Negative Index Materials Based on Rods with Refractive IndexProfile

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Metamaterials: from random to periodic
Jackson Hole, USA

General remarks to the Negative Index Materials (NIM)

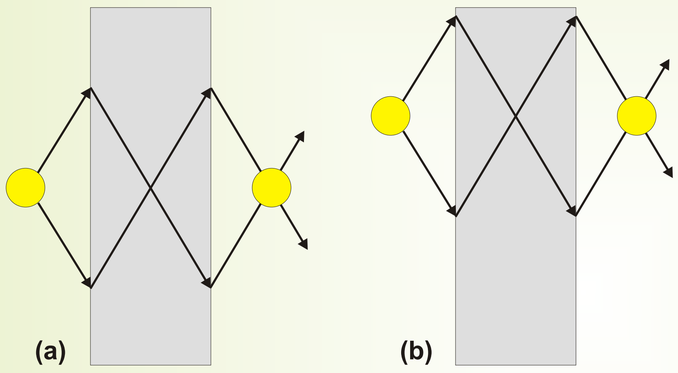


Figure 1 Negative index materials make plane plate lens (a). For the lenses with NIM the optical axis is absent (b).

Negative index materials (NIM):

- $\varepsilon < 0$ and $\mu < 0$

- cannot not be found in nature;

- can be fabricated as Photonic Crystals (PCs) or some other composite materials based on natural materials.

The concept of the *fish-eye* rod

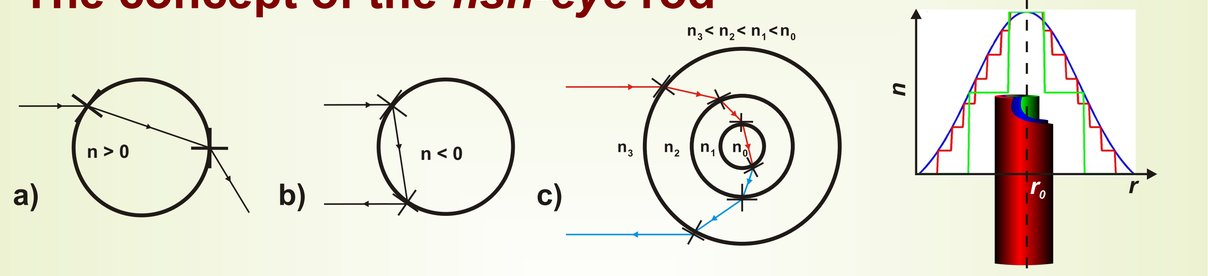


Figure 2 The schematic representation of the origins fish-eye concept. It shows the ray bending in a cylinder with n > 0 (a) and the beam bending similitude between the homogeneous NIM cylinder (b) and the fish-eye cylinder (c).

The elementary building blocks of the design are dielectric rods with a changeable refractive index. Its gradient resembles a "fish-eye" profile given by:

$$n(r) = \frac{n_0}{1 + \left(\frac{r}{r_0}\right)^2}$$

where r is the distance from the center of the rod and n_0, r_0 are some constants

Simulations of the NIM with the *fish-eye* rod

For proving that NIM can be made from *fish-eye* rods:
1. Define the frequencies where the *fish-eye* rod has an $n < 0$;
2. To obtain bulk NIM fill a volume with such *fish-eye* rods, i.e. arrange them in a triangular lattice with $a = d$, d is the fish-eye rod diameter.
3. Check if the filled volume focuses the radiation and if exhibits features of the plane plate lens.

!!! Question: Having a perfect triangular lattice the NIM effect can arise from the PC effect or is it solely determined by the fish-eye features?

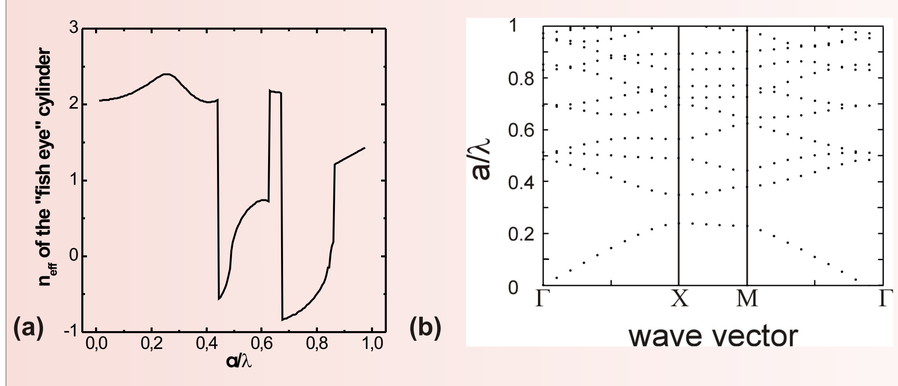


Figure 3 The dependence of the refractive index on the radiation wavelength for a *fish-eye* rod consisting of three layers (a). Photonic band structure of 2D PC consisting of triangular lattice of *fish-eye* rods in vacuum (b).

- Good focusing occurs at the wavelength $a/\lambda = 0.45$ and $a/\lambda = 0.67$, and no focusing is observed at $a/\lambda = 0.55$.

- ***According to the band structure calculations, the slab should not demonstrate focusing at the wavelength $a/\lambda = 0.75$, while the PC slab shows good focusing properties at this wavelength. It is purely an PC effect!!!***

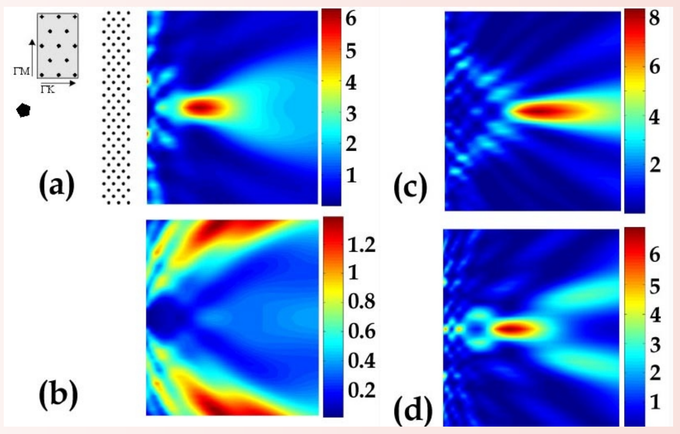


Figure 4 Electric field intensity map of a cross-sectional view of the 2D source-image system when imaging by a triangular lattice PC slab consisting of “fish-eye” rods at the radiation wavelength $a/\lambda = 0.45$ (a), $a/\lambda = 0.55$ (b), $a/\lambda = 0.67$ (c), and $a/\lambda = a/0.75$ (d).

Measurements of the NIM with the *fish-eye* rod

For making the measurements:
1. The microwave range of the frequencies is chosen;
2. Choose the right materials in order to form the desired refractive index profile;
3. The obtained NIM is a model system that can be scaled to IR or even visible provided the right materials and features sizes are properly selected.

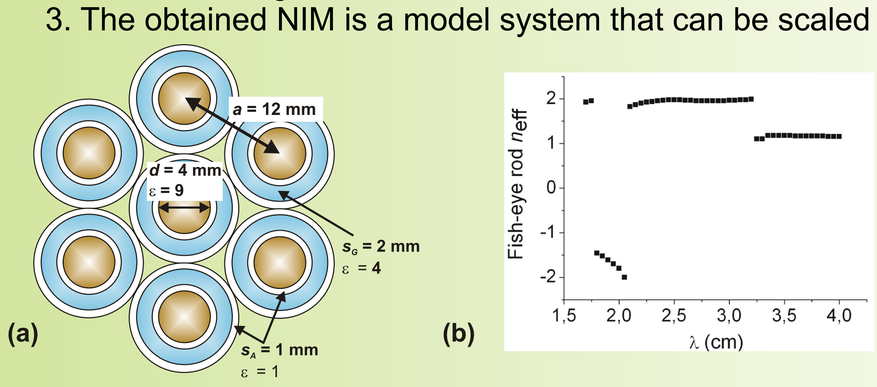
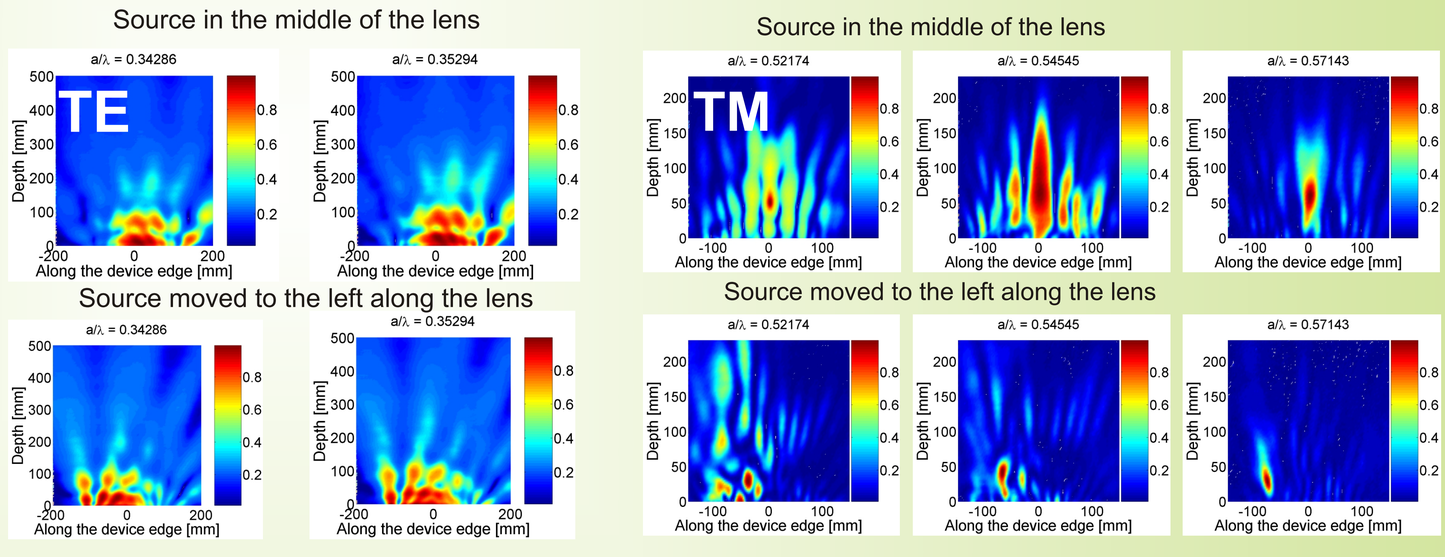


Figure 5 The following materials are considered (a):
(1) inner cylinder - Al_2O_3 rods, d = 4mm;
(2) second layer is formed by a tube of glass with $\varepsilon = 4$ with the wall thickness s_G = 2mm;
(3) as final layer is used air, i.e. a = 12mm.
The fish-eye rod n_{eff} upon the radiation wavelength (b).



Discussion

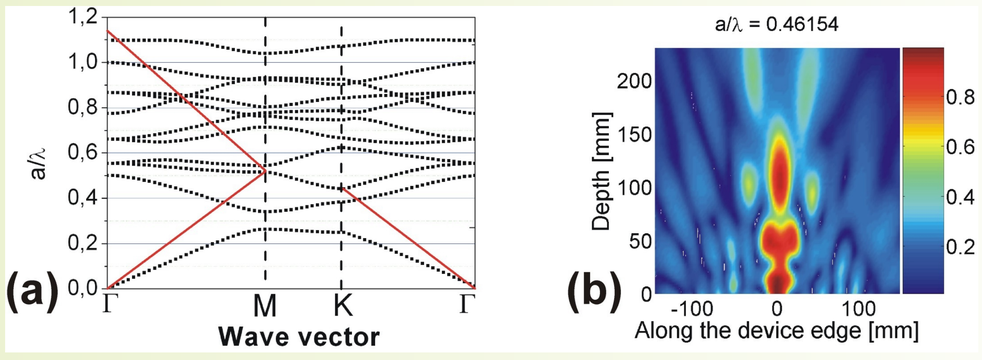


Figure 6 The PBS for the PC consisting of fish eye rods for the geometry shown in Fig.2. Calculations are done for the TM polarization (a). Red line – light line for n = -1. The EM radiation distribution for the *fish-eye* slab for $a/\lambda = 0.46$ (b).

- The NIM effect of the periodically assembled structure is a competition between the properties of the fish-eye cylinders and their group effect.

- The red lines indicate the light lines for n = -1 and their intersection with the PBS show the frequencies where the NIM effect due to the PC is expected to occur.

- A wavelength obtained at the intersection of the light line with the PBS is $a/\lambda = 0.46$ for which good focusing is found purely effect of the PC!!!