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# Beam deflection lens at terahertz frequencies using a hole lattice metamaterial

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***Abstract*—The design and simulation of a dielectric lens for beam deflection in the terahertz range is presented. The device consists of a lattice of sub-wavelength holes in a rectangular dielectric slab, and by varying the radii of the holes with respect to position, a gradient index (GRIN) lens can be realised. Beam deflection is achieved by giving the refractive index a ramp-like characteristic. The lens has a flat-profile, and is likely to be more compact than lenses based on geometric optics. A Fresnel lens-like design is used to expand the lens aperture. Additionally, this lens is expected to have lower loss, higher bandwidth, and be less sensitive to polarisation than similar lenses constructed from resonant metamaterials.**

## I. Introduction

Terahertz technology is a promising prospect for various applications, including medical imaging [1], security screening [2], and communications [3], [4]. At present, however, terahertz technology is lacking in practical applications, partially due to the lack of availability of compact components to generate, manipulate, and direct terahertz radiation. Given the line-of-site propagation requirement of terahertz beams, of particular interest are devices to steer and focus terahertz radiation [5].

By creating sub-wavelength holes in a dielectric, the refractive index of the material can be changed. This technique has been used to create gradient index metamaterial lenses for beam collimation and deflection in the microwave range [6], [7], and for gradient index metamaterial carpet cloaks in the optical range [8]. Note that a similar concept has been employed for carpet cloaks in the optical range, with an important difference being that posts, rather than holes, were used to achieve a gradient index [9].

This article presents a hole lattice metamaterial lens that is designed to deflect a terahertz beam. The design is relatively simple compared to other metamaterial designs, using only a dielectric slab and holes of various radii. Beam deflection is achieved by giving the refractive index a ramp-like characteristic, as this will cause spatially varying wave retardation, and turn the wavefront of a transmitted wave. The resultant lens is highly compact, and has a flat profile, hence it may integrate well into larger systems of optical processing of terahertz radiation. Furthermore, since this is a non-resonant metamaterial, the lens is expected to have low loss, and can potentially operate over a wide bandwidth. This basic design may be extended to serve multiple functions, such as combined deflection and collimation, by careful selection of the refractive index characteristic [10].

## II. Design

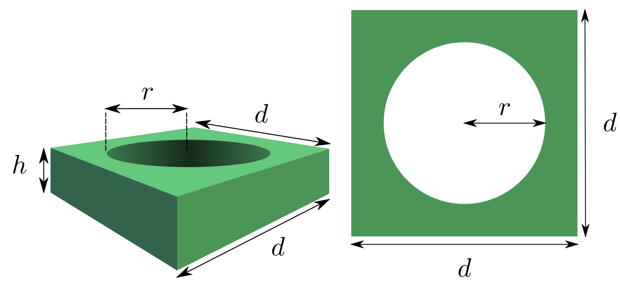


Fig. 1. *Illustration of metamaterial unit cell in 3D (left) and 2D from above (right). The substrate, shown in green, is a square prism of side length $d$ and height $h$. There is a hole of radius $r$ in the centre of the square. The spacing in between the centre of the hole in this cell and the centre of the hole in all adjacent cells is $d$.*

A unit cell of this metamaterial is given in Fig. 1. This metamaterial is non-resonant, and has no conducting components. It therefore exhibits low loss, and can operate over a relatively wide bandwidth. By careful selection of the radius of the hole in the center of the unit cell, one may tailor the observed refractive index to a required value. The width of the unit cell is selected such that the lattice constant is sub-wavelength, taking into account the shortening of wavelength in the substrate. An operating frequency of $0.41$ THz was selected for this device, due to the presence of an atmospheric transmission window at that frequency [11], and a lattice constant of $70$ $\mu$m was found to be suitable at this frequency. High-resistivity float-zone silicon was chosen for the dielectric base, due to its low loss and reasonably high refractive index.

The lens is designed such that an indefinite number of these lenses may be placed side-by-side in order to expand the aperture size. This is achieved by exploiting the fact that a phase shift of $2\pi$ at the output surface of the lens is equivalent to a phase shift of zero. This technique is inspired by the compact design of a Fresnel lens. The sample that has been designed in this work is therefore only a single period of a prospective practical design. See Fig. 2 for an illustration of a single lens period.

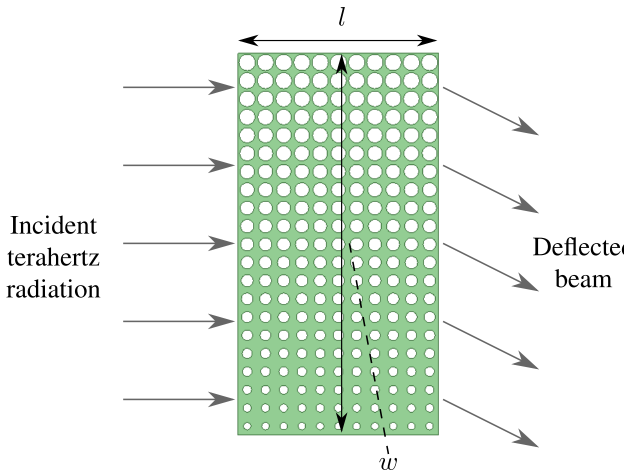


Fig. 2. *One period of the beam deflection metamaterial, showing lens thickness, $l$, and lens period width, $w$. Terahertz radiation is deflected upon transmission through the device.*

All design, simulation, and optimisation was carried out using the commercial electomagnetics software Ansoft HFSS 15.0. Master/slave boundaries were used for the top surface, the bottom surface, and both sides, with the latter case exploiting the periodicity of the device.

A lens with a deflection angle of 45° has been designed. The lens thickness is $l = 770$ $\mu$m, and the lens period width is $w = 1050$ $\mu$m. Hole radii ranged from 12.50 $\mu$m to 29.19 $\mu$m, and with a lattice constant of 70 $\mu$m, this gives a minimum clearance of $11.62$ $\mu$m in between adjacent holes. Note that the dielectric thickness, $h$, was set to an arbitrary value for simulation purposes, as the use of master/slave boundary conditions rendered it meaningless. The design was optimised using HFSS, and as a consequence of this, hole size does not increase monotonically with position as one may expect.

These lenses may be designed to have any deflection angle in between $0^\circ$ and $\pm 90^\circ$, by careful selection of the gradient of the refractive index characteristic and the width of the lens period, $w$. In practical designs, however, the lens period will approach infinity as the deflection angle approaches $0^\circ$, and the performance of the lens will degrade as it approaches $\pm 90^\circ$.

## III. Results

In order to simulate the performance of the lens, a TE plane wave was used to excite the structure at normal incidence. Electric near-field results are given in Fig. 3, and it is clear from the orientation of the transmitted wavefront that the desired beam deflection has occurred. Two images have been included, as the field distribution exhibited a strange, ebbing aberration, possibly due to some form of interference, and it was deemed prudent to include both extrema of its cycle. Additionally, the radiation maximum was determined to be in the $40^\circ$ direction, rather than $45^\circ$. These issues will be addressed in subsequent designs.

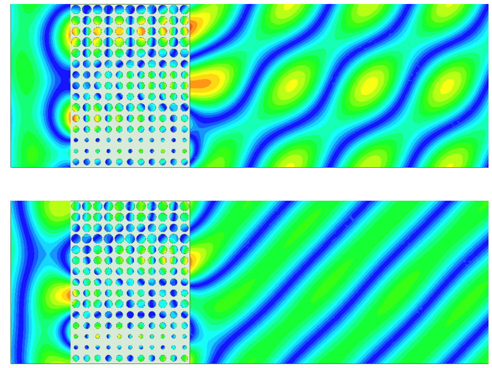

Fig. 3. *Near field results, represented with the magnitude of the electric field, for one period of the $45^\circ$ design. Two images are given, as the animated field is observed to cycle between the two patterns shown.*

## IV. Conclusion

A design for a flat-profile metamaterial lens that deflects a terahertz beam has been presented. The unit cell for this metamaterial is a hole in a square block of a dielectric material. This design is non-resonant. The thickness of the lens is under a millimetre, making it highly compact, and the aperture size can theoretically be scaled up to any multiple of the width of a single period. The simulation results show clear evidence of beam deflection, albeit with some unexpected issues which will be the subject of further work. Fabrication of this device is presently underway.

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