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Whispering gallery mode propagation in photonic crystals in front of subwavelength slit arrays
Interplay with extraordinary transmission

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A B S T R A C T

We numerically study the propagation of light in 2D photonic crystals (PC) made of infinite cylinders of high refractive index, via the excitation of their morphological dependent resonances, in the presence of metallic arrays of subwavelength slits, either corrugated or not, that may produce extraordinary transmission. In this way, we confirm and illustrate previous theoretical findings on PCs and show new effects when combined with slits. Among them, we show that the whispering gallery mode excitation in the PC couples dominates the transmission of the slit arrays alone. Appropriate design of the system parameters and the illumination conditions, selects the transport and confinement of energy.

1. Introduction

Optical energy transport, filtering, spectroscopic splitting, intensity enhancement, confinement and emission directionality, are subjects of active research in photonics [1–3]. Also, the study of these phenomena at the subwavelength scale, either in plasmonics [4–6], in high refractive index dielectric elements like coupled resonant optical waveguides (CROWs), either with coupled microcylinders or microspheres [7–13], or in hybrid systems [14], suggest promising applications. On the other hand, extraordinary, or enhanced, optical transmission through subwavelength apertures in metallic slabs [15–21] has been a subject of much attention in connection with its potential for light concentration, detection and wavefront steering. In addition, it is well known that one slit supertransmission is further enhanced by substituting it by a periodic array of apertures, patterned in a metallic slab [15–21].

In this paper we investigate the effects of placing a photonic crystal (PC) [22] of high refractive index elements, in front of an array of slits, in such a way that each row of the PC is in front of each slit of the array. We address the situation in which light propagation in the PC occurs via excitation of the morphology dependent resonances (MDR) [23,24] of its elements, and we choose the illumination conditions such that at the same time the slit array may also be in the supertransmission regime.

The subject of Mie resonance propagation in a PC has been previously addressed in the literature as regards its influence on the crystal bandgap size and position [25,26]. Band diagrams have been calculated under different approaches; among them, the tight binding (TB) method of solid state physics [27] has been widely employed at large frequencies where the light wavelength is comparable to the size of the crystal spheres or cylinders, in such a way that when their MDRs are excited, they constitute the propagation vehicle in those upper bands. Their localization in the PC particles helps the accuracy of the TB result [25] and, on the other hand, the modes associated to those "localized orbitals" have small group velocity manifesting almost flat bands of potential interest in applications. Based on the analogy with atomic physics, optical crystals in this regime have been named *molecular photonic crystals (MPC)* [28]. In addition, transmission properties of both silicon coated and metal coated microspheres photonic crystal arrays have been studied [29–33].

From a qualitative point of view, the essential features of resonance excitation and propagation, are similar in 2D and 3D PCs of cylinders and spheres [25,28], apart from the well known larger difficulty of observing absolute gaps in the latter case. In addition, 2D resonances have shown [34,35] to constitute an appropriate model with equivalent effective constitutive parameters for microdisks in CROWs. Also, disordered distributions of large parallel cylinders, illuminated normally to their

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axis have exhibited interesting effects like light localization phenomena [36].

We next report numerical simulations that show the propagation in 2D MPCs made of high permittivity dielectric cylinders through the excitation of their MDRs, in this way we confirm and illustrate the findings of [25,26,28]. We show not only a hopping mechanism between neighbour cylinders due to the transport of MDRs between adjacent cylinders, but also as a result of the coupling of these MDRs with the weak diffracted waves from each of these elements, and their conversion into MDRs when they hit the cylinders. Further, we study the interplay between the photonic crystal and the array of subwavelength supertransmitting apertures in front of which the PC is placed. Finally, we address the effects of grating beaming [37] by introducing periodic corrugation in the slab.

2. Light propagation and field concentration enhancement in photonic crystals illuminated through a slit array

2.1. Numerical simulations

We consider Si cylinders (refractive index $n = 3.670 + i0.005$ at $\lambda = 919nm$) [38]. The metal of the slab is assumed to be highly conducting and has $n = i32$. The 2D geometries constitute transversal sections of 3D infinite cylinders. The incidence is normal to the

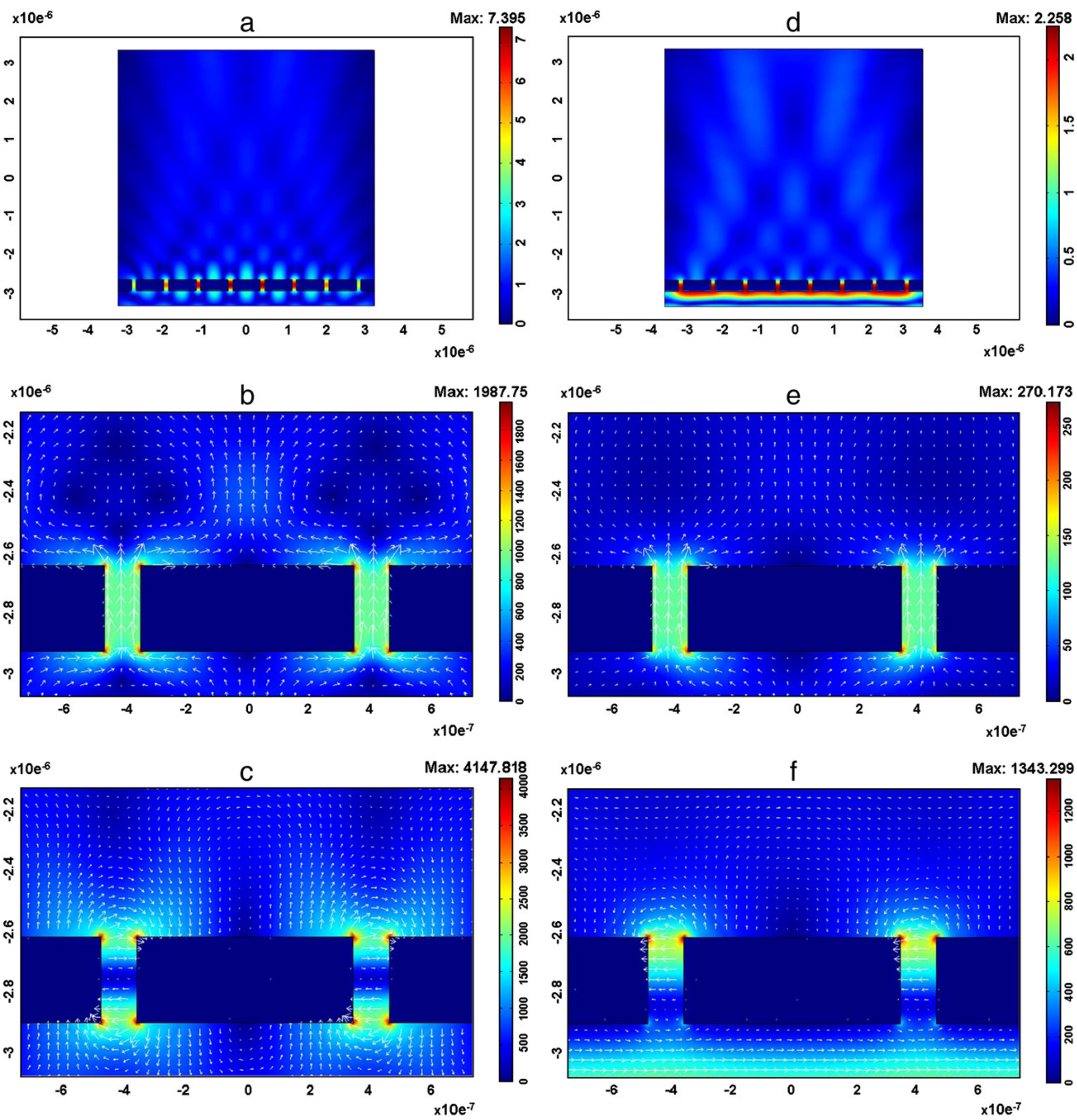

Fig. 1. (a) Magnetic field modulus $|\mathbf{H}(\mathbf{r})|$ distribution (colors in A/m units) from an array of eight slits (refractive index $n = i32$, period $P = 826.87nm$, slab width $D = 8P$, slab thickness $h = 283.5nm$, slit width $d = 118.12nm$) under p-wave illumination at the resonant wavelength $\lambda = 950nm$. (b) Detail of the time average energy flux $<\mathbf{S}(\mathbf{r})>$ (in $J/(m \cdot s)$ units, maximum arrow length $\approx 1.24 \cdot 10^{13} eV/(nm \cdot s)$ at $\lambda = 950nm$, minimum arrow length $\approx 0 eV/(nm \cdot s)$), both norm (colors) and components (arrows) are shown at the same conditions as in Fig. 1(a). (c) Detail of the electric field $\mathbf{E}(\mathbf{r})$ (in V/m units) at $\lambda = 950nm$, both its norm (colors) and components (arrows), at the same conditions as in Fig. 1(a). (d) Magnetic field modulus $|\mathbf{H}(\mathbf{r})|$ distribution for the same configuration as in Fig. 1(a) illuminating at $\lambda = 1250nm$, out of the resonant wavelength. (e) Detail of the time average energy flux $<\mathbf{S}(\mathbf{r})>$ at $\lambda = 1250nm$ (maximum arrow length $\approx 1.69 \cdot 10^{12} eV/(nm \cdot s)$, minimum arrow length $\approx 0 eV/(nm \cdot s)$). (f) Detail of the electric field $\mathbf{E}(\mathbf{r})$ at $\lambda = 1250nm$.