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 $n_0=2.4$ (corresponding to a 160 nm-thick GaAs membrane for a wavelength $\lambda=1550$ 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 $U (a/\lambda)$ in the $\Gamma M$ direction as reported on Figure 1. Self-collimation occurs for a reduced frequency $U_{sc} = 0.2754$. For reduced frequencies
above $U_{sc}$, $n_c$ is negative and mesoscopic self-collimation can be obtained when the following relation is satisfied [4]:

$$\frac{l_b}{n_b} + \frac{l_{PhC}}{n_{PhC}} = 0$$

(1)

where $l_b$, $n_b$ are the length and refractive index of the bulk slices and $l_{PhC}$, $n_{PhC}$ 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 $o_p$ in one mesoscopic period:

$$o_p = n_{PhC} l_{PhC} + n_b l_b = k \frac{\lambda}{4}$$

(2)

where $k$ is an integer and $\lambda = \frac{a}{U}$. 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 $\Gamma M$) 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 $\lambda_0=1550$ 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 8.5a) 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 1.02$\lambda_0=1581$ 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.

REFERENCES