Young's double-slit experiment in photonic crystals

Lei Zhang [a,*], Thomas Koschny [a], C.M. Soukoulis [a,b]

[a] Ames Laboratory—U.S. DOE and Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA
[b] Institute of Electronic Structure and Lasers (IESL), FORTH, 71110 Heraklion, Crete, Greece

ABSTRACT

We present an experimental and numerical study of the transmission of a photonic crystal perforated by two subwavelength slits, separated by two wavelengths. The experimental near-field image of the double-slit design of the photonic crystal shows an interference pattern, which is analogous to Young's experiment. This interference arises as a consequence of the excitation of surface states of the photonic crystals and agrees very well with the simulations.

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In 1998, Ebbesen et al. [1] observed an extraordinary optical transmission through subwavelength hole arrays in optically opaque metal films. It has been shown that this enhancement of transmission is due to the excitation of surface plasmons on the metal dielectric interfaces [2]. The key feature was to corrugate the surface surrounding the aperture, allowing the excited surface plasmons at the metallic surface to couple to outgoing beam (propagating modes) leading to a well-directed beam [3]. The potential application of such a kind of structure has been mentioned in different publications [4–6]. Similarly, photonic crystals (PCs) have been shown to support surface waves in their operational frequency is within the photonic band gap. PCs do not support surface waves unless they are appropriately terminated [7,8].

In the present letter, we perform a double-slit experiment with photonic crystals to reveal the strong analogy of wave propagation in PCs with Young's interference experiments.

The PC examined in this paper consists of a two-dimensional square array of dielectric square bars with a dielectric constant of $\epsilon = 9.8$ in air. The dimension of the structure is 25 layers in the lateral direction and 5 layers in the propagation direction with a lattice constant of $a = 11$ mm. The width of each dielectric bars is 3.18 mm. A schematic picture of the PC structure with two slits is shown in Fig. 1. In order to create two slits (like a waveguide) we omit the 10 bars and the distance between the two slits is 33 mm. The actual aperture's width of the two slits is approximately 1.1 cm measured from the outer-most bars of the PC. Therefore, for all the frequencies of the incident plane wave (between 8.2 and 12.4 GHz), the aperture of the two slits is smaller than
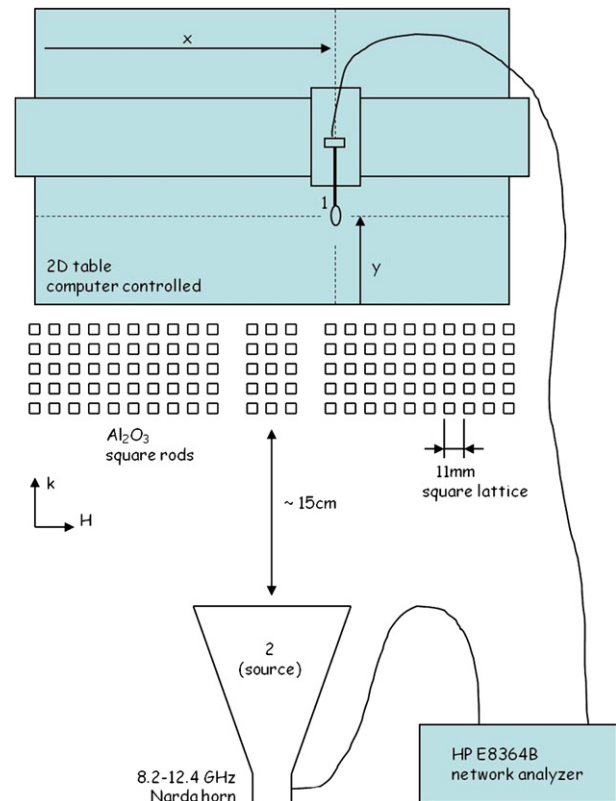

Fig. 1. The photonic crystal structure's configuration which is used to visualize Young's double-slit experiment for surface waves. A loop antenna is used to measure the local field intensity and the propagation, diffraction and interference of the surface waves can be imaged in a 2D plot.

* Corresponding author. Tel.: +1 515 294 4316.
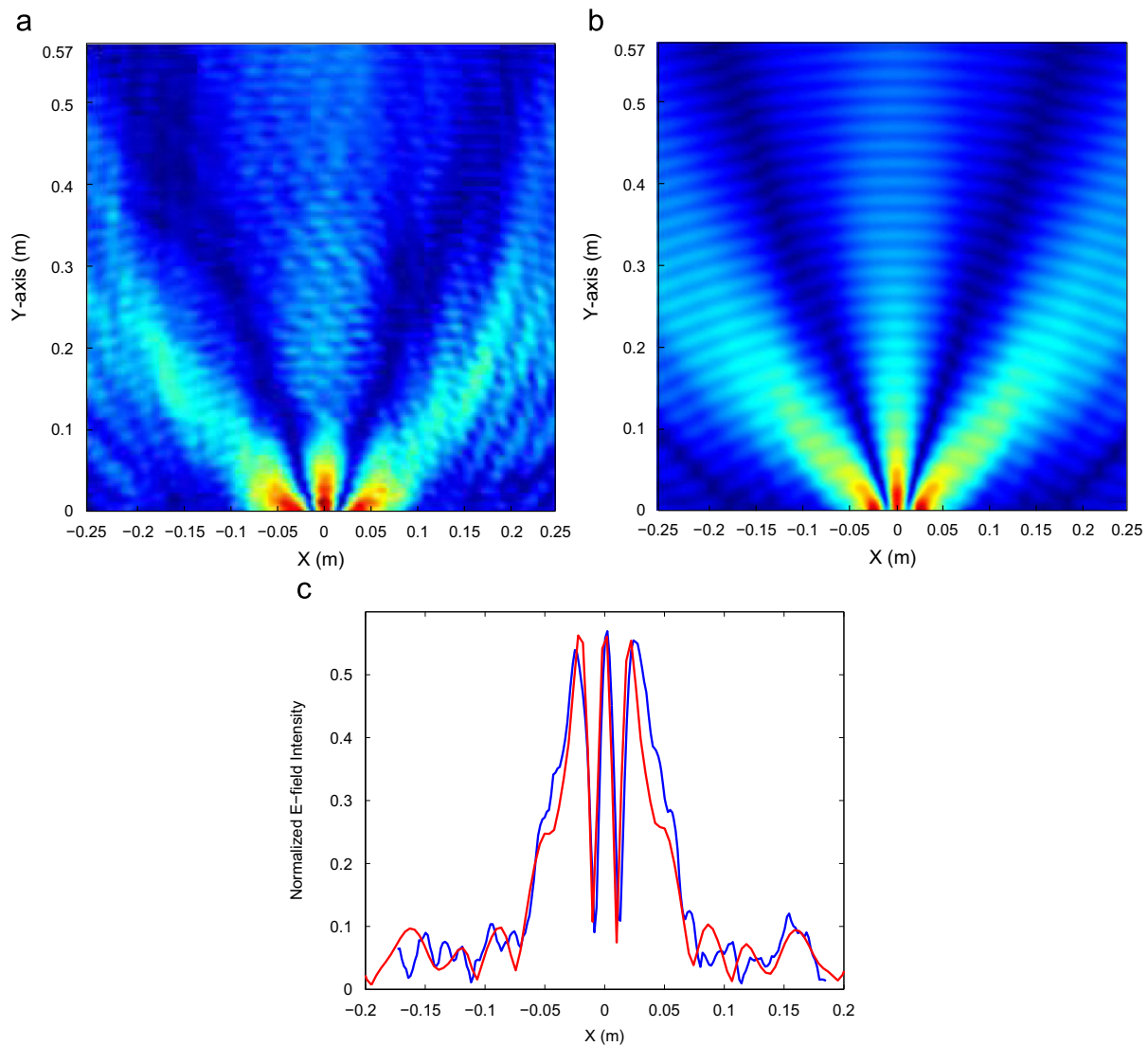 E-mail address: mywaters@iastate.edu (L. Zhang).

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b

c

Fig. 2. (a) Experimental 2D plot of the strength of the outgoing electric field demonstrating Young's interference pattern. (b) Numerical simulations of 2D plot of the strength of the outgoing electric field. (c) Comparison of lateral cross-sections for experimental data (blue line) and results for simulations (red line) with plots for $y=2$ mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the wavelength of the incident beam. Consequently, we expect the one slit to transmit poorly and diffract lightly in all directions. When we use the two slits we see propagation and interference effects. Similar to previous experimental studies [8], an antenna was used to visualize the propagation and the interference of the double-slit experiment in photonic crystals. In short, an antenna can be used as a probe to measure the local field intensity directly under the antennas. Similar Young's double-slit experiments have been done with surface plasmons [9,10].

The 2D plot of the strength of the electric field is shown in Fig. 2a. The electric field intensity closely resembles the well-known diffraction and interference pattern of Young's original double-slit experiment. Notice that the diffracted beams overlap and the interference pattern, shown in Fig. 2a, is observed. This Young's interference pattern has a central maximum due to the constructive interference of wave emitted by the two slits (like waveguide). The experimental 2D image is in good agreement with the numerical simulations as shown in Fig. 2b. This agreement is clearly illustrated in Fig. 2c, which shows lateral cross-section taken from the experimental (blue line) and simulated (red line) from Fig. 2a and b.

In conclusion, we have demonstrated experimentally the two-slit Young interference effect in photonic crystals with the two slits (waveguides). These experimental data agree very well with the simulations. These findings will improve the beaming properties of our photonic crystal waveguides. There are two factors that improve the beaming phenomenon in photonic crystals. One factor is to modify the surface layer which will excite the surface states and this enables them to couple to the outgoing beam and improve the beaming and the directionality. Another factor is to have finite slab and the termination of the waveguide, which is dictated by the back and forth transmission (Fabry–Perot effects) and improves the directionality. This way, we will find what frequency gives excellent beaming and the directionality of the photonic crystal waveguide.

Acknowledgments

References

[1] T.W. Ebbesen, H.J. Lezec, H.F. Ghaemi, T. Thio, P.A. Wolff, Nature (London) 391 (1998) 667.

[2] L. Martin-Moreno, F.J. Garcia-Vidal, H.J. Lezec, K.M. Pellerin, T. Thio, J.B. Pendry, T.W. Ebbesen, Phys. Rev. Lett. 86 (2001) 1114.

[3] H.J. Lezec, A. Degiron, E. Devaux, R.A. Linke, L. Martin-Moreno, F.J. Garcia-Vidal, T.W. Ebbesen, Science 297 (2002) 820.

[4] J.R. Sambles, Nature (London) 391 (1998) 641.

[5] S.I. Bozhevolnyi, J. Erland, K. Leosson, P.M.W. Skovgaard, J.M. Havm, Phys. Rev. Lett. 86 (2001) 3008.

[6] C. Genet, T.W. Ebbesen, Nature (London) 445 (2007) 39.

[7] P. Kramper, M. Agio, C.M. Soukoulis, A. Birner, F. Muller, R.B. Wehrspohn, U. Gosele, V. Sandpghdar, Phys. Rev. Lett. 92 (2004) 113903.

[8] R. Moussa, B. Wang, G. Tuttle, T. Koschny, C. Soukoulis, Phys. Rev. B 76 (2007) 235417.

[9] H.F. Schouten, N. Kuzmin, G. Dubois, T.D. Visser, G. Gbur, P.F.A. Alkemade, H. Bolk, G.W. Hooft, D. Lenstra, E.R. Eliel, Phys. Rev. Lett. 94 (2005) 053901.

[10] R. Zia, M.L. Brongersma, Nat. Nanotechnol. 2 (2007) 426.