Additive manufactured dielectric Gutman lens

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In this Letter, the design of a 3D printed fully dielectric Gutman lens is presented. The authors demonstrate the feasibility of using highly accessible and cheap additive manufacturing technology to produce a compact and high performing antenna lens. The lens is designed to operate at \( K_s \) band and utilises a flat feed surface that approximates the focal sphere. The flat feed surface allows for beam steering that requires only translational movement of the feed. The lens has a measured realised gain of 20 dBi with 3 dB scan loss at ±45°. The lens finds applications in systems that require high gain antennas, such as the new generation of satellite and 5G communications and radar technology.

Introduction: Emerging wireless technologies require antennas with a highly directive radiation pattern. For instance, high gain antennas are used in satellite communications to mitigate the effect of the long propagation distance [1], and in radars to increase the resolution [2]. Furthermore, future mobile communication systems (5G and beyond) are expected to operate at higher frequencies where high gain antennas are needed to mitigate the increased free-space path loss [3]. One realistic solution for producing high gain at low cost is lens antennas [1–3].

A lens antenna employs a focusing structure, usually dielectric, to increase the gain of a low-gain radiator. This property can be maintained over a very large bandwidth. The lenses are typically classified into two groups: homogeneous and gradient index. Homogeneous lenses, which makes use of only one dielectric material, are usually easy to design and manufacture but have usually limited scanning capabilities [4]. In contrast, gradient index lenses have a permittivity that varies throughout space, and they may be used to produce wide-scanning antennas [5]. Traditionally, gradient index lenses were difficult to manufacture [6, 7]. However, recently, with the advent of additive manufacturing (commonly known as 3D printing), it is possible to easily tune the material parameters as a function of space [8, 9]. By simply varying the amount of material that is deposited in a small sub volume of the lens (i.e. by varying the fill density), different effective permittivities can be realised. This method has been used to manufacture lenses for various frequency bands and applications [8–10]. These works, however, exclusively suggest the use of different expensive 3D printing techniques such as polymer jetting [8, 9]. Furthermore, they all focus on Luneburg lenses [11], which require a relatively small range of refractive indices.

In this Letter, we propose a more cost-effective approach, based on a normal desktop 3D printer, specifically the Raise3D Pro2. Additionally, a significantly larger range of permittivities is achieved for the design of a Gutman lens [12] operating at \( K_s \) band.

Gutman lens: The Gutman lens is a rotationally-symmetric gradient index lens that transforms a spherical wave to a pseudo-planar wave at the opposite side of the lens [12]. The focal point of a Gutman lens is distributed on a sphere which may have a smaller radius than the lens itself, as illustrated in Fig. 1. In fact, a Luneburg lens is a particular case of a Gutman lens, where the focal point is located at the lens perimeter. The Gutman lens concept can be used to reduce the size of a Luneburg lens [12, 13]. The Gutman lens also retains several of the attractive properties of the Luneburg lens, e.g. rotational symmetry and polarisation independence. The rotational symmetry enables beam steering by simply moving the feed along the focal sphere. Consequently, this type of lens is appropriate for applications in which high gain antennas with wide beam steering are needed.

The refractive index of a Gutman lens is defined by

\[
n(r) = \sqrt{\frac{1 + (f/R)^2 - (r/R)^2}{(f/R)^2}},
\]

where \( f \) is the radius at which the focal point is located, \( R \) is the lens radius and \( r \) is the radial position. A colour map of the refractive index in the cross section of the lens, and two illustrations of the Gutman lens, are depicted in Fig. 1. For our specific design, the focal point \( f \) is located at half the lens radius \( R \), which requires materials with refractive indices within the range \( 1 \leq n < 2.2 \).

Unit cell: The key principle to achieving the gradient refractive index that the lens requires is to alter the material density locally inside the structure. The lens is designed using a large set of cubic unit cells from which a cubic cavity has been removed. Other shapes could be used, such as the ones suggested in [8, 9]. When synthesising the lens, each periodic cell is assumed to be homogeneously filled with a medium with an effective refractive index, \( n_{ef} \). Therefore, it is important that the cells are of sub-wavelength size so that the homogeneity condition is sufficiently satisfied. However, since a standard desktop 3D printer is used for the manufacturing, the unit cells need to be large enough so that all geometrical details can be properly resolved. Consequently, the unit cell cube size is set to 5 mm, which is significantly smaller than the wavelength at the working frequency of 13 GHz and is, at the same time, within the precision of the 3D printer.

The unit cell analysis is carried out using the Eigenmode Solver of CST Microwave Studio [17]. A relation between the fill density and the effective refractive index is sought, where the fill density is the volume ratio between the vacuum and dielectric in the unit cell. Since the maximum effective refractive index required in this work is 2.2, a host medium with a permittivity of 4.4 is chosen. The results of these investigations are displayed with the blue line in Fig. 2. The smallest values of the refractive index (highlighted in the red zone in Fig. 2) are not achievable using a desktop 3D printer, as they require too fine details. However, it should be noted that the lower limit of the feasible refractive index could be reduced by using a less dense host medium.
This is illustrated with the red line in Fig. 2, which is obtained assuming a host medium with a permittivity value of 3.

![Fig. 2 Effective refractive index versus fill density](image)

Simulated effective refractive index versus the fill density of the unit cell at 13 GHz, where \( a = 5 \text{ mm} \) for two different permittivities. \( b \) is varied to realise different fill densities. A cross section of a typical unit cell is depicted in the top left inset.

**Manufacturing**: The manufacturing method to which we resorted to is commonly known as fused filament fabrication (FFF) and is the most widely used 3D printing technology available. It is based on the principle of extruding plastic filament through a hot nozzle layer upon layer until the model is completed. Ordinary plastic filaments for such 3D printers are well available but general lead to unaffordable dielectric losses. As this property is crucial to achieve a high performing antenna, special low-loss filaments are needed. Such filaments are available in a wide range of permittivity values (from 3 to 10) from the Premix group [18]. The manufactured lens has a radius, \( R \), of 45 mm.

**Measurement results**: For evaluation of the lens performance, the \( H \)-plane far-field pattern was measured in the anechoic chamber at the Royal Institute of Technology. The lens was excited with a standard WR62 waveguide feed, placed facing the flat feed surface. The feed is incrementally moved along with one axis to evaluate the beam steering performance of the lens. The results are presented in Fig. 3. Naturally, as the flat feed surface coincides with the focal sphere at the centre, the gain is at a maximum when the feed has zero displacement. The gain decreases monotonically as the feed is being displaced. The measurements show a peak gain of \( \sim 20 \text{ dBi} \) and a scan loss of \( 3 \text{ dB} \) at \( \sim 45^\circ \) from the broadside. This scan angle corresponds to a displacement of the feed of 15 mm. Even though only 1D scanning is illustrated here, 2D scanning is achieved if the feed is allowed to be displaced along with the orthogonal axis as well.

![Fig. 3 Lens measurements](image)

Far field measurements for different displacements of the source at 13 GHz. The anechoic chamber measurement setup is depicted in the top left inset.

**Conclusions**: In this Letter, we have demonstrated how gradient refractive index lenses can be cost-efficiently manufactured. More specifically, a Gutman lens operating at \( K_e \)-band has been designed and manufactured using standard FFF 3D printing. Considerations regarding the manufacturability of the lens have been discussed. The lens was measured in an anechoic chamber and the achieved gain is \( \sim 20 \text{ dBi} \). Moreover, by flattening the feed surface of the lens, beam scanning capabilities are obtained by simple translational displacement of the feed. 3 dB scan loss is obtained at \( 45^\circ \) from broadside.

Current desktop 3D printers are limited in their building precision, but based on the successful results in this work, it may be possible to construct lenses that are further reduced in size, and that can operate at higher frequency bands. These lenses could find applications in future satellite and mobile communications, and radars.

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