



**HAL**  
open science

# Mesoscopic Self-Collimation under oblique incidence in hexagonal-lattice mesoscopic photonic crystal

Sergio Iván Flores Esparza, Olivier Gauthier-Lafaye, Antoine Monmayrant

► **To cite this version:**

Sergio Iván Flores Esparza, Olivier Gauthier-Lafaye, Antoine Monmayrant. Mesoscopic Self-Collimation under oblique incidence in hexagonal-lattice mesoscopic photonic crystal. EOS Annual Meeting (EOSAM 2023), EOS, Sep 2023, Dijon, France. pp.04021, 10.1051/epjconf/202328704021 . hal-04770770

**HAL Id: hal-04770770**

**<https://laas.hal.science/hal-04770770v1>**

Submitted on 7 Nov 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Mesoscopic Self-Collimation under oblique incidence in hexagonal-lattice mesoscopic photonic crystal

Sergio Iván Flores Esparza<sup>1,\*</sup>, Olivier Gauthier-Lafaye<sup>1,\*\*</sup>, and Antoine Monmayrant<sup>1,\*\*\*</sup>

<sup>1</sup>LAAS-CNRS, Université de Toulouse, CNRS, 7 Avenue du Colonel Roche, 31400 Toulouse, France

**Abstract.** We demonstrate numerically mesoscopic self-collimation under arbitrary oblique incidence in hexagonal-lattice mesoscopic photonic crystal and propose a fast and simple methodology for design and parametric exploration of such geometries.

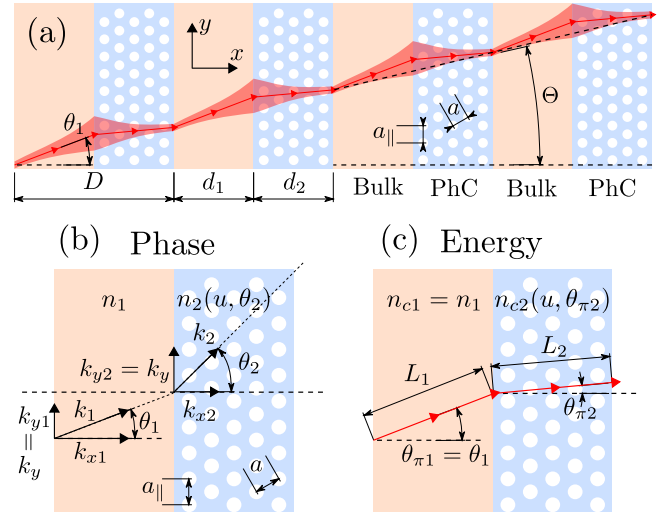
## 1 Introduction

In Photonic Crystals (PhCs), light guiding can be achieved by self-collimation (SC) without relying either on total internal reflection, as in standard integrated waveguides, or on bandgap and lattice defects, as in PhC waveguides. SC in PhCs does not require non-linear effect and is, therefore, independent of the light intensity. When working outside the bandgap in periodic structures, the direction of light propagation is normal to the dispersion surfaces. Therefore, the curvature of dispersion surfaces determines the divergence or convergence of the beam propagating in such structures. Considering the iso-frequency curves (IFCs), calculated from the dispersion surface for fixed frequencies, the beam can be self-collimated when its angular spectral content falls in a flat region of the IFC [1]. This means that the optical signal can propagate undistorted without significant broadening or change in its profile. The engineering of spatial dispersion can, therefore, enable the propagation of self-guided beams and SC has been widely investigated and demonstrated in PhCs with either rectangular or hexagonal lattices.

A different approach to achieve SC is based on mesoscopic periodic structures composed of alternating natural or artificial materials [2]. These structures are characterized by a multiscale periodicity with a subwavelength periodicity within each slab of artificial material (e.g. PhC slabs) and with a few-wavelength periodicity for its supercell (i.e. the alternating slabs of the different materials composing the mesoscopic structure). These artificial materials are generally referred to as Mesoscopic Photonic Crystals (MPhCs) and, if suitably designed, they can sustain a self-collimated beam by compensating spatial dispersion in the alternating slabs.

## 2 Mesoscopic Self-Collimation modelling

In this contribution, the hybrid numerical-analytical method proposed in [3] is used to analyse hexagonal MPhCs under normal incidence (i.e. the high symmetry direction) and oblique incidence conditions. The design method allows to find solutions that guarantee MSC without out-of-plane losses and in-plane scattering losses.



**Figure 1.** (a) Principle of MSC at oblique incidence: the balance of lateral spreading in bulk slabs (orange) and self-focusing in PhC slabs (blue) results in beam propagation without beam expansion; (b) Anti-reflection phase conditions must be fulfilled to ensure forward propagation only; (c) Energy propagation (ie Poynting vector) conditions are required to balance spreading and self-focussing.

The MPhCs under investigation are schematically represented Fig. 1 (a) and they are made of alternating slabs of bulk medium (orange) and hexagonal PhC (blue). The period of the mesoscopic structure is  $D = d_1 + d_2$ , where  $d_1$  and  $d_2$  are, respectively, the lengths of the slabs of bulk material and of the PhC.

\*e-mail: [ivan.flores@almae-technologies.com](mailto:ivan.flores@almae-technologies.com)

\*\*e-mail: [olivier.gauthier-lafaye@laas.fr](mailto:olivier.gauthier-lafaye@laas.fr)

\*\*\*e-mail: [antoine.monmayrant@laas.fr](mailto:antoine.monmayrant@laas.fr)

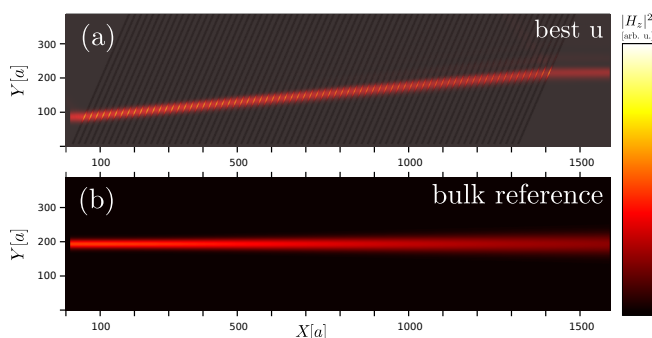
The key benefits of the generic approach described in [3] for square lattice PhC and applied here for hexagonal lattice is that it's extremely simple and fast as compared to using only numerical simulations. Indeed, the structure described in Fig. 1 (a) is multiscale and thus requires a large simulation volume and long simulation times whatever the method used (like rigorous couple wave analysis, finite element method or finite difference in time domain, ...). Moreover, simulations need to be repeated whenever any parameter of the structure is modified (like the slabs lengths  $d_1$  or  $d_2$  for example). In our approach, an initial and fast numerical simulation is carried out for an infinite defect-less PhC corresponding to the PhC used in the PhC slabs, from which few key properties like the refractive index  $n_2(u, \theta_2)$  as a function of both the reduced frequency  $u$  and the phase propagation angle  $\theta_2$  in the PhC or the index of curvature  $n_{c2}(u, \theta_{\pi 2})$  governing the energy spreading in the PhC as a function of the reduced frequency  $u$  and the Poynting vector angle  $\theta_{\pi 2}$  in the PhC. Similar quantities can be derived from first principles for the bulk slabs.

From these quantities, using an analytical propagator model, we can quickly determine the beam propagation for various bulk and PhC slabs combinations and various angles of incidence on the structure and reduced frequencies. The key elements in this model are (1) to find a set of reduced frequencies and angles of incidence that fulfil several phase conditions (Fig. 1 (b)) in order to avoid in-plane and out-of-plane diffraction or backward reflection at the bulk/PhC interfaces and (2) to find among this set solutions that also respect energy propagation conditions that ensure a good balance between energy spreading in the bulk slabs and focussing in the PhC slabs.

The output of this model is a set of MPhC parameters together with sets of reduced frequencies  $u$  and angle of incidence in the bulk material  $\theta_1$  that ensure MSC. This solutions are then validated using pulsed FDTD simulations and the exact reduced frequency ensuring best MSC in FDTD is usually slightly adjusted from our model prediction.

### 3 Mesoscopic Self-Collimation in hexagonal lattice MPhCs

A surprising result when studying hexagonal lattice MPhCs is that contrary to their square lattice counterparts,



**Figure 2.** (a) Mesoscopic self-collimated propagation in hexagonal lattice MPhC over 75 mesoperiods (MPhC length of  $1200a$ ); (b) Reference propagation in bulk material (same distance and same reduced frequency); The intensity of the vertical component of the magnetic field  $|H_z|^2$  is plotted in black to white color scale. In (a), the MPhC structure is overlaid in gray.

they only exhibit mesoscopic self-collimation for oblique incidence and for one particular orientation of the hexagonal lattice with respect to the MPhC meso-periodicity. This is due to a particular interplay between diffraction at the interfaces and regions in the Brillouin zone that ensure efficient self-collimation in the PhC slabs. This behaviour will be fully discussed, together with all the modelling strategy during our oral contribution.

Using our modelling strategy, we managed to unveil a complete set of solutions for mesoscopic self-collimation under oblique incidence in hexagonal lattice MPhC. The propagation of a beam with initial waist of  $w = 20a$  for a typical solution ( $N = 7$  rows of holes in the PhC,  $d_1 = 9.98a$ ,  $\theta_1 = 23.56$ ,  $u_0 = 0.23$ .) is presented in Fig. 2 (a), together with a reference propagation at the same frequency in bulk material only in Fig. 2 (b).

Contrary to the reference propagation where lateral energy spreading is clearly visible, for the MPhC, the beam stays well collimated across the structure, demonstrating mesoscopic self-collimation in hexagonal lattice MPhCs.

### 4 Conclusion

Fast and accurate modelling strategy for MPhC structures was adapted to hexagonal lattice MPhCs where, surprisingly, MSC propagation can only occur at oblique incidence and for specific orientation of the PhC.

All the modelling strategy and simulation details will be presented during our oral presentation.

Current work aims at experimental demonstration of these structures on suspended PhC membranes.

### References

- [1] H. Kosaka *et al.*, "Self-collimating phenomena in photonic crystals", Appl. Phys. Lett. 74, 1212-1214 (1999) [10.1063/1.123502](https://doi.org/10.1063/1.123502)
- [2] J. Arlandis *et al.*, "Mesoscopic Self-Collimation and Slow Light in All-Positive Index Layered Photonic Crystals", Phys. Rev. Lett. 108, 037401 (2012) [10.1103/PhysRevLett.108.037401](https://doi.org/10.1103/PhysRevLett.108.037401)
- [3] S. I. Flores Esparza *et al.*, "Design of mesoscopic self-collimating photonic crystals under oblique incidence," Opt. Express 29, 33380-33397 (2021) [10.1364/OE.439030](https://doi.org/10.1364/OE.439030)