NANO, MESO, MICRO : SCIENCES ET INNOVATIONS POUR LA RADIO ET LA PHOTONIQUE.

Oblique mesoscopic self-collimation: lossless, and diffraction-less light beam propagation

Sergio Iván Flores Esparza[1], Olivier Gauthier-Lafaye[1], Giovanna Calò[2], Giovanni Magno[2], Vincenzo Petruzzelli[2], Antoine Monmayrant[1]

[1]LAAS-CNRS, Université de Toulouse, CNRS, 7 avenue du colonel Roche, F-31400 Toulouse, France
[2]Department of Electrical and Information Engineering, Polytechnic University of Bari, Via Orabona, 4, 70125, Bari, Italy

---

Mots clés : cristaux photoniques, autocollimation, cône de lumière, intégration photonique.

Résumé/Abstract

L'autocollimation mésoscopique (MSC) est un nouveau régime de propagation de la lumière se produisant dans les cristaux photoniques mésoscopiques (MPhCs) et permettant une propagation des faisceaux sans étalement. Les cristaux photoniques mésoscopiques sont constitués d'une alternance périodique de courtes sections de matériau non-structuré et de courtes sections de cristal photonique (PhCs). Ils présentent une structure multi-échelle avec une périodicité sub-longueur d'onde dans le cristal photonique et une périodicité de quelques longueurs d'onde à l'échelle de la mésopériode : le grand nombre de degrés de liberté de cette structure permet d'obtenir la MSC à la fois selon des directions de haute symétrie mais aussi selon des directions obliques par rapport aux interfaces des sections de MPhC. Nous proposons ici une nouvelle méthode de conception des MPhCs où la MSC est obtenue pour des incidences arbitraires tout en évitant les pertes lors de la propagation du faisceau : pas d'étalement transverse du faisceau, pas de diffraction dans le plan (due aux interfaces structurées), pas de diffraction hors du plan (due au couplage vers le cône de lumière). La méthode proposée permet une recherche systématique de structures MSC optimales, en tenant compte des effets de taille finie et des réflexions parasites aux interfaces qui sont des points clefs pour l'intégration dans des systèmes photoniques.

Mesoscopic self-collimation (MSC) is a novel beam propagation regime occurring in Mesoscopic Photonic Crystals (MphCs) enabling diffraction-free beam propagation. MPhCs consist of the periodic alternation of short slabs of bulk material and short slabs of Photonic Crystal (PhCs). They present a multiscale structuring with a subwavelength periodicity within each PhC slab and a few-wavelength periodicity for its supercell: a large number of degrees of freedom of this structure allow MSC to be achieved both along with directions of high symmetry and along with directions oblique to the MPhC slab interfaces. Here, we propose a new design method vital for conceiving MPhCs where MSC is attained under oblique incidence and avoiding any diffraction of the beam: no lateral diffraction due to expansion of the beam, no in-plane diffraction (due to the presence of structured interfaces), no out-of-plane diffraction (due to light-cone coupling). The proposed method allows a systematic search for optimal MSC structures, considering finite-size effects and parasitic reflections at the interfaces that are key for efficient integration in larger photonic systems.

1 Introduction & Context

Self-collimation (SC) has been widely investigated in long monolithic PhCs [1]. More recently, an analogous propagation regime, the mesoscopic self-collimation (MSC), was demonstrated in mesoscopic photonic crystals (MPhCs), mesoscopic structures alternating PhC and bulk slabs [2].

An MPhC is a structure whose elementary cell allows diffraction-less propagation (or self-collimation) of light beams through compensation of spatial dispersion under specific direction and frequency conditions. In its simplest configuration, an MPhC alternates slabs of raw material and slabs of artificial material (PhC) with opposite spatial dispersion (see Fig. 1(a)).

Previously, we have demonstrated that MSC can be achieved along the direction of high symmetry for the MPhC, i.e., the direction normal to the interfaces between PhC and bulk slabs [2]. We proposed a hybrid numerical-analytical method [3] to combine MSC condition at the wavelength scale with the control of impedance matching between the alternating slabs composing the MPhC at the mesoscopic scale. In particular, this method allows finding optimal parameters to achieve MSC with tailored reflectivity. This allows fast and simple design of MPhC in which diffraction-less propagation is combined with total transmission or total reflection of the beam. This method allowed to numerically [4] and then experimentally [7] demonstrate complete confinement of a stable optical mode within a 1D Fabry-Pérot cavity bounded by a pair of mesoscopic self-collimating mirrors.

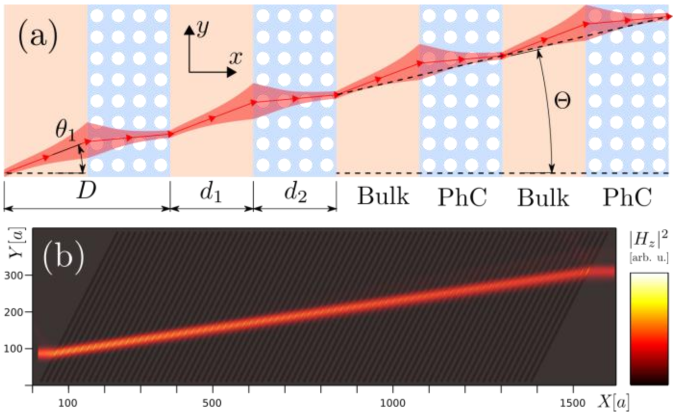

Figure 1: (a) Principle of oblique mesoscopic self-collimation: transverse beam expansion in bulk (orange) is compensated by self-focusing in PhC (blue) while parasitic reflection, planar diffraction, and out-of-plane diffraction are cancelled. (b) 2D-FDTD simulation of oblique mesoscopic self-collimation in a structure designed with the proposed method.

However, this design method was limited to normal incidence at the MPhC interfaces and directions of high symmetry within each PhC slab. This first method relies on perfectly satisfying the MSC conditions and on an approximate control of the interference conditions at the interfaces to obtain a given overall reflectivity. In particular, this method is unable to predict or properly design MSC at oblique incidence that was numerically observed within structures originally designed to work at normal incidence [6]. Under certain conditions these MSCs at oblique incidence can occur below the light cone, potentially offering diffraction-free in-plane propagation, without the high-losses (due to coupling to the light cone) that are usually observed in MPhCs with large mesoscopic periodicity [7].

2 Design of oblique mesoscopic self-collimating structures

Here, we propose to detail a novel analytical model that can predict and design MPhCs offering MSC at oblique incidence, without any in-plane diffraction at the interfaces and any out-of-plane losses [8]. It relies on a fast, simple analytical model that excludes right from the start any geometry that could induce propagation losses due to unwanted reflection and in-plane or out-of-plane diffraction. It only requires the easy calculation of the first band of one elementary cell of the PhC used in the PhC slabs, avoiding the challenging and time-consuming calculation of the band diagram of the whole mesoperiod *D*. One key aspect of this method is to first focus on designs ensuring lossless propagation and then to select the ones that offer the best approximate MSC. Within a few seconds on a desktop computer, this method provides all the possible designs for a given MPhC geometry. Each design forms a set of continuous solutions parametrized as a function of the reduced frequency $u=a/\lambda$ (with a the PhC lattice constant and λ the target wavelength) and the incidence angle θ_1. The method also provides a figure of merit to compare the quality of the MSC offered by each design. It is worth noting that among this continuous set of approximate MSC solutions, the method also provides a discrete set of solutions providing perfect MSC.

This method accurately predicts self-collimating structures under oblique incidence that can later be validated using long 2D-FDTD simulations (see Fig. 1(b)). In our oral presentation and paper, we will explain how this method simultaneously:

(i) ensures coexistence of both MSC and reflectivity control;
(ii) includes all MSC solutions at an arbitrary angle with respect to the interfaces of the slabs;
(iii) selects the solutions free from both out-of-plane and in-plane diffraction losses.

We will also detail the characteristics of several MPhCs geometries designed with this method, based on square- and on triangular-lattice PhC. In particular, the strengths and limitations of oblique-incidence mesoscopic self-collimation will be discussed.

References

[1] H. Kosaka, et al. “Self-collimating phenomena in photonic crystals,” Appl. Phys. Lett. 1999.
[2] J. Arlandis, et al. “Mesoscopic self-collimation and slow light in all-positive index layered photonic crystals,”

Phys. Rev. Lett. 2012.
[3] G. Magno, et al. “Controlled reflectivities in self-collimating mesoscopic photonic crystal,” J. Opt. Soc. Am. B 2014.
[4] G. Magno, et al. “Stable planar mesoscopic photonic crystal cavities,” Opt. Lett. 2014.
[6] G. Magno, et al. “Mesoscopic self-collimation along arbitrary directions and below the light line,” Opt. Express 2019.
[7] A. Monmayrant, et al. “Full optical confinement in 1D mesoscopic photonic crystal-based microcavities: an experimental demonstration,” Opt. Express 2017.
[8] S. I. Flores Esparza, et al. “Design of mesoscopic self-collimating photonic crystals under oblique incidence,” Opt. Express 2021.