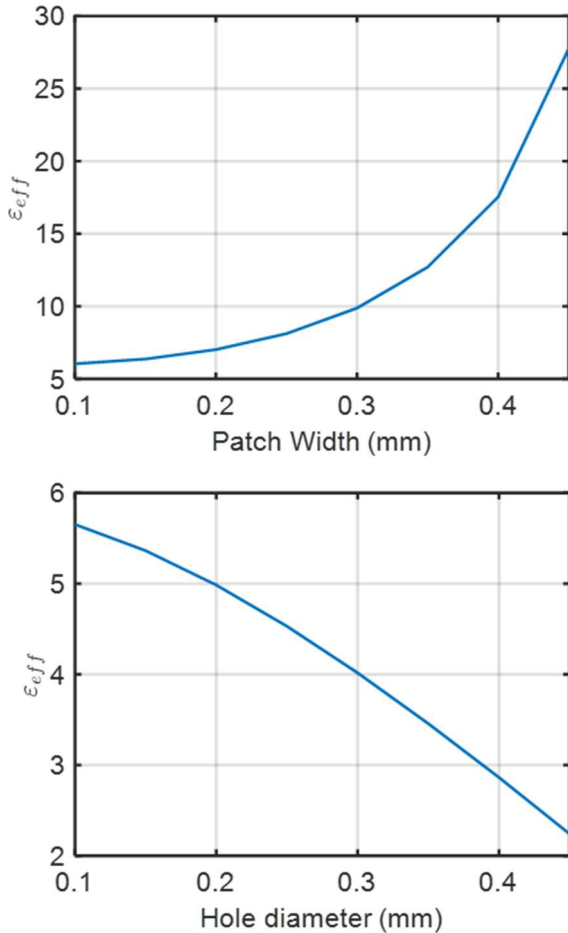


Fig. 3. The permittivity of the metamaterial. Top: vs patch width; bottom: vs hole diameter.

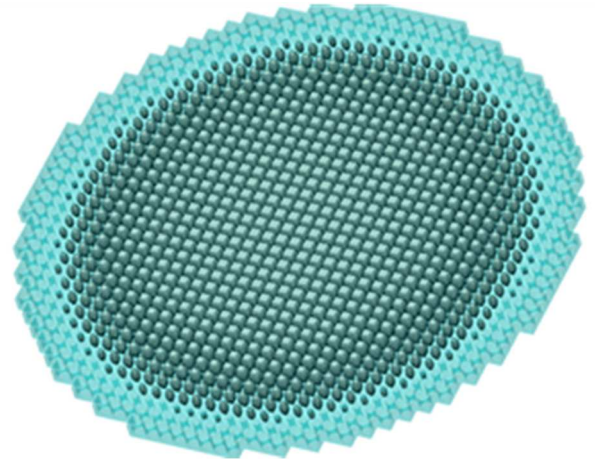


Fig. 4. LTCC Metamaterial Luneburg lens.

presented in Fig. 1. One can see that the permittivity must be as high as 20 for this realisation.

The lens was designed compatible with the LTCC process with host material Ferro A6M-E $\epsilon_r = 5.9$, $\tan \delta = 0.02$ and layer thickness of 0.096 mm . In order to achieve the permittivity variation shown in Fig.1 two types of unit cells with the period of 0.5 mm were implemented: with a patch and with a hole, see Fig. 2. The structures were simulated with CST Microwave Studio and the extracted permittivity is shown in Fig. 3.

III. RESULTS AND DISCUSSION

The resultant metamaterial Luneburg lens model for a 20-layer LTCC process is shown in Fig. 4. One can see that the majority of the structure is composed of patch unit cells with the hole unit cells occupying a small area close to the outer surface of the lens.

The lens has been simulated in the CST Microwave Studio using an open-ended waveguide (OEWG) excitation at 60 GHz. It has been noted elsewhere [4] that for the compressed lens an optimal focal position is not at the surface of the lens, but has to be found empirically. In our case, a focal distance of 5 mm has been chosen after a parametric study.

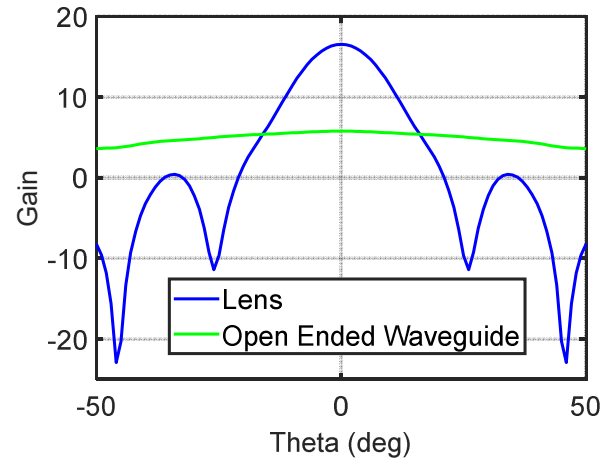


Fig. 5. Simulated gain enhancement with the compressed Luneburg lens.

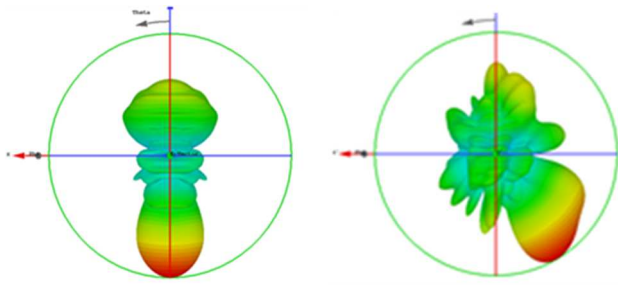


Fig. 6. The radiation pattern of the metamaterial lens that is fed by the OEWG antenna. Left: the OEWG is centered; right: the OEWG is displaced laterally by 5 mm.

The radiation properties of the Luneburg lens antenna have been simulated in CST Microwave Studio. In comparison to the OEWG without the lens the antenna gain has been enhanced by 11 dB to 16.5 dBi, see Fig. 5. The sidelobe level in this particular case is 15 dB.

By moving the horn antenna in lateral position by 5 mm the beam has been steered to 25 degrees from the broadside, see Fig. 6. The simulations have also shown that the peak gain 16 dBi could be achieved with 1 dB scan loss within the specified field of view.

As the structure is designed for industrially compliant LTCC process it can be further integrated with more complex feeding arrangements, e.g. a multi-feed structure for multiple user wireless communications.

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