# Negative refracting materials at THz frequencies

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***Abstract*—We demonstrate here, for the first time, the construction of artificial materials, which theoretically possess two separate pass-bands utilizing the difference between positive and negative refraction in the terahertz frequency regime. Experimental testing of these devices is currently being undertaken using both broadband pulsed sources and narrow frequency quantum cascade lasers.**

## I. Introduction And Background

NEGATIVE refraction was first observed in uniform materials which are characterized by both negative permeability and permittivity. However, this is not a necessary condition for its observation. In more recent times it has been demonstrated that this phenomena can be achieved using the lowest photonic band of a dielectric structure possessing neither a negative refractive index nor a negative group velocity [1]. Recently, we have demonstrated the use of photonic structures within the terahertz frequency region to both filter the radiation [2] and cause a narrowing to the pass band at normal incidence [3]. This work has been extended to consider the propagation of waves, incident obliquely on prism-like two-dimensional hexagonal structures and utilizes the distinction between positive and negative refraction to form a filter. By varying the angle of incidence, it is in principle possible to tune the filter.

## II. Theoretical Considerations

In a recent paper, calculation of the dispersion relation for a hexagonal metallic photonic crystal has been undertaken [4]. These calculations indicate that the group velocity is parallel to the wavevector in band 1 and anti-parallel to the wavevector in band 2. For a wave incident on this photonic crystal matching the component of the wavevector parallel to the interface indicates that frequency components within band 1 are positively refracted, whilst those of band 2 must be negatively refracted since the transmitted wave must propagate away from the interface. Finite-difference time-domain simulations have also been undertaken using plane waves with frequencies within both bands and the results can be seen in figure 1.

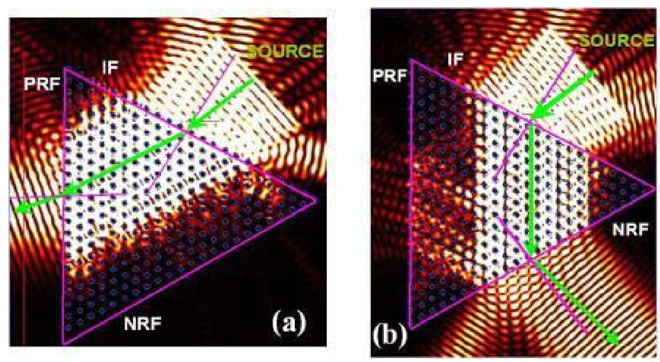


Figure 1: Simulation of electric field when plane wave is incident on prism. (a) For frequency f=1.136 THz positive refraction occurs, while in (b) with f=1.344 THz negative refraction occurs.

The spectral dependence of the radiation flux of both the positive and negative refraction facets is shown in figure 2. Here, an incident broadband pulse has been filtered, with frequencies within band one emerging through the positive refraction facet, and frequencies within band two at the negative refraction facet.

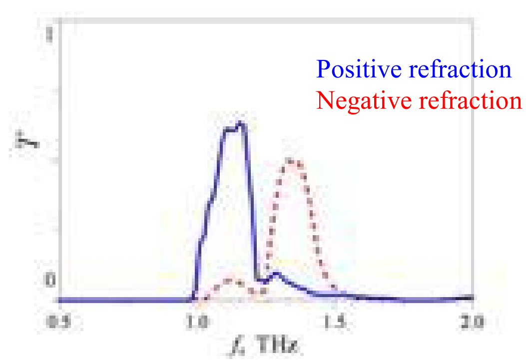


Figure 2: Spectral dependence of radiation flux for incident beam at an incident angle of 20°.

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## III. Experimental work

Micromachining techniques have been used to construct various prisms, having a hexagonal lattice structure, as shown in figure 3. This technology is ideally suited for the fabrication of THz metamaterials, since it produces three-dimensional surfaces and structures on a sub-micron to millimeter scale. The prisms are made from gold coated, high aspect ratio polymer pillars. Briefly, backside UV exposure of SU8-50 on glass was used to fabricate the structures, before they were sputtered with gold, since the polymer SU8-50 is transparent to terahertz radiation. More details of this technique have been published elsewhere [2], but it should be noted that for the high fill factor structures, critical point drying was used to ensure a stiction free release.

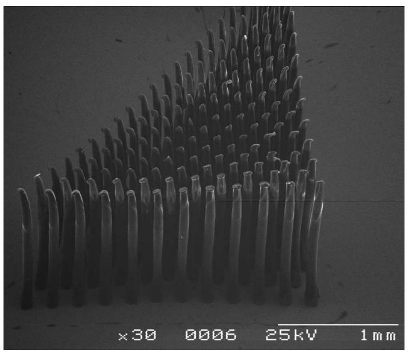


Figure 3: SEM image of micro-machined photonic crystal.

Within each structure, the fill factor and lattice parameter determine the J point frequency, the frequency at which the onset of negative refraction occurs. Lower fill factors and larger periods correspond to a decreasing of this frequency, and hence the point at which the onset of negative refraction occurs. Furthermore, altering the angle at which light is incident on the structures leads to a change in the frequency range over which negative refraction is allowed, which allows one to tune the filter in principle.

Currently, experimental testing of these devices is being undertaken using both a broadband pulsed THz source and also a narrow frequency quantum cascade laser. In both sets of measurements, great care must be taken to ensure that the THz beam is confined within the prism structure.

## IV. Conclusion

Recent theoretical work has shown that it is possible, in principle, to produce photonic crystals whose band structure is such that they will negatively refract THz radiation which is incident upon them. These structures have been fabricated using micromaching techniques, and are currently being tested to validate the predictions.

## V. Acknowledgments

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