Acta Universitaria
DIRECCIÓN DE APOYO A LA INVESTIGACIÓN Y AL POSGRADO

Slow light in photonic crystals waveguides

Luz lenta en guías de onda de cristales fotónicos

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ABSTRACT

We analyzed the scattering produced by technological imperfections in a strip photonic crystal waveguide. Modeling and losses analysis of the slow light structures were carried out by plane wave expansion method using the MPB software.

RESUMEN

Se analizó la dispersión producida por las imperfecciones tecnológicas en una guía de cristal fotónico. El modelado y análisis de las pérdidas de las estructuras de luz lenta se llevaron a cabo por el método de expansión de la onda plana usando el *software* MPB.

INTRODUCTION

Slow light is an interesting phenomena characterized by a low group velocities v_g. Whose interest has been motivated by a vast number of applications such as optical delay lines or buffers (Boyd, Gauthier & Gaeta, 2006), spectroscopy (Shi & Boyd, 2011) and by providing an efficient non-linear material interaction (Soljačić, Johnson, Fan, Ibanescu, Ippen & Joannopoulos, 2002). Slow light can be obtained in structured systems (structural slow light) such as photonic crystals or Photonic wire grating Bragg structures (Gnan, Bellanca, Chong, Bassi & De la Rue, 2006) among others. Photonic crystals (PhC) show band gaps where electromagnetic waves cannot propagate. Their sharp dispersion bands exhibit dispersion curve flat regions where a low v_g can be achieved (Yablonovitch & Gmitter, 1989). Such behavior can also be observed in PhC type w_1 (with a line defect) waveguides (Li, White, O'Faolain, Gómez-Iglesias & Krauss, 2008) and in strip waveguides with holes (García, Sánchez, Martínez & Martí, 2008). However, scattering losses have made some applications of slow-light structures difficult. There are two types of losses: Intrinsic losses, such as diffraction losses by leaky modes; and extrinsic losses such as random variation of fabrication (disorder and surface roughness) (Hughes, Ramunno, Young & Sipe, 2005). Nowadays, a great number of experiments are focusing in extrinsic losses. The design of the nanostructure geometry is idealized, but in the real world, imperfections in the geometry are frequently caused by fabrication processes, meaning significant losses. In this work we investigated the extrinsic losses originated by technological imperfections.

Recibido: 13 de noviembre del 2012
Aceptado: 5 de junio del 2013

Keywords:
Multiple scattering; Photonic crystal waveguides; Optical design and manufacturing.

Palabras clave:
Dispersión múltiple; guías de onda de cristales fotónicos; diseño óptico y fabricación.

Process of modeling and loss analysis

We modeled two realistic, viable to be fabricated, slow light structures: Strip waveguide photonic crystal with periodic SiO_2 holes, as shown in figure 1(a). The lattice constant of the periodic holes is represented by a and radius r; the waveguide width is w_i and the height is h. The waveguide is

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surrounded by silica. And corrugated photonic crystal waveguide, surrounded by silica, as the one shown in figure 2(a). This structure is created by introducing the periodic transversal corrugations, with lattice constant a. The corrugations have length w and width d; the strip waveguide width is w_i.

We carry out the numerical analysis by using the plane wave expansion (PWE) (Johnson & Joannopoulos, 2001) and by using the MIT Photonic Bands (MPB) software. In order to get the optimal design geometrical parameters we target a working point near $\lambda = 1550$ nm in our search for the Tranverse-electric (TE) slow modes. For the loss analysis we utilized the Thomas Krauss MPB code and the results were analyzed using Matlab code from the Thomas Krauss group as well (O'Faolain *et al.*, 2010).

RESULTS AND DISCUSSION

We calculated the parameters of these devices for a working point close to $\lambda = 1550$ nm, the telecommunications window using MPB simulations. We have studied both the backscattering losses coefficient that scale as n_g, and therein lies a serious problem for the slow light structures, the out of plane scattering losses coefficient that scales as n_g and it is a continuum radiation modes. This kind of backscattering only occurs in mono mode structures where it can be observed as backward propagation of the guided mode.

We worked the strip waveguide with periodic silica holes with the optimum geometrical parameters shown in figure 1(a). We selected the second band, which has a mono mode and posses a group index $n_g = 8.5$ with bandwidth of 14 nm. See figure 1(b).

We also observed that the strip waveguide has lower values of backscattering losses coefficient in almost all the first Brillouin zone while the larger values are located around k=0.49. Meanwhile, we detected the out of plane scattering losses coefficient is stronger than backscattering (figure 3(b) and (c)). We have also perceived that around k=0.45 to 0.5, both backscattering and out of plane scattering increase simultaneously. In this region the strip waveguide shows a flatter band, figure 1(b), and this behavior is related with the scaling of backscattering n^2_g and out plane scattering (n_g) predicted by the theory (O'Faolain *et al.,* 2010). From our simulations, we can get values of the total extrinsic losses near 1.2 dB/cm with $n_g = 15$ at k=0.42 for the strip waveguide, see figure 4(c).

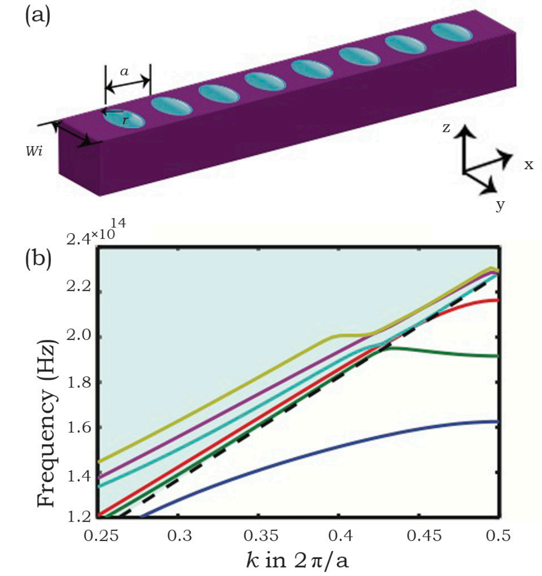

Figure 1. (a) A Strip waveguide with silica holes, lattice constant a=456 nm, hole radio r=115 nm, w=490 and h=220 nm. (b) Dispersion curves showing the bands supported by this waveguide. Where the dotted line is the light line. The green line corresponds to second band, in which the TE slow mode propagates at λ=1550 nm.
Source: Authors own elaboration.

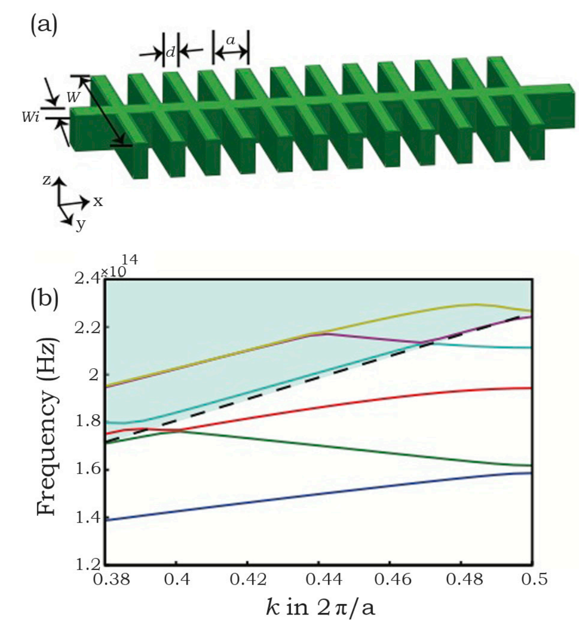

Figure 2. (a) Corrugated waveguide with the follow geometrical parameters used: a = 460 nm, d = 210 nm, w_i = 380, w = 710 nm y h = 220 nm. (b) Dispersion curves showing the bands supported by this waveguide. Where the dotted line is the light line. The red line corresponds to third band, in which the TE slow mode propagates at λ =1550 nm.
Source: Authors own elaboration.

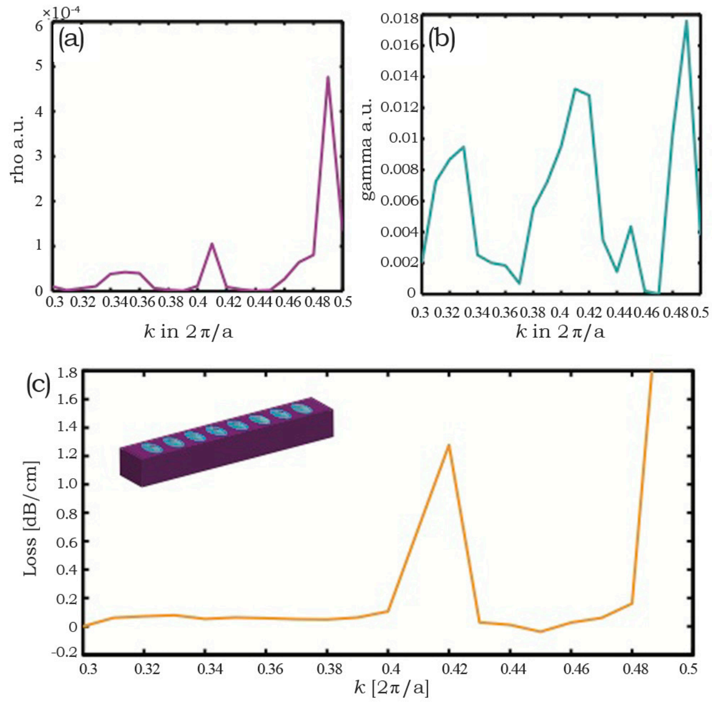

Figure 3. (a) Backscattering *vs k* for strip waveguide photonic crystal. (b) Out plane scattering *vs k* for strip waveguide photonic crystal. (c) Total losses variations as a function of the wave number *k* in the first Brillouin zone.
Source: Authors own elaboration.

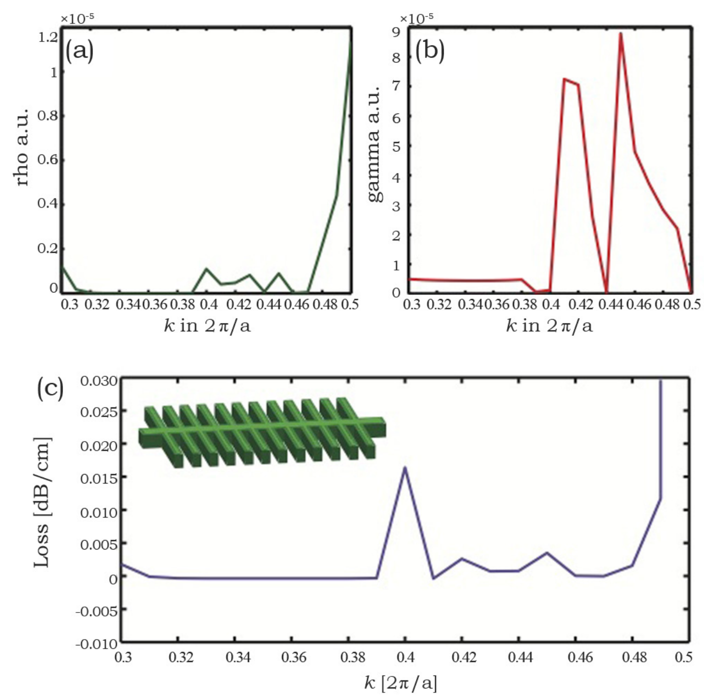

Figure 4. (a) Backscattering *vs k* for strip waveguide photonic crystal. (b) Out plane scattering *vs k* for strip waveguide photonic crystal. (c) Total losses variations as a function of the wave number *k* in the first Brillouin zone.
Source: Authors own elaboration.

For the corrugated waveguide which the geometrical parameters shown in figure 2(a), we have the following results: We worked with the third band where we obtained $n_g = 7.8$. Whose backscattering losses have relatively low values over the Brillouin zone. Although near its border, for $k = 0.5$, the backscattering increases up to 1.16·10-5 dB/cm. Now, for the case of out of plane radiation losses these are relatively high compared with backscattering losses, see figure. 4(a) and (b). We can note the total loss for this structure is two orders of magnitude lower than that of strip waveguide with values of 0.015 dB/cm in $K = 0.4$. Losses of 2 dB/cm are considered very low losses in the photonic crystals (O'Faolain *et al.*, 2010). In addition we got group indexes values of $n_g = 10$ without significant losses as it shown in the figure 4(c).

CONCLUSIONS

Our simulations shows that the strip waveguide with silica holes has slow light properties with $n_g = 8.5$. Regarding the extrinsic losses, this structure shows values up to 1.2 dB/cm over the first Brillouin zone. While, the corrugated waveguide has extrinsic losses of 0.015 dB/cm with values of group index being $n_g = 10$. The corrugated waveguide has two orders of magnitude lower than the strip waveguide. We modeled two slow structures with high group index values and low extrinsic losses. The optimization of mode coupling is a pending work.

ACKNOWLEDGEMENT

We thank Dr. S. Murugkar of Univ. of Ottawa, for instructive discussions about Slow Light. This work was supported by the following CONACyT projects: CONACyT CB-2010- 01 (under contract 157866) and CONACyT CB-2008 (under contract 101378). We also acknowledge to the SEP-SES Dirección General de Educación Superior Universitaria project 2012-01-21-002-205 and CONACyT project 000000000189688 for supporting in part the ways to publish and release this work.

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