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High numerical aperture and low-loss negative refraction based on the fishnet rich anisotropy

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Abstract

In this paper we report both numerical and experimentally high numerical aperture on a mesostructure based on fishnet-like building blocks. Under the indefinite media framework, we are able to identify a negative refraction never cutoff band (3rd band of the extraordinary transmission metamaterial) with low-losses at millimeter-waves. We relate negative refraction with the diffraction modes of the periodic structure. The work is another step forward in the new but rapidly evolving subfield of negative refraction metamaterials by anisotropy. The breadth and utility of this approach suggests that metamaterials at their meso-scale may circumvent the problem associated to narrowness and losses exhibited by negative refractive index media at their subwavelength domain, while still being away from the wavelength scale of electromagnetic band-gap.

Keywords: Negative refraction; Fishnet; Indefinite media; Anisotropy; Metamaterials; Extraordinary transmission

1. Introduction

Negative refraction [1] is probably the most widespread and successful result amongst the numerous achievements of metamaterials. Indeed, the experimental observation of negative refraction [2] – using a wedge made of the nowadays classical combination of split ring resonators ($\mu < 0$) [3] and wires ($\varepsilon < 0$) [4] – was a crucial push to develop the topic in its infancy, along with the possibility to get perfect resolution, which also invoked negative refraction [5]. The difficulty of obtaining negative refraction metamaterials working at optical frequencies with the aforementioned traditional arrangement was soon noticed, and other strategies were inspected. On the one hand, other topologies were investigated with more or less fortune [6]. On the other hand, some efforts were directed towards finding alternative routes to negative refraction beyond the strategy of doubly negative structures, as for instance anisotropic media, termed as indefinite media in this context [7]. Four different cases (cutoff, anti-cutoff, never cutoff and always cutoff) were identified depending on the relative sign of the permittivity and permeability tensors. Cutoff media support wave propagation for any transverse component of the wave vector below cutoff, whereas anti-cutoff media only propagate above it. Of special interest is the case of never cutoff media that admit a propagating wave for any transverse wave vector or angle of incidence. This tensor description has also its translation into isofrequency curves as follows: cutoff, anti-cutoff, never cutoff and always

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cutoff correspond to elliptic, hyperbolic, hyperbolic and imaginary, respectively.

Unquestionably, the most promising realization of a negative refraction metamaterial at optics is the so-called ''fishnet'' structure [8,9]. Although not evident at first sight, this structure is simply a pair of Extraordinary Optical Transmission (EOT) [10–13] plates, as we identified in 2006 [11]. EOT refers to those peaks of high transmission through subwavelength hole arrays.

From initial work on EOT phenomena at millimeter-waves [11], we found that stacking perforated plates (termed by us extraordinary transmission metamaterial) a backward-wave mode emerged inside [12,13] and, later, could demonstrate negative refraction employing a wedge [14]. As negative refraction took place exactly at the extraordinary transmission resonance (a phenomenon originally found in the infrared), we explicitly stated that the same structure should work at optics. This point was soon after confirmed in the infrared [15] (although here it was termed as stacked ''fishnet''), demonstrating factually our assumption.

However, negative refraction in the wedge depends on the geometry: the backward-wave excited in the longitudinal dimension gives rise to a negative phase difference at the output face, which combined with the wedge geometry leads to a negative beam deflection [14–16]. Thus, we performed a further study to demonstrate intrinsic negative refraction with a flat stacked hole array (i.e. backward-wave propagation in two axes, leading to negative refraction without any geometrical assistance) [17], a fact confirmed in theory in [18]. Recently we extended the analysis in [19] with an important conclusion: the negative refraction numerical aperture in the extraordinary transmission band is moderately narrow and highly lossy. Similar results for 2 stacked plates in the near infrared have also been recently reported [20].

In this letter we address accordingly the challenges of enhancing the numerical aperture and minimizing losses on the fishnet-like metamaterial by investigating in detail the higher order bands under *P*-polarization. The analysis is done in terms of the indefinite media of [7], where four different cases (cutoff, anti-cutoff, never cutoff and always cutoff) are identified depending on the relative sign of the permittivity and permeability tensors. As a final remark, notice that at these higher frequencies, the fishnet-like metamaterial falls within the realm of mesostructures.

2. Infinite structure: isofrequency curves

The structure under investigation is a doubly periodic and dielectric loaded hole array, the same used in [13,17,19], see inset of Fig. 1. The parameters of the structure are: transversal periodicities, $d_y = 3.4$ mm and $d_x = 1.5$ mm; hole diameter, $a = 1.2$ mm; nominal dielectric slab characteristics, permittivity $\varepsilon = 2.43$ and height $h = 0.49$ mm; metallization (copper) with conductivity $\sigma = 5.8 \times 10^7$ and thickness $t = 0.035$ mm; stack periodicity $d_z = h + t = 0.525$ mm. Numerical results were obtained using the commercial code CST Microwave Studio™ [21] and measurements were done employing an ABmm™ quasi-optical vector network analyzer, with the set-up described also in [17,19], see Fig. 1.

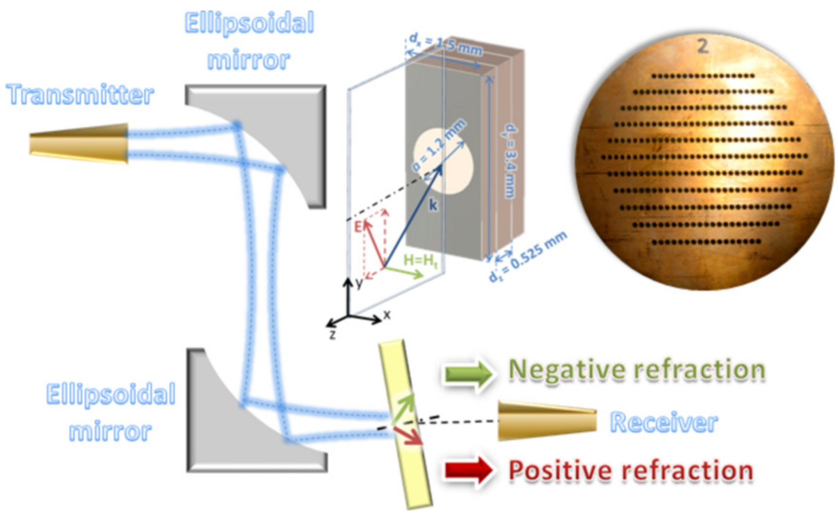

Fig. 1. Schematic showing the experimental setup to characterize the sign of refraction. (Inset left) Unit cell representation showing the dimensions and the field components. (Inset right) Photograph showing a hole array wafer.