# Quasi-zero Average Refractive Index Photonic Crystals Metamaterials Collimating Infrared Light over Large Scale

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Negative refraction has been the precursor effect opening the road to new possibilities in materials properties, now classified as metamaterials, i.e. artificial materials with properties which are beyond their constituent real materials. Complementary media introduced by Pendry and Ramakrishna [1] are a generalization of the concept of perfect lens. However, alternating positive index and negative index material, a gap appears when the condition of zero average refractive index is obtained [2]. Such unusual zero-average index bandgap doesn't scale as usual bandgap based on the Bragg phenomenon. Respect to Double Negative Refraction (DNR) materials, Photonic Crystal (PhC) represent an alternative way to realize NIMs [3], that can be usefully described using spatially dispersive approach [4], an approach that is consistent with usual approach follow in NIMs based on ε and μ negative. In the present work we consider a silicon based PhC working at frequencies around 1500 – 1600 nm, where the guiding silicon layer is 1.5 μm thick in a Silicon on Insulator (SOI, with a $SiO_2$ layer 1 μm thick) that provide the vertical confinement. Realising in such SOI a hexagonal air-holes PhC where the hole radius *r* and lattice parameter *a* have a ratio r/a=0.38, at the normalised frequency $\omega_n$=0.305 behaves as a medium with effective index $n_{eff}$=-1. In fact the EquiFrequency Surface of such PhC calculated for $\omega_n$=0.305 (Fig. 1) has practically the circular shape of an isotropic medium whereas the group velocity is inward directed in opposite direction of the corresponding wavevector $\vec{k}$ . We pay a particular attention to the design of the PhC termination in order to slightly move from the zero average index condition and to match, in meantime, the energy flux at PhC interface. In such a way the transmission of the incident wave is maximized, optimizing also the coupling of the evanescent component. Following such requirements we design a Quasi-Zero Average Index heterostructure based on PhC that is shown in Figure 1b. Figure 2 shows the SEM images of the fabricated device on SOI with an area of 2x2 $mm^2$ò the devive is made by Electron beam lithography using the new VB300 by Vistec and RIE-ICP etching by Oxford Plasmalab 100 (Chromium etching: Cl – $O_2$ 24 min, ICP Silicon etching: gas chopping process 30 steps, $SF_6$-Ar for the Etching step (6 sec) $CHF_3$-$CH_4$ for the deposition step (7 sec)[5]). We characterized the device using an experimental set-up sketched in Fig. 3a. A CW laser, emitting at 1.55μm wavelength is connected to a lensed input fibre that produces an incident beam spot with a Full-Half-Width-Maximum FHWM=3 μm nominal value that we check experimetally using a knife edge integrated on the head of a optical fiber (made by Focused Ion Beam). Using input and output fibres we control the optimal coupling between incident beam, as delivered from lensed fibre, and PhC heterostructure. The light propagation inside the heterostructure is directly observed from the top using an IR camera. Figure 3b shows the entire propagation of the light along the 2 mm. Figure 3c shows the magnification of the beam image taken at the end of the device where the FHWM is still around 3 μm as the source. Propagation along a 2mm device is demonstrated theoretically and experimentally for the first time.

**References**

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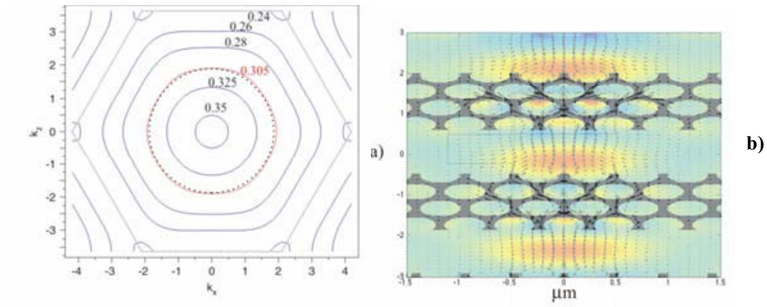


Figure 1: **a)** the EquiFrequency Surface of PhC calculated for $\omega_n$=0.305. **b)** Quasi-Zero Average Index heterostructure based on PhC, made by alternating positive and negative refractive index regions

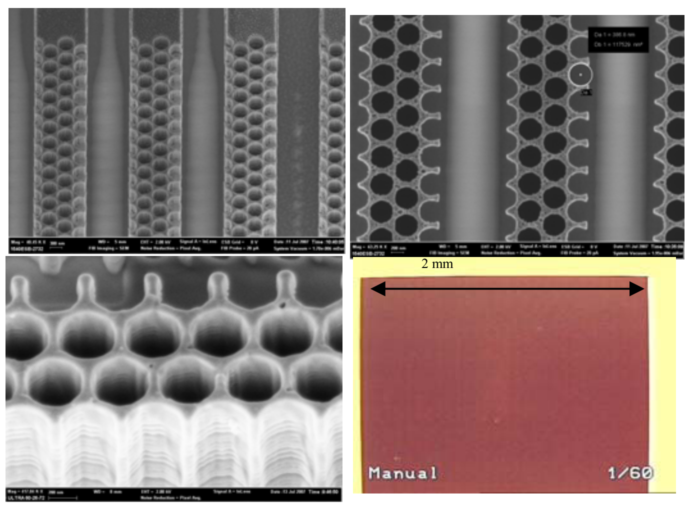


Figure 2: SEM images of the PhC structure made on the SOI substrate. The last optical micro-image shows the entire device 2x2 mm$^2$

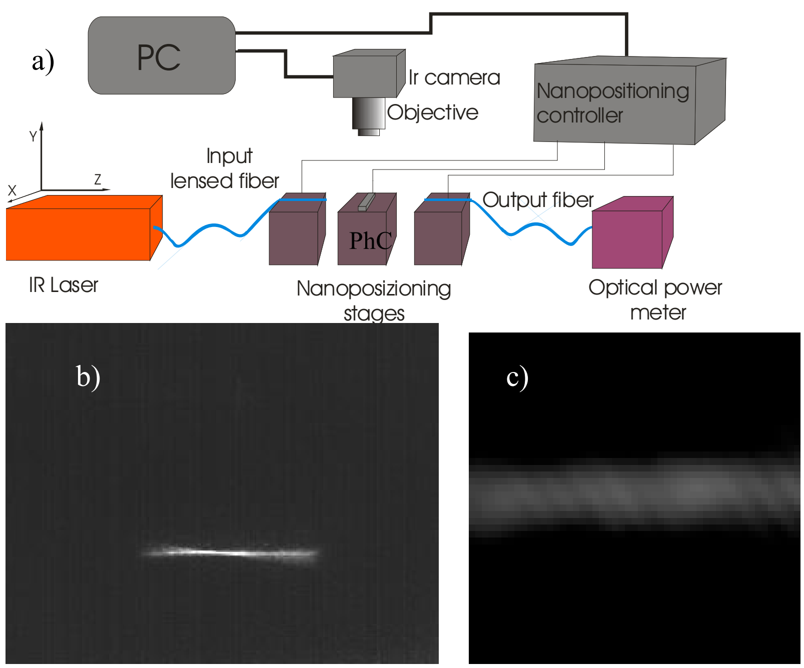


Figure 3: **a)**Optical set up. **b)** propagation of the light along the 2 mm. **c)** magnify image of the beam taken at the end of the device by the camera where the FHWM is still around 3 µm