Rapid Research Note

Focusing effect of photonic crystal concave lenses made from porous dielectrics

V. V. Sergentu[1], **E. Foca**[*, 1, 2], **S. Langa**[1, 2], **J. Carstensen**[2], **H. Föll**[2], and **I. M. Tiginyanu**[1]

[1] LLDSP, Institute of Applied Physics, Technical University of Moldova, Stefan cel Mare av. 168, 2004 Chisinau, Moldova

[2] Faculty of Engineering, Christian-Albrechts University of Kiel, Kaiserstr. 2, 24143 Kiel, Germany

Received 5 February 2004, revised 25 February 2004, accepted 25 February 2004
Published online 2 March 2004

PACS 41.20.Jb, 42.25.Bs, 42.25.Dd, 42.70.Qs, 42.79.Bh, 78.20.Ci

In the present paper we show the photonic band structure and transmittance spectra of photonic crystal (PC) consisting of porous dielectric and compare the results with the earlier published. Frequency ranges, where PC can be ascribed an effective index of refraction, are given and approximately indicated on the transmittance spectra. This helps to identify optical elements' properties made of porous dielectric: lenses in our case. The focusing effect of PC concave lens, working in the long wavelength limit and spectral regions with a negative refractive index, is investigated. We prove the good focusing effect of such lenses that can be easily fabricated.

It was suggested recently that periodic dielectric structures known as photonic crystals (PC) may exhibit an index of refraction n less than one or even negative [1, 2] which would enable one to design and fabricate novel optical elements with enticing properties [3]. While the first consideration of a negative n by Veselago in 1968 was largely ignored [4], Pendry's suggestions [3] started an intense debate about the meaning of a negative n and its practical realization. In this Rapid Research Note we present results of calculations of the interaction between electromagnetic waves and 2D photonic crystal in the form of porous structure using a modified version of the multiple scattering techniques [5]. We prove the focusing effect of a 2D PC concave lens in both the long wavelength limit where $n > 1$ and in spectral regions characterized by negative refractive index.

Calculations were undertaken for a 2D photonic crystal consisting of a cubic lattice of $8 \times 32 = 256$ parallel pores embedded in a dielectric matrix with the dielectric constant ε. The radius of the pores is $r = 0.49a$ where a is the lattice constant. We used a novel approach enabling us to determine whether n is well defined (at least in a good approximation) or undefined. The approach takes into account that the interface between two (homogeneous) materials with indices of refraction n and $-n$ would act as a perfect lens, i.e. a point source in the medium with index n will result in a symmetric point image in the medium with index $-n$. According to Veselago [4], there is also no reflection at such an interface. The basic idea of the method is the following: add a fictitious optical probe material with a variable refractive index n_p (the index p stands for "probe") to the PC under investigation, introduce a point light source into the photonic crystal, and calculate the wave propagation for various n_p. If conditions can be found where an acceptable image of the point source occurs in the probe material under mirror symmetry conditions, simple geometric optics dictates that (i) n_{PC} is well defined, and (ii) $n_{PC} = -n_p$. These conditions are quite general and apply to both $n_{PC} > 0$ and $n_{PC} < 0$. Due to space restrictions more details will be published elsewhere.

[*] Corresponding author: email: ef@tf.uni-kiel.de, Phone: (+49) 4318806188, Fax: (+49) 4318806178

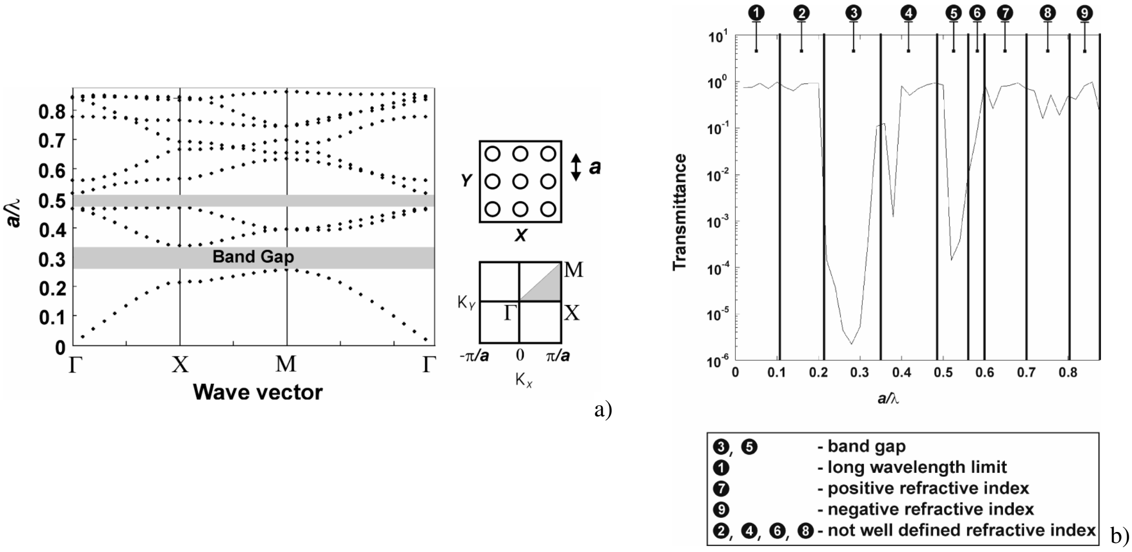
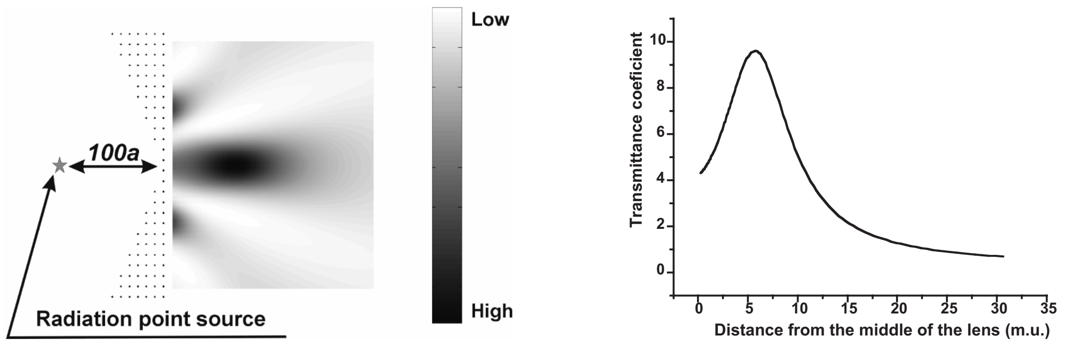


Fig. 1 a) Photonic band structure and b) transmittance spectrum of 2D PC consisting of square lattice of pores with $r = 0.49a$ in dielectric matrix with $\varepsilon = 11.4$.

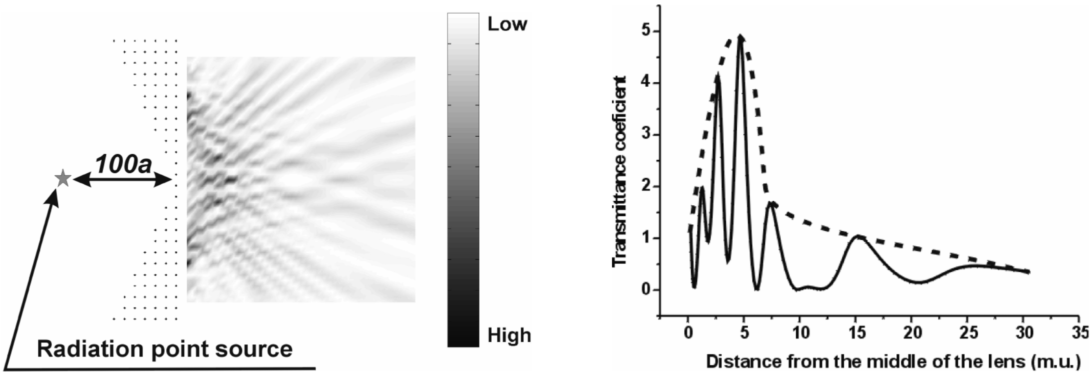
Figure 1 illustrates the photonic band structure and the calculated transmittance spectrum (TM mode) of the PC. The photonic band structure is essentially comparable to that published by J. D. Joannopoulos [6] and proves the general validity of our approach.

We used the concept of the effective medium according to Lalanne [7] to identify the frequency ranges for which the PC can be described as an (approximately) optically homogeneous medium with a given, if unconventional index of refraction. After identifying those wavelength regions, the n_{PC} value obtained then can be used to calculate the formation of images with PCs. This will be demonstrated for $n_{PC} > 1$ as well as for the particularly interesting case of $n_{PC} < 0$. Simple geometric optics (which should be applicable for a well-defined n_{PC}) predicts that a concave lens then should focus light for the case when the refractive index of the lens is less than that of the surrounding material, and the calculations show that this is indeed the case.



a) b)

Fig. 2 Focusing effect of a porous PC concave lens: a) the electromagnetic field distribution in vacuum for long wavelength limit and b) the transmittance coefficient along the optical axis of the lens for $\lambda = 10a \gg a$; effective $n_{PC} = 1.8$.



a) b)

Fig. 3 Focusing effect of a porous PC concave lens: a) the electromagnetic field distribution in vacuum and b) the transmittance coefficient along the optical axis of the lens for wavelength $\lambda = 1/0.81a$; effective refractive index $n_{PC} < 0$. The dotted line shows that the radiation distribution resembles the distribution for a lens imaged in Fig. 2.

Ordered parallel pores embedded in a dielectric matrix to form a concave lens as shown in Fig. 2a indeed focus light in the long wavelength limit associated with $n > 1$. Note that there is only one row of pores in the center of the lens. Calculations were made for a radiation point source situated left from the lens at a distance $100a$ where there is homogeneous dielectric material with $\varepsilon = 11.4$. Figure 2b shows the distribution of the light intensity as a function of the distance from the middle of the lens. As one can see from Figs. 2a and 2b, the focusing effect proves to be rather strong.

Figure 3 illustrates the results of calculations made for a frequency where $n_{PC} < 0$ ($a/\lambda = 0.81$). The radiation coming from a point source placed in homogeneous dielectric material with $\varepsilon = 11.4$ proves to be focused by the PC concave lens although the electric field modulus exhibits a more complicated spatial distribution than in the case of $n_{PC} > 1$ (compare Figs. 2a and 3a). The focusing effect is seen also in Fig. 3b where the distribution of the light intensity as a function of the distance from the middle of the lens is illustrated.

In conclusion, our calculations show that concave lenses made from porous dielectrics focus electromagnetic waves both in the long wavelength limit where $n > 1$ and in the spectral regions characterized by negative refractive index. The obtained results may be used for the purpose of designing and manufacturing novel micro-lenses ready to be integrated in optoelectronic circuits. Note that single crystals of nanopores can be easily introduced into semiconductor materials using electrochemical etching techniques [8].

References

[1] S. Enoch, G. Tayeb, and D. Maystre, Opt. Commun. **161**, 171 (1999).
[2] B. Gralak, S. Enoch, and G. Tayeb, J. Opt. Soc. Am. A **17**, 1012 (2000).
[3] J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).
[4] V. G.Veselago, Usp. Sov. Fiz. **10**, 509 (1968).
[5] Lie-Ming Li and Zhao-Qing Zhang, Phys. Rev. B **58**, 9587 (1998).
[6] J. D. Joannopoulos, R. D. Meade, and J. N. Winn, Photonic Crystals: Modeling the Flow of Light (Princenton University Press, Princenton, NJ, 1995), p. 123.
[7] Ph. Lalanne, Appl. Opt. **35**, 5369 (1996).
[8] S. Langa, I. M. Tiginyanu, J. Carstensen, M. Christophersen, and H. Föll, Appl. Phys. Lett. **82**, 278 (2003).