Interface engineering for improved light transmittance through photonic crystal flat lenses

Geoffroy Scherrer[1], Maxence Hofman[2], Wojciech Śmigaj[3], Boris Gralak[3], Xavier Mélique[2], Olivier Vanbésien[2], Didier Lippens[2], Colette Dumas[1], Benoit Cluzel[1], and Frédérique de Fornel[1]

[1]Groupe d'Optique de Champ Proche, Laboratoire Interdisciplinaire Carnot de Bourgogne (ICB), UMR CNRS 5209 Université de Bourgogne, 9, Avenue A. Savary, BP 47870, 21078 Dijon, France
[2]Institut d'Electronique, de Microélectronique et de Nanotechnologie (IEMN), UMR CNRS 8520, Université des Sciences et Technologies de Lille, Cité Scientifique, BP 60069, F-59652 Villeneuve d'Ascq Cedex, France
[3]Institut Fresnel, CNRS, Aix-Marseille Université, Ecole Centrale Marseille, Campus de St Jérôme, 13397 Marseille Cedex 20, France

Abstract

We present photonic crystal flat lenses with interfaces engineered to improve the light transmittance thanks to a broad angles impedance matching. The interface engineering consists in the realization of antireflection gratings on the edges of the lenses which are designed to reduce the propagative waves reflectivity over a wide range of incident angles. The fabricated structures were measured in optical near-field and a four times enhancement of the light transmission efficiency is reported.

Introduction

The use of negative refraction has enabled the emergence of new concepts for optical imaging including flat lenses or Pendry's perfect lenses [1,2,3]. Among the different PC geometries proposed in the literature, we study here the two-dimensional photonic crystal (2D PC) which consists in a triangular lattice of air holes etched in a semiconductor slab. These structures could present a negative refractive index which is isotropic enough to build flat lenses[4]. Obviously, in this field the transmission of the lens is a key figure merit for future applications. This has been theoretically investigated and it has been shown that interface truncation of the 2D PC structures plays a crucial role in the light transmission process, for evanescent as well as for propagative waves [.5-7]. In that way, several designs of 2D PC interfaces have been suggested, summarized in reference [8], but only few of them have been experimentally tested. The truncation of ref. [9] is devoted to evanescent waves enhancement by surface mode excitation whereas in ref. [10,11], a hole shape engineering is performed to decrease propagative waves reflectivity at 2D PC input interface. However, the air hole deformation proposed in ref. [10] has a restricted angular tolerance and its experimental demonstration effect is made indirectly in far-field. Although direct near-field observations of the effect of a tapered air holes layer are shown in ref. [11], no focusing regime, only negative refraction, is reported.

1-interfaces engineered to improve the light transmittance

In this work, we fabricated a 2D PC flat lens with input and output interfaces engineered in order to improve the lens transmittance with a broad angular acceptance and we quantify experimentally the transmission improvement using Scanning Near-field Optical Microscopy (SNOM) observations. A huge increase of the transmittance of the lens studied in ref. [4], from 0.05 to 0.2, is reported.

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

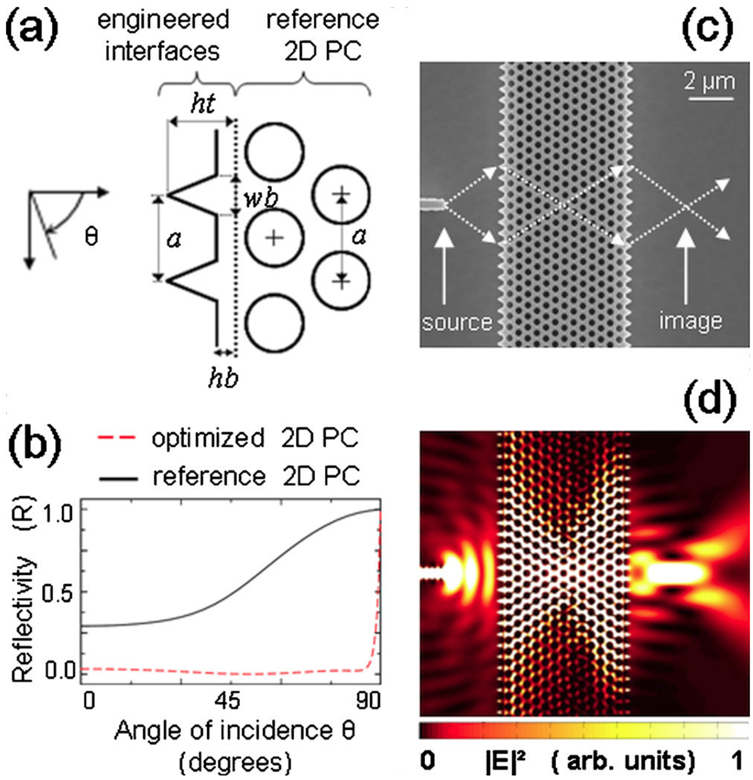

Fig.1a- Schematic top view of the 2D PC lens covered with the triangular pattern. b- Reflectivity of reference and optimized (ideal case for λ=1530 nm) semi-infinite 2D PCs as functions of the angle of incidence. c- SEM view of one fabricated optimized lens with the associated waveguide. A ray tracing corresponding to an effective negative index of n=−1 is superimposed. sd- 2D FDTD simulations of the electric field intensity plane distribution at 1550 nm for the ideal optimized lens. c and d are plotted at the same scale.

At last, to assess the wavelength sensitivity of the reported structure, we analyzed the spectral dependence of the LTE of the best optimized lens. We thus realize local nearfield spectroscopy experiments[23] for the image point and the REF IN positions. We stop the near-field probe scan at these positions (height scan is set to 1.5 µm above the substrate) and record the intensity of the detected light as a function of the injected wavelength for the image point and for REF IN. The bare spectra are plotted in Figs. 3(b) and 3(c), and we present in Fig. 3(d) the normalized transmittance of the lens, i.e., the ratio between image point and REF IN spectra. On the REF IN spectrum, a flat transmittance until the beginning of the detector cut-off at 1.55 µm (H10330 Hamamatsu NIR PMT Module) is measured whereas a Gaussian shape spectrum is recorded at the image point. As a consequence, this leads to a normalized spectrum with an optimal peak transmittance at λ=1533 nm in good agreement with the nearfield observations. Finally, we note that the near-field spectroscopy experiment leads to a value of transmittance (35%) higher than the LTE measured on the pictures (21%). This mainly comes from the uncertainties of the near-field probe lateral position in the REF IN region for the spectroscopy experiment that could lead to an over evaluation of the LTE.

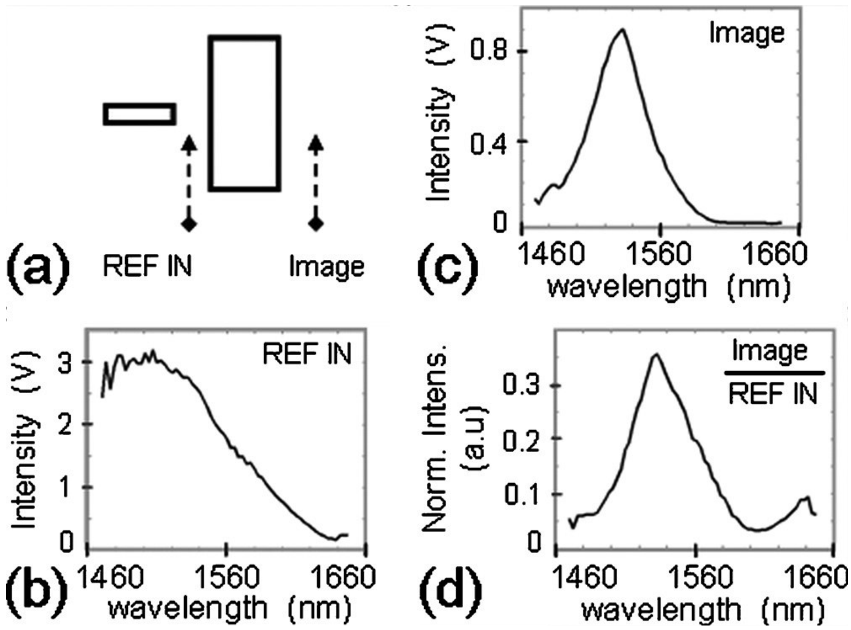

FIG. 2. Local near-field spectroscopy (1470 nm<λ<1650 nm) of the optimized lens (wb=0.43a, hb=0.06a, and ht=0.64a) with the higher LTE: a- schematic top view, b- spectral response for the REF IN position, c- spectral response for the image point, and d- normalized spectral response (maximal value at λ=1533 nm).

Conclusion

To conclude, we realized interfaces engineering for a two-dimensional photonic crystal flat lens which provides a negative refraction focusing regime at optical frequencies. The appropriate joint truncation is engineered to decrease propagative waves reflectivity at input and output interfaces over a wide range of incident angle. A four times enhancement of the light transmission efficiency is clearly observed and measured by using optical near-field microscopy technique. It is believed that such an optimized structure appears as an efficient free space focusing device for optical interconnected nanosystems.

References

[1] V. G. Veselago, Sov. Phys. Usp. 10, 509 (1968).
[2] J. B. Pendry, Phys. Rev. Lett. 85, 3966 (2000).
[3] X. Zhang and Z. Liu, Nature Mater. 7, 435 (2008).

[4] N. Fabre, L Lalouat, B. Cluzel, X. Mélique, D. Lippens, F. de Fornel, and O. Vanbésien, Phys. Rev. Lett. 101, 073901 (2008)..
[5] C. Luo, S. G. Johnson, J. D. Joannopoulos, and J. B. Pendry, Phys. Rev. B 68, 045115 (2003).
[6] A. Martinez and J. Marti, Phys. Rev. B 71, 235115 (2005).
[7] W. Śmigaj and B. Gralak, Phys. Rev. B 77, 235445 (2008).
[8] W. Śmigaj, B. Gralak, R. Pierre, and G. Tayeb, Opt. Lett. 34, 3532 (2009).
[9] B. D. F. Casse, W. T. Lu, R. K. Banyal, Y. J. Huang, S. Selvarasah, M.R. Dokmeci, C. H. Perry, and S. Sridhar, Opt. Lett. 34, 1994 (2009).

[10] T. Matsumoto, K. S. Eom, and T. Baba, Opt. Lett. 31, 2786 (2006).
[11] L. Gan, Y. Z. Liu, J. Y. Li, Z. B. Zhang, D. Z. Zhang, and Z. Y. Li, Opt. Express 17, 9962 (2009).