MICROWAVE COMPONENTS BASED ON 2D PHOTONIC CRYSTALS WITH UNUSUAL INDEX OF REFRACTION

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ABSTRACT: This work reports on measurements of microwave components based on Photonic Crystals (PC) with unusual index of refraction, i.e. $n_{eff} < 1$. Particularly lenses based on different PC structures are investigated. All measurements are done in the microwave regime, i.e. for frequencies ranging between 6 and 15 GHz. Intensity gains ranging from 15 to 40, depending on the lens shape and radiation polarization, could be found. Some lens structures focus only in a very narrow wavelength interval, where always a optimum can be find, thus they operate as filters as well. Different kinds of beam splitting could be measured as well. Depending on the lens shape maxima of the beam split occur at different positions and with different intensities. Most of the experimental results will be compared to the ones predicted by theory. A very good agreement between measurements and simulations is evienced.

Keywords: photonic crystals; microwave components; microwave lenses.

INTRODUCTION

This work is focused on the analysis of different microwave components based on Photonic Crystals (PC) with an effective refractive index $n_{eff} < 1$. Still an open question remains under which conditions can a PC be considered as a homogeneous material described by a material parameter like effective refractive index. While for the long wavelength limit n_{eff} of the PC will be given by $n_{eff} = ck/\omega$, in the case of radiation wavelength comparable to the PC's lattice constant, their homogenisation becomes a difficult task. Notomi [1] stated that in this case, n_{eff} of the PC will be calculated as the ratio between the modulus of the quasi wave vector of the Bloch wave in the PC to the wave vector in vacuum. For those quasi wave vectors that are near the Γ point in the dispersion diagram at the band openings, the PC will behave as a homogenous material with $n_{eff} < 1$ or even negative. We consider that a PC shaped in the form of a concave lens, would have to focus the radiation. In what follows we prove that this is indeed the case.

EXPERIMENTAL

In our work the PC is built from alumina rods arranged in a square or hexagonal lattice. In the frequency range employed for the measurements, the dielectric constant of alumina is equal to 9. Lattice constant of the PCs is a = 2.8 cm, while the radius of cylinders is r = 0.18a. Calculated dispersion spectra diagram together with the frequency ranges where the PC is expected to behave as a homogenous material with an $n_{eff} < 1$ can be found elsewhere [2]. Employing a somewhat modified version of the multi scattering approach, the optimum shape for the concave lenses can be found for both types of the PCs, i.e. cubic, Fig. 1a, and hexagonal one, Fig. 1b. Due to the scalability of the Maxwell equations they can be reduced to the infrared or optical regions.

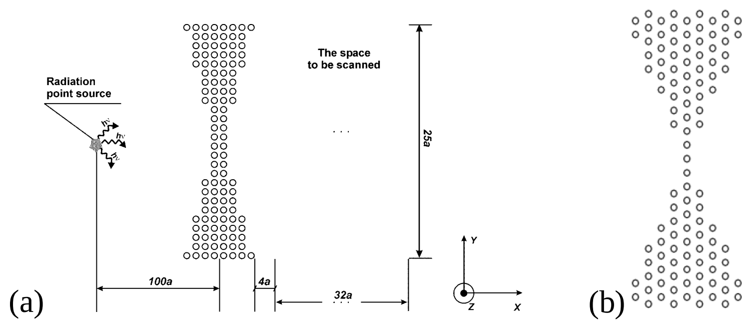


Figure 1 Top view of the concave lenses under consideration. (a) Cubic PC and (b) hexagonal PC. In (a) also a schematic representation of the measuring procedure is shown.

All measurements are performed in an anechoic room aligned with specially absorbing plates that help to avoid any reflections from room walls or formation of the standing waves. Figure 1b illustrates the measuring procedure. A dipole is used as radiation point source placed at 100a from the vertex of the lens. Another dipole is used as receiver in order to scan the field behind the lens. By means of a computer controlled machine the receiver dipole will be moved in the (X,Y) plane that cuts the lens in the middle. The total area that might be scanned is equivalent to 32ax25a. All the results throughout the work are presented as the distribution of the intensity gain (IG) which is calculated as the ration of the local field intensity with the lens to the field intensity without the lens: $IG = E^2(x,y)/E_0^2(x,y)$. Where this ratio is bigger than 1 local intensity gain is attested (or intensity is lost otherwise).

RESULTS AND DISCUSION

Results with the concave lens based on cubic PC are shown in Fig. 2 (more data can be found in [3]). Figure 2a shows measured focus, for the TM polarization at a/λ = 0.77, that is predicted by simulation as well, see Fig. 2b. It can be seen in [2] that the corresponding a/λ lies in the interval where the PC is supposed to behave as homogenous material with $n_{eff} < 1$ and thus focuses the radiation. We performed more measurements in the corresponding wavelength diapason and analyzed IG versus the inverse of the wavelength, Fig. 2c. One can see that values for the IG as high as 40 can be achieved. Moreover, there exist an optimum wavelength for which the lens exhibits strongest focusing (i.e. IG=40) and the focusing strength will decay sharply with changing the radiation wavelength. Hence, the lens might be used as a filter as well, i.e. it will efficiently focus only for a very narrow range of wavelengths (if not a single wavelength). Since the idea of the present lens is inspired by the geometrical optics (e.g. shape of the lens), the thin lens formula is used to asset the values for the effective refractive index of the lens n_{eff}^{lens} calculated from the measured focal length as a function of the (inverse) wavelength. Results are shown on the same cartoon in Fig. 2c. As expected, the obtained values are below 1 and even negative. One can observe that an inflection point exists. This point will correspond to the maximum in the IG. While it is hard to conclude whether the calculated n_{eff}^{lens} will match with the values of the n_{eff} of the PC for the same wavelengths, the obtained numbers could be used as characteristics of the lens. So far one can assume that the closer n_{eff}^{lens} is to 0, the stronger is the focusing effect.

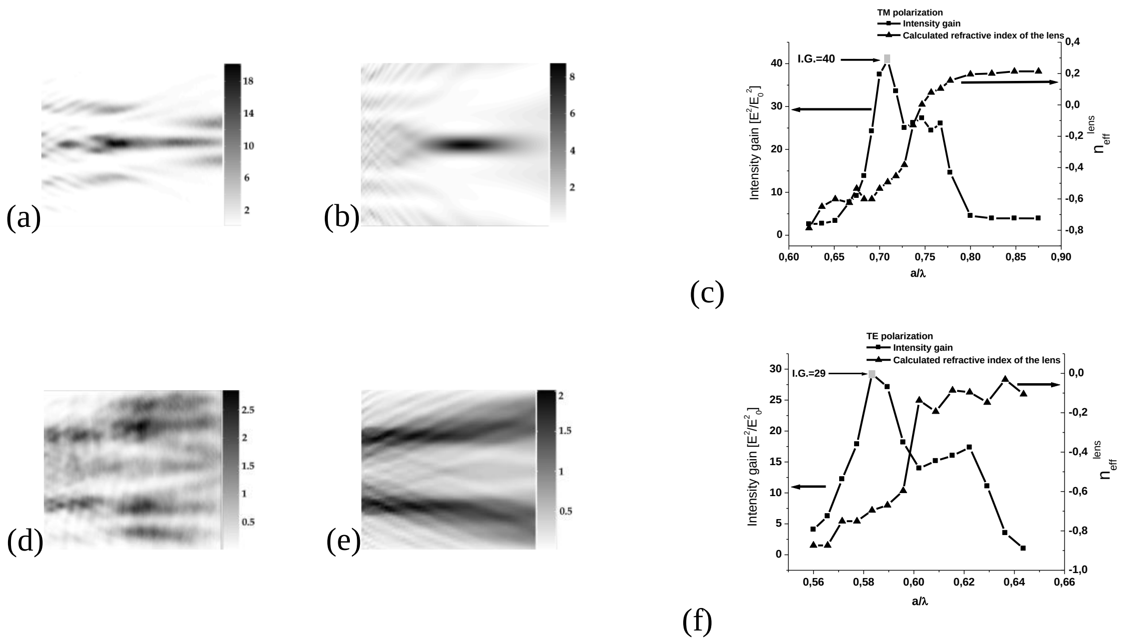
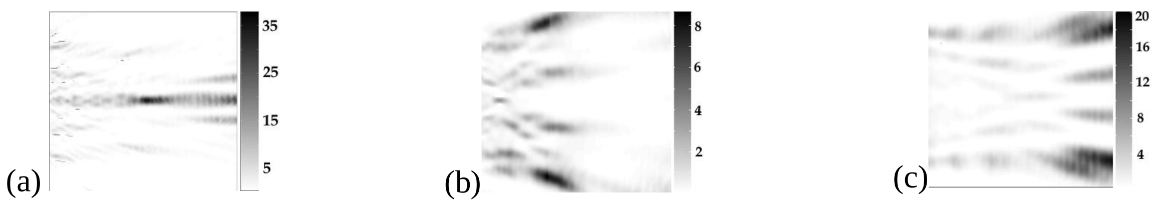


Figure 2 (a) Typical focusing for the cubic lens confirmed by the (b) simulation. (c) The lens efficiency and n_{eff}^{lens} variation with the inverse of the wavelength is shown for the TM polarization. (d) Beam splitting for the TE polarization could be measured and confirmed by the (e) simulation. (f) The lens efficiency and n_{eff}^{lens} variation with the inverse of the wavelength is analyzed for the TE polarization.

One particularity for the TE polarization is splitting of the beam. Figure 2d shows the corresponding measurements confirmed by the simulations in Fig. 2e. It is observed that beam splitting occurs at short wavelengths (a/λ = 0.8 for the case represented in Fig. 2d), whereas for longer wavelengths good focusing could be achieved. A quantification in this sense can be seen in Fig. 2f where the IG versus the (inverse) wavelength is plotted. For the TE polarization (similar to the TM) an optimum wavelength exists where the lens shows strong focusing effect, i.e. IG=29, thus the lens works as a filter for the TE polarization as well. Applying thin lens formula n_{eff}^{lens} can be calculated and the same behavior as for the TM polarization is observed. This allows, with stronger certitude, to state that the lens will focus stronger as $n_{eff}^{lens} \to 0$.

First results for the triangular lens are presented in Fig. 3. For the TM polarization a strong focusing could be observed for a/λ = 0.98, see Fig. 3a. In contrast to the cubic lattice lens, the focusing interval is very narrow and the change of a/λ with 5 % leads to the total absence of the focusing. Focusing over a larger interval of a/λ could be found indeed, c.f. Fig. 3d. Strongest value for the IG is slightly less than 30 and, as compared to the cubic lattice lens, the "filtering" effect is less pronounced. Again, an interesting feature of the TE polarization is the beam splitting. In contrast to the cubic lattice lens, it occurs here in two places depending on the radiation wavelength. Thus, if the wavelength is large the beam will split near the lens, c.f. Fig. 3b. As soon as the wavelength is decreased the beam will be split far beyond the lens margin, see Fig. 3c. A quantitative analysis of this effect is shown in Fig. 3e, where the "first splitting" is meant the one in the proximity of the lens and the "second splitting" stands for that occurring far from the lens edge.



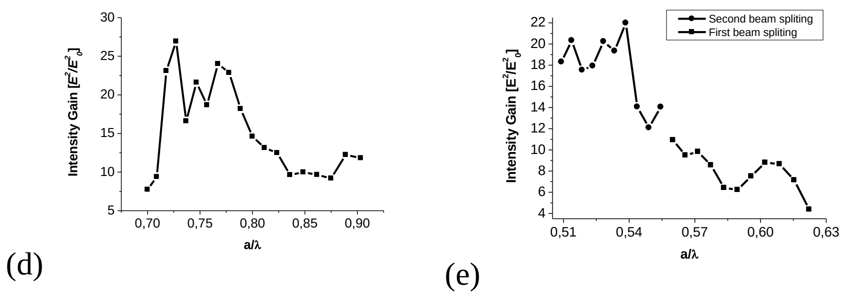


Figure 3. (a) Strongest focusing with the triangular lattice lens and (b-c) beam splitting. (d-e) Detailed analysis of both phenomena.

Note the following peculiarity of the triangular lattice lenses. According to the obtained results, the IG on the areas where the beam is split is much more intense as compared to that of the lens based on the cubic lattice. Particularly, IG as high as 22 was achieved, whereas with the cubic lattice lens IG of only 3 could be measured so far. Due to the lack in space simulations for the triangular lattice lenses are not illustrated here.

Generally, for the PC with $n_{eff} < 1$, as is the case here, the effective wavelength in the crystal is very large (if not approaching infinity): $\lambda_{eff} = \lambda / n_{eff}$. We proved elsewhere [4] that the functionality of the optical elements is tolerant, at least to some extent, to the fabrication imperfections: arrangement of the cylinders, their diameters, etc. For the cubic lattice lens, by a displacement of the cylinders with up to 30 % from their position, focusing effect will be still well preserved.

CONCLUSIONS

Photonic Crystals with $n_{eff} < 1$ prove to have a high potential for the design of enticing microwave and optical elements. The unusual beam propagation inside the crystal will enable one to design various types of lenses, filters and beam splitters. Depending on the type of the lattice involved in the design, lenses with additional functionality can be fabricated. Last, but not least, microwave and optical elements based on PC with $n_{eff} < 1$ prove to be tolerant to the fabrication imperfections, thus making them a serious competitor as host material for the emerging field of integrated optics. This work can be easily extended to porous (i.e. cylinders replaced by air columns) dielectrics as well [5].

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