Mater. Res. Soc. Symp. Proc. Vol. 869 © 2005 Materials Research Society D4.4.1

Efficient Focusing with an Ultra-Low Effective-Index Lens Based on Photonic Crystals

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ABSTRACT

This work focuses on photonic crystals (PC) that can be ascribed an effective index of refraction < 1 or even < 0. We investigate the possibility to design optical elements (in this case a lens) based on this type of PC. A new approach for determining the effective refractive index of PCs with unusual index of refraction is used, which is simpler than earlier methods based on analyzing equi-frequency surfaces in k-space. An ultra-low refractive index PC is given a form approximating a concave lens and is proven theoretically and experimentally that it efficiently focuses the electromagnetic radiation in the microwave range. Strong focusing effects are found for both polarizations (TE and TM mode). Intensity gains as large as 35 for TM polarizations and 29 for TE polarizations are found. Measurements are in a good accordance with simulations.

INTRODUCTION

Propagation of electromagnetic radiation in a Photonic Crystal (PC) is well understood in the long wavelength range, i.e. where the wavelength is large compared to the crystals' periodicity and energetically below the band gap. In this case PCs can be treated as homogeneous materials and all their parameters like n_{eff}, the effective index of refraction, are (relatively) easily calculated. In this case devices based on a PC have an $n_{eff} > 1$, given by $n_{eff} = ck/\omega$, where ω is the radiation frequency and **k** is the wave vector of the Bloch wave propagating in the PC.

However, more interesting phenomena are encountered in the short wavelength limit (energies above the band gap), where unusual dispersion functions and beam propagation are found. In this wavelength range, PCs may, for example behave as homogeneous material with an ultra-low index of refraction, meaning a $n_{eff} < 1$ or even a $n_{eff} < 0$ [1]. However, an index of refraction may also not be defined at all, or only in some approximation. We will therefore first discuss a method that allows to check rather easily if for a given wavelength and polarization state a given PC can be described, at least approximately, by an effective index of refraction, and what numerical value must be assigned to n_{eff} in this case. Using this method, suitable wavelength ranges are identified for which designing optical elements (here a concave lens) with ultra-low n_{eff} makes sense. The resulting lens is characterized exhaustively in two configurations: perfect order (perfect crystal) and strongly disturbed ("amorphous"). In what follows we report on extensions of the previous work [2] and present new results.

"PROBE MEDIUM" APPROACH

The probe medium approach exploits an earlier idea of Veselago [3]: At the interface of two media that have refractive indexes with identical absolute values, but different signs, no reflection will take place. As a result, a point source embedded in medium 1 at some distance to the interface, will be perfectly imaged in medium 2 on the other side of the interface (neglecting size effects); cf. Fig. 1a. Let medium 1 be a PC with an embedded point source, and now calculate the wave propagation for a homogeneous probe medium 2 with an adjustable index of refraction. Since the range of possible n_{eff} for the PC is limited, it is easy to see within a few relatively quick simulations, if point to point imaging is possible at all and if yes, which value of the index of refraction n_{p} of the probe medium produces the best image. Fig. 1b shows a case of optimal imaging; note that the small dimensions of the set-up cause the apparent non-perfection for this case. Larger PCs would give much better imaging, but this is not necessary at this stage and only increases computation time.

A result as shown in Fig. 1b thus asserts that i) an effective index of refraction can be defined for the case investigate, and ii) its value is given by $n_{\mathrm{eff}} = -n_{\mathrm{p}}$.

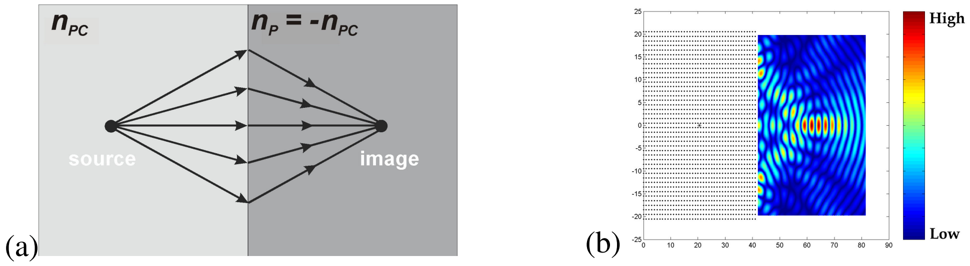

Figure 1 (a) Schematic view of the "probe medium" approach. (b) An example of simulation results for the case that n_{eff} exists.

PHOTONIC CRYSTALS WITH AN ULTRA-LOW INDEX OF REFRACTION

Using the probe medium approach the interesting (i.e. $n_{\mathrm{eff}} < 1$) wavelengths regions for a simple PC consisting of dielectric rods with diameter d and dielectric constant ε_{r} arranged in a square lattice with lattice constant a were identified; the result is shown in Fig. 2 for the electrical or magnetic field of the incoming radiation transversal to the rods (TE and TM mode), respectively.

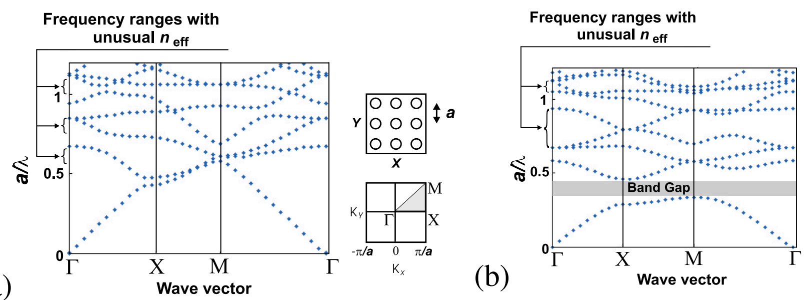

Figure 2 Dispersion diagram for the (a) transversal electric polarization and (b) transversal magnetic polarization. Intervals where $n_{\mathrm{eff}} < 1$ are outlined for both polarizations.

The lattice constant of the PC is $a = 2.8$ cm and the radius of the cylinders is $d = 0.19a$. The dielectric constant was chosen as $\varepsilon_{\mathrm{r}} = 9.6$, which gives a refractive index of $n_{\mathrm{r}} = 3.1$, consistent with Al_2O_3 as material. As the dimension suggests, the corresponding PC is scaled to the microwave frequencies of $f \approx 10$ Ghz. It goes without saying, however, that the basic set-up scales linearly to any frequency; their features are identical to dispersion curves calculated with more involved methods. In quantitative terms, the effective index of refraction, calculated using the probe medium approach, will generally be smaller than unity for the following (approximate) values of a/λ: $a/\lambda \in (0.5;0.68) \cup (0.7;0.86) \cup (1;1.15)$ for the TE mode and $a/\lambda \in (0.67;0.92) \cup (1;1.1)$ for the TM mode. From this calculations it can be expected that a concave lens shaped from this PC will focus the radiation in the frequency regions outlined above. In what follows we prove that this is indeed the case.

EXPERIMENTAL RESULTS AND DISCUSSION

The concave lens used for the experiments consists of 112 alumina cylinders and has the form shown in Fig. 3a or 3b. While Fig. 3a shows a lens "cut" form a perfectly periodic PC, Fig. 3b shows an arrangement, where each rod has been randomly displaced from the regular lattice position by up to 30 %; this lens will be called "amorphous".

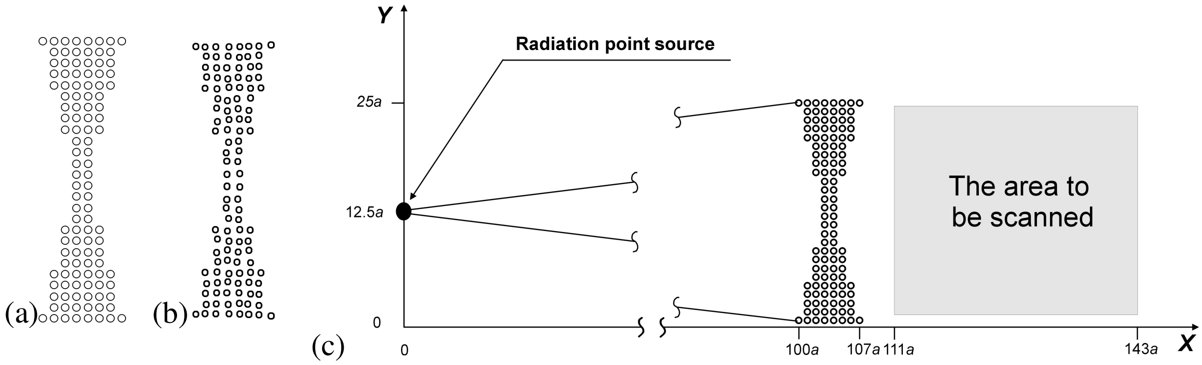

Figure 3 (a) Top view of the measured lens that consists of periodically arranged alumina rods. (b) An "amorphous" lens is used as well. c) The electromagnetic field distribution is scanned behind the lens at a height of half of the rod length.

All experiments are performed in an anechoic room that is "dressed" with special microwave absorbing plates. A radiation point source is placed at 100a from the lens edge (Fig. 3c). The field behind the lens is scanned in the (XY) plane that cuts the rods axis in the middle. All the scans involve an area of 32a x 25a, see Fig. 3c. The scanning resolution is 0.5 cm. Fig. 4 compares several experimental results with the respective simulations; including cases where n_{eff} is not defined. Shown is the power gain distribution that is calculated as the ration of the $E^2(x,y)/E_0^2(x,y)$, where $E^2(x,y)$ is the local electromagnetic power in the presence of the lens and $E_0^2(x,y)$ is the local electromagnetic power in its absence. The simulations are done using a somewhat modified version of the multi scattering approach [4,5]. Fig. 5a shows the case when focusing hardly exists (note the scale!). The measured power gain distribution is relatively noisy, but still in good agreement with the simulations. Fig. 4b shows a peculiar case for the TE polarization: Beam splitting, a potentially useful feature, indicating that in wavelength regions where obviously n_{eff} does not exist, PCs may still be used for special applications. While in this case both excited modes are relatively weak, they exist, and optimization appears possible. Finally, Fig. 4c and 4d give clear evidence of focusing for both polarizations. While efficient focusing was achieved, and the measured results agree quite well with the simulations, a quantitative comparison shows some minor discrepancies, which indicate that more work is needed for a complete understanding.

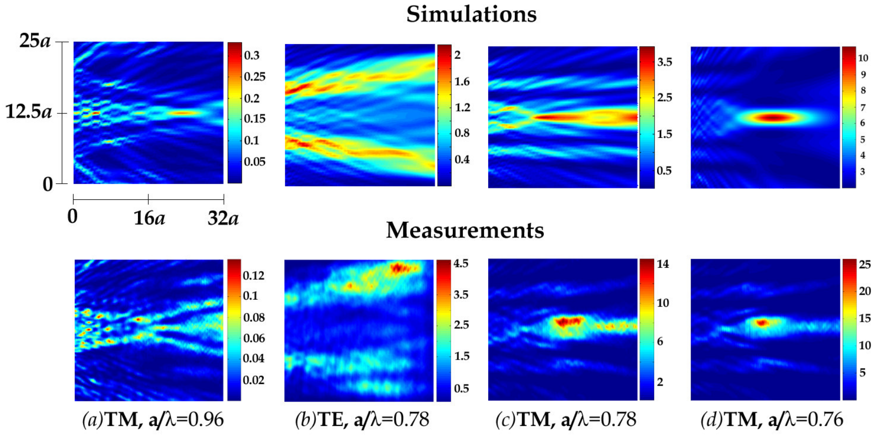

Figure 4 (a) – (d) Simulated and measured power gain of the concave lens for the TE and TM polarizations and various configurations. Note the difference in the power gain scale! For details refer to the text.

Fig. 4c-d indicate that the focusing lobe is still very "noisy", i.e. the focal spot is not clearly defined because of the slow radiation decay from the middle of the focusing spot. Fig. 5 presents the best focusing that could be obtained for the TE and TM mode. So far, power gains as high as 29 for the TE mode and 35 for the TM mode could be achieved. To the best of our knowledge no other experimental results were presented so far with comparable focusing power.

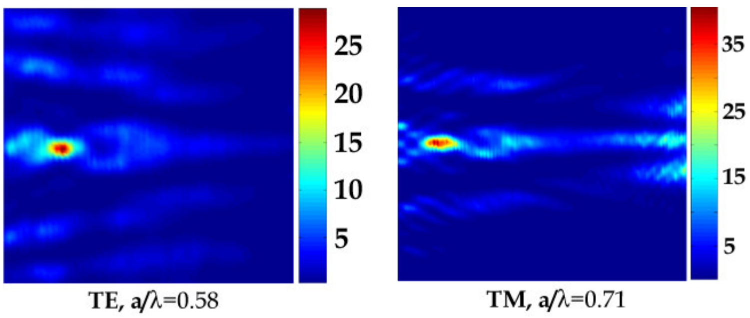

Figure 5 Best measured power gain distribution for TE and TM polarization. This is the highest efficiency that could be measured with the lens under investigation.

Nominally, the wavelength λ_{PC} of radiation propagating inside a PC with an ultra-low index is large since it is given by $\lambda_{PC} = \lambda_{vac}/\, n_{eff}$ and one might expect that this large effective wavelength is not sensible to crystal irregularities. If that expectation can be transferred to optical elements like the concave lens that in itself is smaller then or just comparable to λ_{PC} is doubtful and best checked by experiments. Generally, it is difficult to calculate this effect since an amorphous structure like the one shown in Fig. 3b, will definitively not have any band structure like those shown in Fig. 2a-b.

While simulations predicted that a displacement of the cylinders up to 30 % from their regular positions would not fully destroy the focusing effect, this was only partially confirmed by the experiments. The amorphous lens usually does not show focusing in frequency regions where the regular lens focuses, but focusing was found in other regions.

In Fig. 6 and Fig. 7 a direct comparison of the intensity gain distribution for the regular lens and the amorphous lens is presented. For the TE polarization is observed that the amorphous structure "collects" better the rays. For some frequencies, where for the regular lens no evident focusing spot could be defined, the amorphous lens focused the radiation, however weakly, c.f. Fig. 6a and Fig. 6c. Note also that the intensity gain remains unaffected, although it is relatively small.

Why the amorphous lens focuses the radiation for some frequencies where the regular lens simply behaves as a strong disperse medium as is shown in Fig. 6b, is open to speculation at present. The focusing spot is poorly defined, and its intensity is relatively weak, but that the rays tend to converge to a spot is clearly visible.

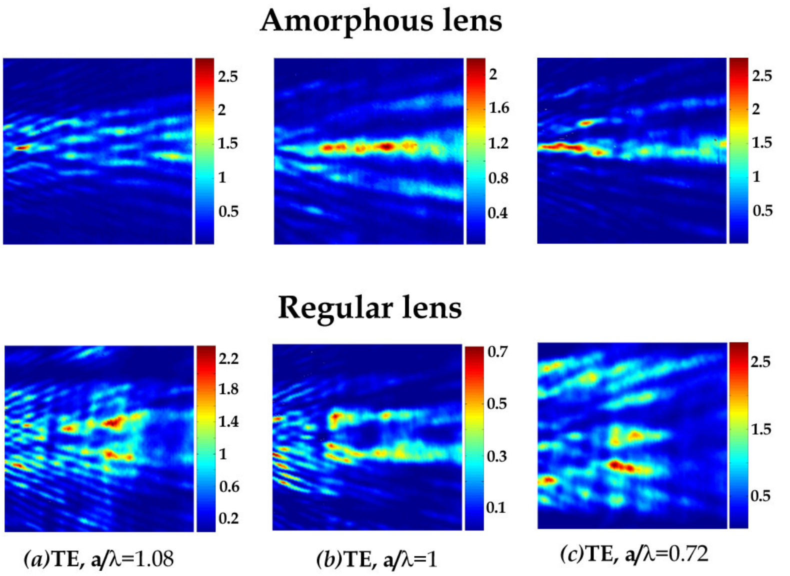

Figure 6 (a) – (c) Experimental results for the TE polarization and various wavelengths in comparison to the field distribution for the crystalline lens.

In Fig. 7 several cases of focusing for the amorphous lens are shown for the TM polarization. As for TE polarization, the amorphous lens tends to focus better for the wavelengths used than the crystalline lens, c.f. Fig. 7a-b. As the wavelength increases, the focusing lobe becomes sharper, but the focusing power gets weaker. In contrast to the TM polarization the focusing spot area becomes smaller with increased wavelength. Thus, for $a/\lambda = 0.64$ the area of the focusing spot is about $0.65 \cdot \lambda^2$, which is well beyond the focusing limits of generic lenses known from linear optics. However, it is certainly premature to invoke the term superlens at this point.

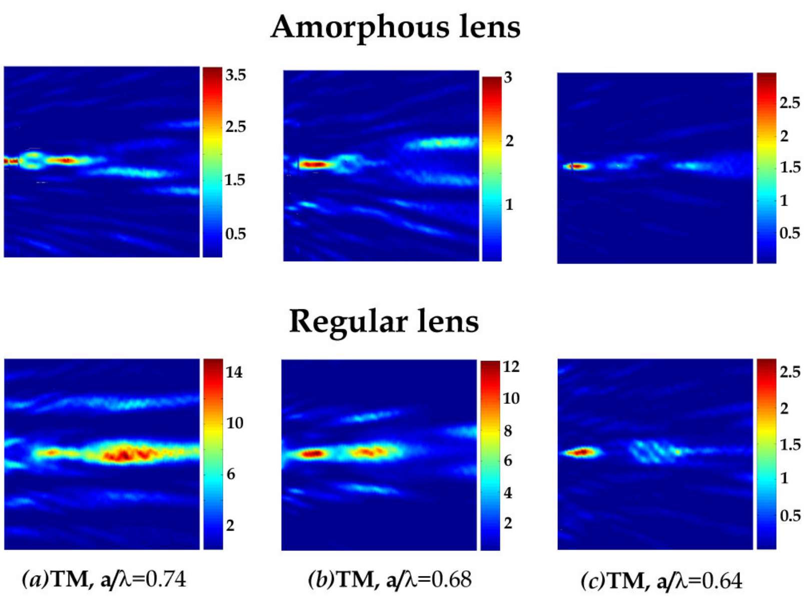

Figure 7 (a)- (c) Focusing results for the amorphous lens in the case of TM polarization in comparison with the results obtained with the regular lens for increasing wavelength.

CONCLUSIONS

Some earlier works also discussed possible lenses made from PCs [6,7], but good focusing with unusual n_{eff} has not been shown before. Gupta and Ye [6], e.g., proposed and measured a convex lens based on alumina rods PC, but with an $n_{eff} > 1$. For our lens, having a radius of curvature of 62.5 cm, best focussing conditions correspond to an n_{eff} = (-0.3 – +0.5), and its focusing efficiency is at least three times better than the lens discussed in [7].

In conclusion, our approach to unusual index metamaterials allowed for the first time to produce efficient "unusual index" devices based on PCs. This work is not limited to the PCs based on dielectric rods. It can be also extend to lenses done based on porous dielectrics [8] or 3D PCs.

The authors acknowledge the very helpful discussions with Prof. Dr. Georgi Popkirov and Dr. Sergiu Langa, as well as the great help of Jörg Bahr in lens construction and design.

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