Tailoring reflection of self-collimating multilayer structures

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***Abstract*—In this paper we propose and demonstrate a simple conception scheme for multilayered planar photonic crystals (PhC) offering self-collimated propagation with tailored transmission and reflection. In particular we report on the design of a Distributed Bragg Reflector and anti-reflection structure both composed of 2D PhC layers and unstructured high-index layers. Finally we analyze the propagation of a Gaussian pulse in the periodic structures and we numerically prove the behaviour of the two proposed configurations.**

Keywords: Photonic Crystals, Mesoscopic self-collimation, DBR, antireflection, laser design.

I. Introduction

Even if Photonic Crystals have been extensively studied in the last decades, they still own exceptional properties that can be investigated and exploited for new kind of optical devices. In particular, self-collimating photonic crystals [1] allow the propagation over long distances of collimated optical beams without requiring any waveguide for the confinement. Self-collimation has also been demonstrated in zero-average-index metamaterial that consist of a 1D structure alternating positive and negative refractive index [2,3]. Recently Arlandis *el al* [4] have demonstrated that mesoscopic self-collimation also arises in photonic crystal superlattices of all-positive index material, proving that zero-average-index is not necessary. Instead, they have shown that the key physical parameter in the PhC slice is a *curvature index* that can be extracted from the iso-frequency curves. The PhC slice is thus designed to provide a negative curvature index that fully compensates the divergence of the beam in the un-patterned slice. Reference [4] also shows how the properties of the superlattice are obtained with accuracy better than 1% by simply inspecting the band diagram of the elementary cell consisting of a single hole. Last, they show how the new degrees of freedom on the phase index and the mesoscopic period can be harnessed to simultaneously provide self-collimation and slow-light.

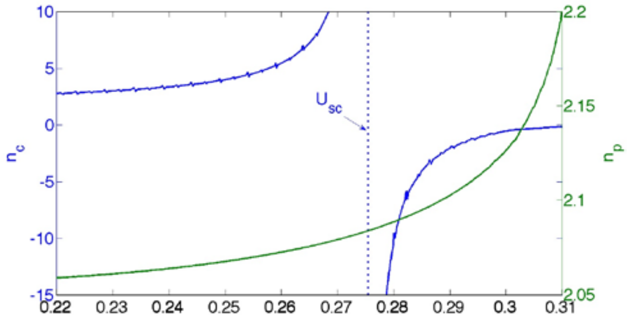

Figure 1. Phase index and curvature index of the first band versus the normalized frequency for the single-hole unit cell of an infinite 2D PhC (*a*/*r*=0.28); dashed line corresponds to self-collimation (U_{sc}~0.2754).

In this contribution we extend the concepts introduced in [4] in order to propose and demonstrate a new scheme to design multilayered PhC structures offering simultaneously mesoscopic self-collimation and tailored transmission and reflection. As an example, we design two different structures that realize a Distributed Bragg reflector (DBR) and an anti-reflection stack (AR). Both structures work without resorting to half-hole tapering used in [4] to limit impedance mismatch.

II. Design and Results

In this work, the design scheme follows the electromagnetic theory proposed in [4]. We first consider an infinite 2D PhC of square lattice with period *a* and radius *r*: the effective refractive index of the bulk material is n_b=2.4 (corresponding to a 160 nm-thick GaAs membrane for a wavelength λ=1550 nm). Using Plane Wave Expansion (PWE) method, we compute the first band of this infinite PhC, the unit cell simply consisting of a single hole. Then, we extract from the band diagram, the phase index n_p and curvature index n_c versus the normalized frequency U (a/λ) in the ΓM direction as reported on Figure 1. Self-collimation occurs for a reduced frequency U_{sc} where the curvature index diverges: U_{sc}~0.2754. For reduced frequencies above U_{sc}, n_c is negative and mesoscopic self-collimation can be obtained when the following relation is satisfied [4]:

$$\frac{l_b}{n_b} + \frac{l_{PhC}}{n^c_{PhC}} = 0 \tag{1}$$

where l_b, n_b are the length and refractive index of the bulk slices and l_{PhC}, n^c_{PhC} are the length and curvature index of the PhC slices. At the same time, the mesoscopic structure can be seen as a 1D multilayer structure where two materials with different refractive index n_b and n_{PhC} are alternated. As Equation (1) does not impose any constraint on the mesoscopic period $l = l_{PhC} + l_b$ (it only sets the ratio l_b / l_{PhC}) and does not involve the phase index n_{PhC}, we can harness these two free parameters to tailor the reflection property like in a standard multilayered structure while preserving self-collimation. For that purpose we introduce a new equation for the optical path *op* in one mesoscopic period:

$$op = n_{PhC} l_{PhC} + n_b l_b = k\frac{\lambda}{4} \tag{2}$$

where k is an integer and $\lambda = a/U$.When this equation is satisfied for k even we obtain a DBR and for k odd an AR stack. There is infinity of solutions that satisfy both equations (1) and (2) for DBR or AR configuration. We arbitrarily set $l_{PhC} = a\sqrt{2}$ (i.e. one period of PhC along ΓM) and choose to search solutions where $l_b > l_{PhC}$ (i.e. more bulk than PhC). With these constraints, the resolution of Equation 2 shows that the lowest values for k are 8 and 9 for a DBR and an AR stack, respectively. The corresponding computed values for a wavelength of λ_0=1550 nm are a_{DBR}=448 nm and $l_b = 1.156a\sqrt{2}$ for the DBR and a_{AR}=452 nm and $l_b = 1.396a\sqrt{2}$ for the AR.

Figure 2 depicts the results of 2D Finite Difference Time Domain (FDTD) simulations for the propagation of a Gaussian beam (unidirectional source to the right, initial waist of 8.5*a*) for a reference raw material (a), the AR stack (b) and the DBR stack (c). Beam is propagated over 50 mesoscopic periods *l* (DBR mesoscopic period is used for the reference). Best selfcollimated AR and DBR are observed for a wavelength equals to 1.02λ_0=1581 nm. This small difference in working wavelength (~2%) confirms that our scheme is accurate enough to guide designing and fabrication well within. Moreover preliminary analysis of the energy distributions confirms that the two proposed schemes follow the abovementioned behaviour (reflection around few % for AR and reflection above 94% for DBR) without requiring half-hole tapering at the interface between PhC and raw slices.

CONCLUSION

In conclusion, the proposed scheme allows simple conception of structures exhibiting both mesoscopic self-collimation and tailored transmission and reflection. In our presentation, we will detail all the key steps of our scheme, the performances and limitations of the structures designed with this scheme. We will also present complementary approaches also exploiting curvature index but allowing more precise prediction at the cost of more complex calculations.

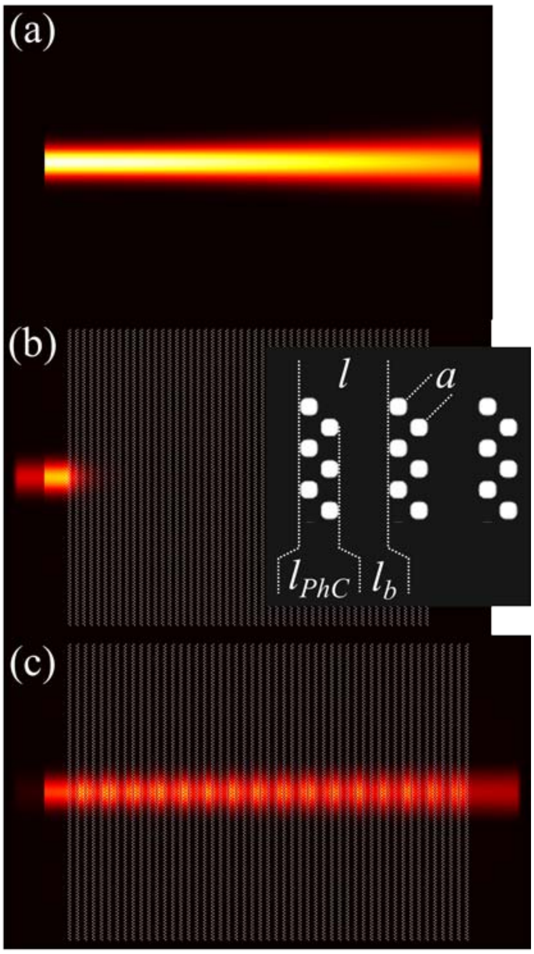

Figure 2. Energy distribution for a) reference raw material, b) DBR (a_{DBR}=448 nm, , l_b=1.156$a\sqrt{2}$) and c) AR (a_{DBR}=452 nm, , l_b=1.396$a\sqrt{2}$) schemes.

ACKNOWLEDGMENT

The authors acknowledge COST Action MP0805 on Novel Gain Materials and Devices Based on III-V-N Compounds. M. G. thanks COST Action MP0805 for the Short Term Scientific Mission and partial financial support from the European Research Office of US Army (contract n. W911NF-11-10284).

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