

Band gap characterization and slow light effects in one dimensional photonic crystals based on silicon slot-waveguides

F. Riboli¹, P. Bettotti^{2*} and L. Pavesi²

¹LENS and INFM-BEC, via N. Carrara 1, 50019 Sesto Fiorentino (FI), Italy

²Nanoscience Laboratory, Department of Physics, University of Trento, via Sommarive 14, 38050 Povo-Trento, Italy

bettotti@science.unitn.it

Abstract: We investigate the photonic properties of one dimensional photonic crystals realized on Silicon On Insulator channel slot-waveguide to engineer slow light effects. Various geometries of the photonic pattern have been characterized and their photonic band-gap structure analyzed. The optimal geometry has been further used to realize a coupled resonator optical waveguide (CROW). A first optimization of these CROW devices shows a group velocity of more than $c/10$ at $1.55 \mu\text{m}$. Full three dimensional calculations based on the planar wave expansion method have been used to compute the band diagram while full three dimensional calculations based on finite difference time domain methods have been used to study light propagation.

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OCIS codes: (130.2790) Integrated Optics: guided waves; (130.3120) Integrated optics devices; (130.5990) Integrated Optics: semiconductors; (190.5530) Nonlinear Optics: pulse propagation and solitons

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1. Introduction

Slot waveguides are a particular geometry of optical waveguides able to confine light in a low-refractive index material surrounded by a higher one [1, 2]. Their typical structure (Fig. 1(a)) assumes a thin layer of a low refractive index material (n_s) sandwiched between two rectangular shaped regions of an high-index material (n_H). The region between the high refractive index materials is called slot, hence the name of slot-waveguides to this waveguide geometry. The whole structure is immersed in a low refractive index material (n_C) to assure lateral and vertical confinement (see Fig. 1(a)).

The principle of operation of slot waveguides is based on discontinuity of the normal component of the electric field at the interface between two dielectrics. In a slot waveguide, the interface of interest is the one between the high and the low refractive index materials in the slot region. The electric field component of quasi-TE mode perpendicular to the walls of the slot, E_x , is discontinuous at the interface and has a discontinuity equals to n_H^2/n_s^2 (see Fig. 1(b)). When the slot width is smaller than the decay length of the evanescent field in the low-index region, E_x remains high within the slot region. Since the magnetic field is continuous through the

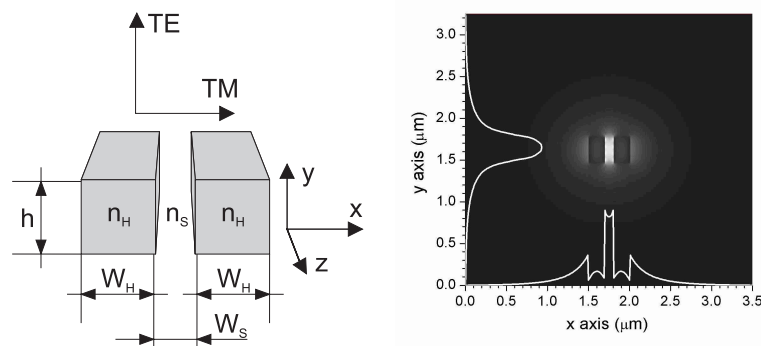


Fig. 1. a) Basic geometry and parameter definition of a rectangular slot waveguide. In the article a SOI structure is assumed, with an air top cladding ($n_C = 1$) and a buffer layer of silica ($n_{buffer} = 1.45$), not shown in Fig. b) Contour plot and spatial profiles of E_x intensity mode. In this Fig. a slot waveguide core of air is assumed.

slot region, the optical intensity in the slot region is much higher than that in the surrounding high-index regions. This waveguide geometry can be used in a wide range of photonic devices, such as ring resonators [2] or high-Q Fabry-Perot resonator [3]; in particular, it is useful when the optical property of a low-refractive index material has to be exploited. In this latter case, in fact, the coupling of a high refractive index material to guide the light with the desired optical properties of the low refractive index material can yield small foot-print photonic devices. This is particularly true in Silicon Photonics, where silicon wires can be used to achieve miniaturized optical devices. In order to add the desired optical functionalities, the slot volume can be filled with silicon nanocrystals. A possible application is to use the non-linear optical properties of silicon nanocrystals to fabricate all optical switches or logical gates. These non-linear effects can be enhanced by structuring the slot waveguides in such a way that slow light effects can increase the non-linearities of silicon nanocrystals.

Therefore, the aim of this work is to characterize one-dimensional photonic crystals embedded into slot waveguides (1D PhoCSloW) to achieve a significant slowing down of photons. In section II we will analyze photonic gap map associated with various geometries of 1D photonic pattern. In section III we will numerically characterize a Coupled Resonator Optical Waveguide (CROW) system composed by five coupled cavities that shows a quasi flat band transmission with a group velocity of about $c/100$. The proposed device can be used to enhance non-linear phase sensitivity [4], to shift carrier frequency of an optical pulse traveling through the structure [5], or to realize delay line [6, 7]. All the calculations have been performed by a full three dimensional Plane Wave Expansion (PWE) [8] and three dimensional Finite Difference Time Domain (FDTD) [9] approaches.

2. Gap Map characterization

The structure simulated in this work is a Silicon waveguide ($n_H = 3.5$) deposited onto a SiO_2 ($n_{buffer} = 1.45$) buffer layer. Silicon core layer thickness is $h = 300$ nm, total waveguide width is $2W_H + W_S = 500$ nm, slot core has a width of $W_S = 140$ nm and a refractive index of $n_S = 1.65$, which is typical of silicon nanocrystals in silicon oxide. Waveguide parameters are the result of a previous geometry optimization analysis performed in order to minimize propagation losses inside the waveguide itself (These data are part of an internal report of PHOLOGIC project). The various symbols are defined in Fig. 1. In addition, we have assumed air ($n_C = 1$) as top cladding. At $\lambda = 1.55$ μm , the slot waveguide has a monomodal behavior with one quasi-TE and one quasi-TM modes. The quasi-TE mode shows an enhancement of the field in the slot region (slot mode), and has an even spatial symmetry both with respect an horizontal and a vertical plane of symmetry (see Fig. 1). Therefore, considering both polarization and spatial profiles, the slot mode will be globally odd respect to a reflection operation in the y - z plane passing in the middle of the slot, and globally even respect to the x - z plane.

To design a one-dimensional photonic crystal inside a slot waveguides, we define trenches (air slits) perpendicular to the propagation direction. For the sake of clarity, we start by analyzing the photonic properties of a one-dimensional photonic crystal realized by air trenches carved into a silicon wire. Fig. 2(a) shows the projected band diagram (left) and the transmission spectrum (right) for the fundamental odd mode of a 1D PhoCSloW. This structure show a well defined stop band at the edge of Brillouin zone. Such gap is not complete, due to the presence of radiation modes above the light line (shaded area in Fig. 2(a)). The gap map of the periodic structure is reported as a function of the filling fraction $f.f.$ (defined as the ratio between air slit thickness and period) in Fig. 2(b). Areas defined by the white circle symbols represents the gap for the fundamental TE-like mode, meanwhile the black symbols represents the gap for fundamental TM-like mode. It is clear that the gap tends to close for $f.f. \sim 0.4$, and opens again for higher $f.f.$ just below the light line (shaded area).

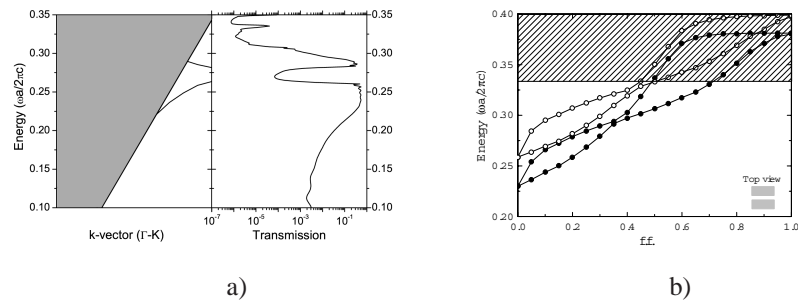


Fig. 2. a) Projected band diagram (left) and transmission spectra of a silicon wire patterned with air slits. Parameters of the silicon wires are: 300 nm thickness, 500 nm width; the parameters of the photonic crystals are period $\Lambda = 450$ nm, air slit width of 100 nm. In the band diagram the dashed region defines the region above the light-line. The dispersion and transmission spectrum are calculated for quasi-TE mode propagating along the wire axis (z -direction). (b) Gap map for the same geometry as a function of the filling factor (defined as the ratio of the air slit width to the period). The inset shows the geometry of the one-dimensional photonic crystal. White circles indicate gap-map for quasi-TE polarization, whereas black circles define the gap region for quasi-TM mode. The dashed line defines the region above the light-line. The inset in lower left corner is a sketch of the top view of the simulated waveguide.

Looking at the gap-map, a Diffuse Bragg reflector (DBR) realized on a silicon wire does not seem to have appealing photonic properties because the gap closing at $f.f. \sim 0.4$ forces either to stay just below the light line, compromising the performance of the device due to scattering, or to work with small $f.f.$ (for example $f.f. \sim 0.2$), which are technically difficult to realize. If we turn now to similar 1D PhoCSloW, we find the gap maps reported in Fig. 3. Different ways to realize the photonic crystals have been considered. In Fig. 3(a) results for air slits which cut the whole slot waveguide (full air slit) are shown; in Fig. 3(b) the air slit is interrupted at the slot region (partial air slit); in Fig. 3(c) the air slit does not extend up to the slot region (external comb); in Fig. 3(d) the pattern is formed by periodic enlargements of the slot region (internal comb).

The map gaps for the full air slit and partial air slit geometries are similar to those shown in Fig. 2(b). The gaps are shifted to higher energies with respect to the one dimensional photonic crystal realized in the silicon wire because the intensity of the optical field is mostly concentrated inside the slot region where the refractive index is low. A significant reduction of the gap width occurs with $f.f.$ between $\sim 0.2 \div 0.3$.

When the photonic pattern is realized with external comb geometry (Fig. 3(c)), only the tails of the optical field experience the modulation in the refractive index. Thus the gap map shows a smaller dependence of the gap with $f.f.$ than in the gap maps for the two previously discussed geometries; moreover, the strong decrease in gap width occurs at higher $f.f.$ values, just below the light line. Fig. 3(d) shows the gap map for the internal comb geometry. Here we find that the gaps are large for all $f.f.$ and that in a wide $f.f.$ region we have overlaps between the TE and TM gaps.

The various results shown in Fig. 3 can be explained by looking at the optical fields of the modes propagating in the one dimensional photonic structures. For the full air slit and partial air slit geometries, optical field in the half periods with the slot waveguide structure has a very different shape than the optical field characteristic of the half periods where air slits have been

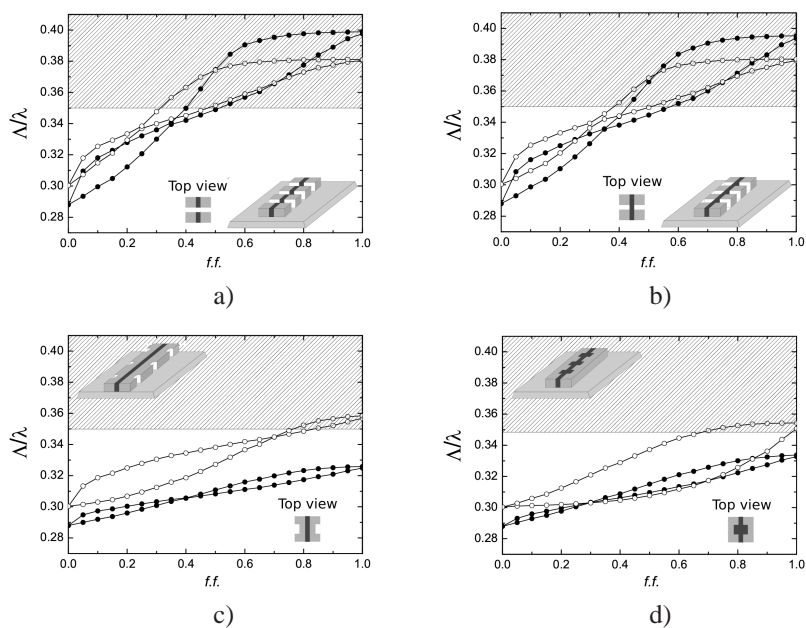


Fig. 3. Gap maps for a) full air slit, b) partial air slit, c) external comb, d) internal filled comb geometries. The parameters of the structure are $\Lambda = 450$ nm, $h = 300$ nm, $W_S = 140$ nm and $W_H = 180$ nm. The inset of each Fig. shows a 3D sketch and the top view of each geometry.

completely or partially formed. Waves propagating in the air slit region behave very differently from waves propagating in the slot waveguide region. As a consequence, the frequency dispersion of the Bloch mode is large, causing the gap to move above the light line for relatively small $f.f.$ values. The other two geometries (external and internal combs) maintain a waveguide structure all along the periodic modulation. Therefore, the frequency dispersion is small and the gap remains below the light line in the whole range of $f.f.$. In particular, for the external comb geometry, the refractive index modulation is experienced by the tail of the optical mode, resulting in quite narrow gaps; while for the internal comb geometry, the modulation overlaps with the intensity maximum of the optical mode propagating in the slot region, which produces large photonic gaps. For these reasons, these two last geometries have to be preferred in realizing photonic devices in slot waveguides.

3. 3D FDTD simulations of slow wave structure on slot waveguide

In this section, we will simulate with a 3D FDTD code [9] a slow wave structure composed by coupled resonators realized on a slot waveguide patterned with the internal comb geometry. CROW structures are composed by a series of optical cavities, where each cavity is coupled to the others through a one-dimensional photonic crystal. The presence of the cavities causes the formation of propagation modes within the photonic band gap. Cavities are separated by mirrors, where the mirror reflectivity determines the coupling between them [10] and the frequency width of the transmission resonance. With an opportune optimization [11, 12, 13, 14], it is possible to engineer the CROW, so that the k -components of the resonant modes above the light line are minimized and, hence, scattering losses are minimized too [15].

A complete optimization of such devices should be performed following a multiparametric

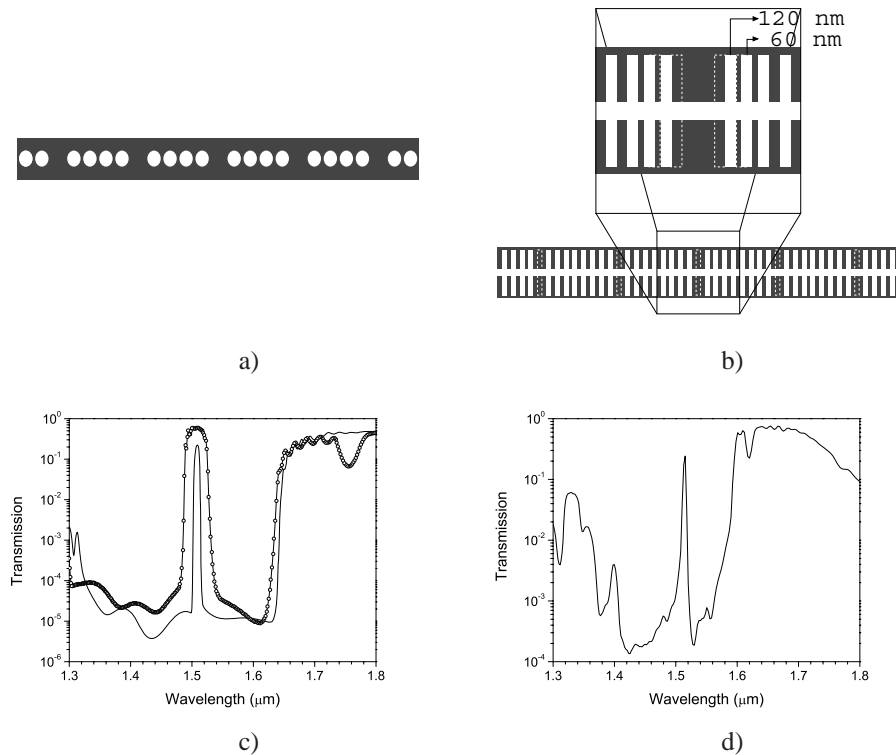


Fig. 4. a) Geometry of 1D photonic crystals carved in a silicon wire. b) Geometry of the CROW device formed by using the internal comb geometry on a slot waveguide. Zoomed area shows how the tapering applied to the two air slits near the defect site. Spatial shifts of the two air slits are indicates. c) FDTD transmission of CROW structure realized by a one dimensional photonic crystal formed by air holes in a silicon wire. d) FDTD transmission of CROW realized by the internal comb geometry on a slot waveguide.

approach, to keep into account all the factors that modify the coupling between guided and radiative modes. Since this kind of process is really time consuming, we limited our optimization to tapering the first periods facing the cavity. Moreover, to take into account the finite size of the CROW, the input and final mirrors must be engineered conveniently [16, 17]. Previous experience shows that a good choice is to halve the number of periods of the input and final mirrors with respect to the internal mirrors. Fig. 4 shows the FDTD transmission of CROW structure realized on a silicon wire (Fig. 4(a)) and on a slot waveguide (Fig. 4(b)). Fig. 4(a) shows the transmission spectrum of a chain of five coupled cavities. The white circle marked line is the spectrum of a CROW with internal mirrors composed by four air holes. The full width at half maximum (FWHM) of the transmission resonance is about 35 nm. The group velocity of light propagating via this resonance is $v_g = 0.1c_0$, where c_0 is the speed of light in vacuum. Increasing the number of air holes from four to six (solid line), the mirrors reflectivity is increased and the transmission resonance at $1.55 \mu\text{m}$ shrinks to about 10 nm with a group velocity reduced to $v_g = 0.03c_0$.

Fig. 4(d) shows the transmission spectrum for the CROW based on a slot waveguide pattern with the internal comb geometry (see Fig. 3(d)). The cavity has been defined removing a single air slit. CROW has been optimized by shifting apart the first slit facing the cavity by 120 nm

and the second slit by 60 nm (see the blow-up in the inset of Fig. 4(b)). We have used a 16 periods long internal mirrors between each cavity, while the external mirrors have 8 periods. The CROW is formed by five cavities. As for the CROW realized with silicon wire, a well defined transmission resonance appears around $1.55 \mu\text{m}$ inside the photonic gap with a transmission of about 0.3 (5.8dB).

Determination of v_g was performed using full three-dimensional FDTD simulations on both a simple slot waveguide and the internal comb structure. A short pulse, 3 nm wide, completely contained inside the cavity transmission peak (Fig. 4(d)), was sent through the structures. For what concerns 1D PhoCSloW pattern with the internal comb geometry, showed in Fig. 4(b), we found a group velocity reduced down to $v_g = 0.09c_0$. In order to obtain both a check of this data and to have a comparison with a reference structure we have simulated also the pulse propagation into a simple slot waveguide founding a group velocity reduction of $v_g = 0.3c_0$; this value is compatible with the group index estimated from an eigen mode expansion method simulation we had performed. The comparison between these two values indicates clearly that the pattern superimposed to the slot waveguide structure play an important role in slowing down light.

4. Conclusions

In conclusion, we have investigated one dimensional photonic crystals based on slot waveguides, where the slot region is filled with a material having a refractive index of 1.65. The choice of this refractive index is motivated by the possibility to deposit silicon nanocrystals in the slot region and, thus, to enhance their non-linear optical properties. We have found a photonic crystal geometry, named internal comb geometry, for which the photonic crystals show a stable and large band-gap for a wide range of $f.f$. In addition, CROW structure designed by using these one-dimensional photonic crystals shows a significant reduction of the group velocity of propagating optical modes, and slow light effects similar to what is obtained in CROW based on 1D PC realized with silicon wires has been observed. Light speed reduction in the order of $c_0/10$ were obtained and, even if this value is not comparable with the best results reported in literature for higher dimensional systems [18, 19], the system studied in this work has some advantages to respect 2D based photonic crystals waveguides: 1) it demonstrated that also patterned slot waveguides can be used for slow light applications; 2) it is directly integrated into a silicon waveguide, reducing both size and complexity of the entire devices; 3) it can be easily impregnated with active materials using standard CMOS technology and thus allow for the exploitation of these active materials properties. Moreover, with a finer optimization of the CROW structures, the slowing-down factor can be shifted to even higher value.

The results showed that slot waveguides behave in a similar way as photonic crystals in silicon wires for photonic devices based on the optical properties of low refractive index materials, provided that an appropriate design of the photonic properties is made.

Acknowledgments

This work was supported by EC through the project FP6-017158 PHOLOGIC.