U.P.B. Sci. Bull., Series A, Vol. 76, Iss. 1, 2014 ISSN 1223-7027

STRUCTURELESS INTERCONNECTS FOR PHOTONIC INTEGRATED CIRCUITS

Oana MIȚĂ[1], Cazimir-Gabriel BOSTAN[2], Paul ŞCHIOPU[3]

An integrated photonic routing system based on non defect waveguides is presented in this paper. The self-collimation effect in photonic crystals with 2D periodicity is used for the design of waveguides. A numerical investigation to determine self-collimation spectral range in hexagonal/rectangular lattice photonic crystals is done. It is demonstrated the routing of more self-collimated Gaussian beams travelling through a hexagonal/rectangular lattice photonic crystal, on the same optical layer. Using these unique advantages of allowing self-collimated beams to cross each other without coupling and the photonic bandgap properties, one can devise structureless interconnects for photonic integrated circuits [1].

Keywords: photonic crystal, equifrequency contours, self-collimation

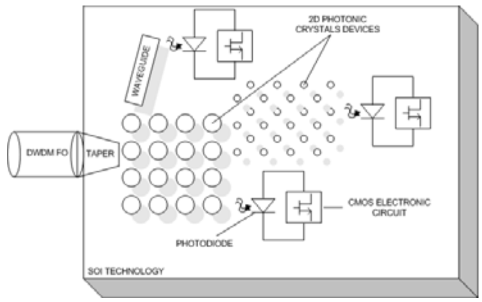
1. Introduction

Due to the continuous and aggressive scaling of CMOS technologies, electrical interconnect faces many difficult challenges - larger power consumption, an increase in the parasitic elements, pins count and routing complexity. In addition, the need for fast data propagation across chips is becoming too big for electrical interconnect to satisfy the requirements regarding the speed and power [1], [2].

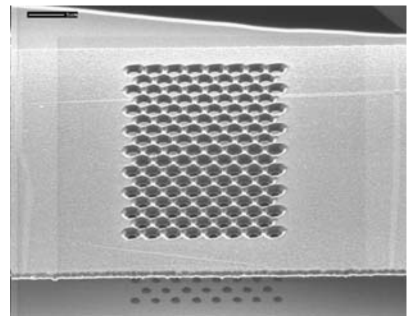
An alternative and a promising approach to the electrical interconnect for on-chip applications is an optical interconnect layer, which allows for the propagation of light through passive and active optical devices across a chip (Fig. 1 (a)) [1]. An integrated optical layer will enable a significant bandwidth increase, immunity to electromagnetic noise, a decrease in pins count and electrical power consumption, synchronous operation within the circuit and with other circuits and will reduce dependence on the thermal gradients. There are also some constraints regarding the developing of this layer: (i) all fabrication steps have to be

[1] Optoelectronics Research Center (CCO). University POLITEHNICA of Bucharest, Bd. Iuliu Maniu 1-3, Bucharest, ROMANIA, e-mail: oana_mita@yahoo.com
[2] Optoelectronics Research Center (CCO). University POLITEHNICA of Bucharest, Bd. Iuliu Maniu 1-3, Bucharest, ROMANIA, e-mail: cgbostan@gmail.com
[3] Optoelectronics Research Center (CCO). University POLITEHNICA of Bucharest, Bd. Iuliu Maniu 1-3, Bucharest, ROMANIA, e-mail: schiopu.paul@yahoo.com

compatible with integrated circuits technology; (ii) the additional cost should be as small as possible.



(a)



(b)

Fig. 1: (a) A proposed architecture using photonic and electronic systems on same chip [1];
(b) SEM picture of Si membrane with hexagonal lattice photonic crystal with 2D periodicity [3].

The compatibility between the optical interconnect layer and state-of-the-art integrated circuit requires a thorough design of the former. In order to "siliconize" photonics [4] and to integrate on the same chip the photonic and the electronic circuit, it is necessary to reconsider the optical routing because the conventional waveguide technology is a limiting factor of the integration of photonic integrated circuits (large waveguide bends are needed). One solution is the optical interconnect based on self-collimation effect in photonic crystals with 2D periodicity - Fig. 1 (b)) (if the modes are excited with frequencies that are outside the photonic bandgap, light can propagate within the photonic crystal with almost no diffraction, without having to introduce defects – this is self-collimation effect).

2. Calculation methods

Photonic crystals are artificial materials whose refractive index is periodically modulated with a lattice constant in the range of operating wavelength. This kind of structures strongly interacts with light: the propagation is forbidden and controlling the flow of light in a structure becomes possible. This wavelength range where the light cannot propagate inside the structure is called a photonic bandgap (PBG) – Fig. 2.

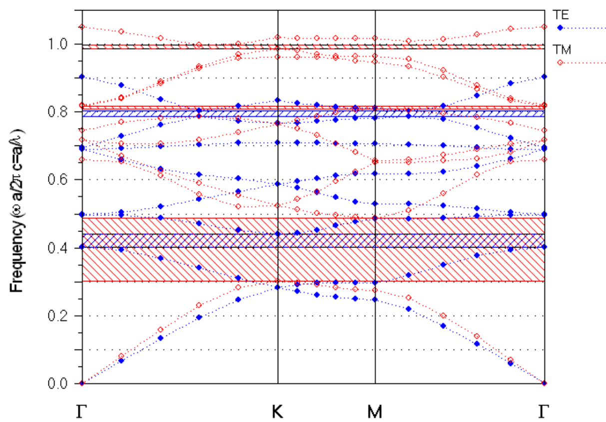
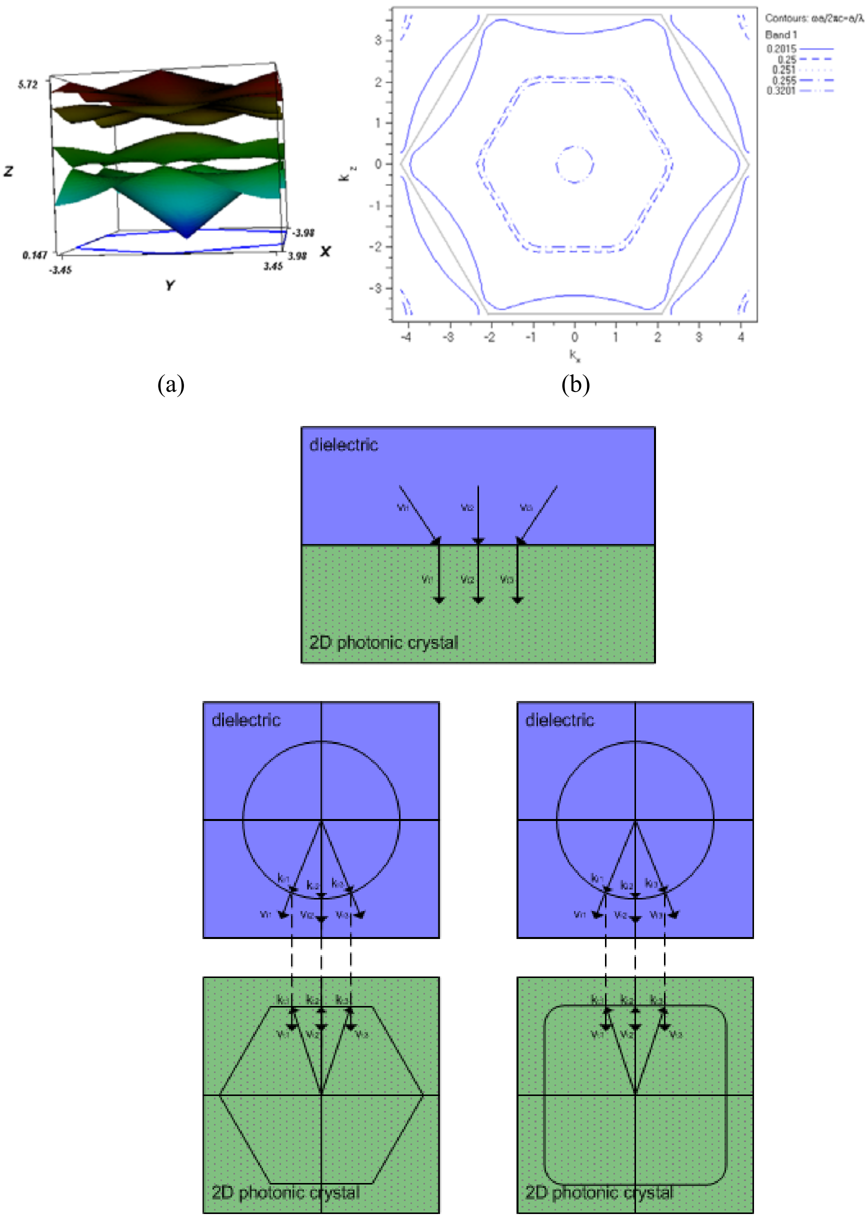


Fig. 2: Photonic bandgap: hexagonal (triangular) lattice with 2D periodicity of air hole in silicon, 0.9μm air hole diameter and the photonic bandgap for transversal electric (TE) and transversal magnetic (TM) polarizations - there is a frequency range (0.40-0.44) where no propagating modes are allowed in the structure – complete photonic bandgap.

In this paper, photonic crystals with 2D periodicity are used because they are easy to fabricate, fabrication being based on current planar process technologies developed by the microelectronic industry. Even though photonic crystals with 2D periodicity have a simple structure, the methods of analysing and interpreting their properties are still being developed. Simulation is one of the cornerstones of the photonic crystal research field. The modelling tools and the simulation methods for the photonic crystals have reached a very good performance regarding the accuracy, taking advantage of the computing power of modern systems [5].

The theoretical methods used for analysing the properties of photonic crystals are the band diagram and the equifrequency contours. The most used simulation methods are the Plane Wave Expansion (PWE) and Finite Difference Time Domain (FDTD). PWE is a method that approximates the solutions to the wave equation using Fourier expansions of the dielectric constant, the electric and magnetic fields as functions of position. The FDTD method reproduces numerically the propagation in real space of time-varying electromagnetic waves. More information about these two methods can be found in [1], [3],[6], [7], [8].



(a) (b)

(c)

Fig. 3: (a) Band surfaces; (b) equifrequency contours for second band for a hexagonal lattice photonic crystal with 2D periodicity – circular air holes in silicon, air hole diameter, d = 0.4·a (a – lattice period), TE polarization; (c) schematic illustration of self-collimation effect: for any incident angle, the electromagnetic wave is normally transmitted to the interface between air and hexagonal (rectangular) lattice photonic crystals with 2D periodicity [9].

3. Theoretical Tools

Photonic crystals have two possible working regimes: (i) photonic spectral bandgap; (ii) allowed frequencies where exhibit a wide variety of anomalous refractive effects (like super-prism effect, self-collimation effect, negative refraction).

The self-collimation effect can be highlighted analysing band diagram and dispersion surfaces of the photonic crystal device. The band diagram is the plot of the frequency versus the input wavector ($\vec{k}$). The dispersion surface is 3–D plot of the frequency versus wavevector (k_x, k_z). Taking a cross section of the dispersion surface at a constant frequency, we obtain equifrequency contours (Fig. 3). Using these contours, we can determine the propagation direction of the incident wave through the photonic crystal. This direction coincides with the direction of the group velocity, $\vec{v}_g$:

$$\vec{v}_g = \nabla_{\vec{k}} \omega(\vec{k}) \tag{1}$$

The equifrequency contours for an isotropic material are circles. For a photonic crystal, these contours take on peculiar shapes that are not circular. In order to obtain self-collimation effect, we look for contours that have a hexagonal shape (because lattice is hexagonal) (Fig. 3 (c)). When the contours have this shape, the radius of these shapes is infinite, the group velocities are parallel, so it can be obtained the self-collimation effect.

4. Simulation results

We start from the designs proposed by Mita [1], [5] and we demonstrate the structureless interconnects for photonic integrated circuits using photonic crystals with 2D periodicity, silicon background patterned with hexagonal and rectangular lattice of air holes: we demonstrate the non – interactig crossing on the same optical layer of three self - collimated beams signals.

First design consists in a hexagonal lattice patterned with circular air holes, air hole diameter d = 0.4·a (a is the lattice period).

For the hexagonal lattice photonic crystal, the invariance with respect to the 60º rotation creates a convenient coordinate system to facilitate the design and the alignment of different devices with the propagation direction [1]. In addition, self-collimated beams can also be bent towards a symmetrically direction through reflection: a mirror can be also formed by a photonic crystal with a bandgap in the frequency range of interest – self-collimation range [10]. This mirror can be obtained using a photonic crystal with 2D periodicity, hexagonal lattice with air hole diameter d = 0.87·a. From the band diagram presented in Fig. 5, it can be

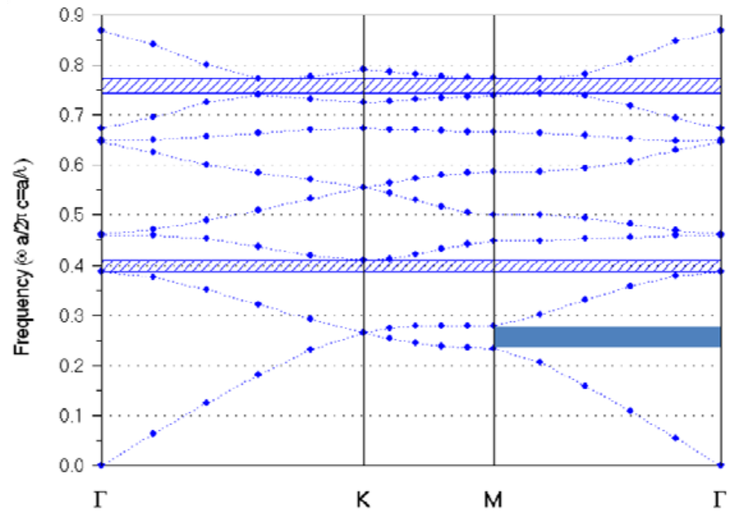


Fig. 5: Photonic band diagram for hexagonal (triangular) lattice photonic crystal with 2D periodicity, air hole in silicon, 0.87·a, air hole diameter for TE polarization.

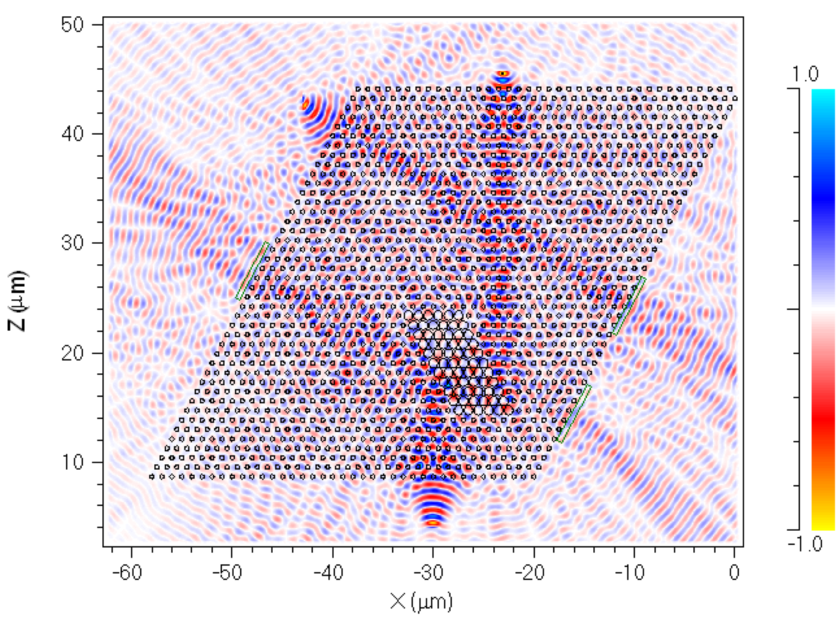


Fig. 6: FDTD simulation: E_y profile - routing three beams with different wavelengths within a single layer using the structureless photonic crystal waveguides.

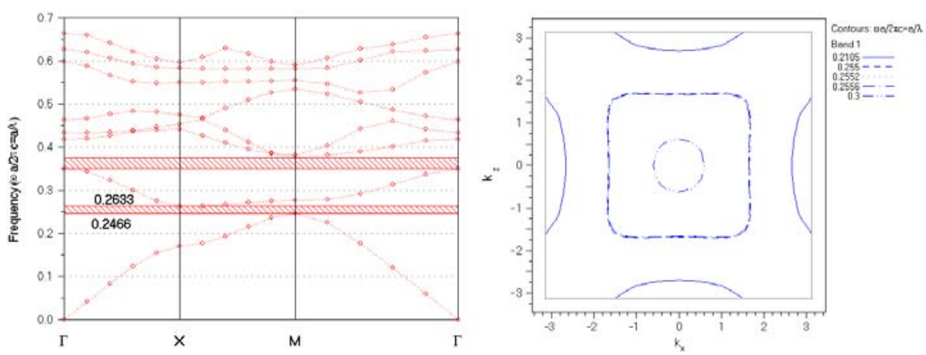
observed that for the range of normalized frequencies a/λ∈[0.23,0.28], for TE polarization, it appears a partial photonic bandgap for the MΓ propagation direction (Fig. 5 – the blue band).

This frequency range corresponds to the region of the self-collimation effect in a hexagonal lattice photonic crystal with hole diameter d = 0.4·a, as we have seen before (Fig. 3).

This unique combination of guiding and propagation behavior allows compact routing of signals on one optical signal plane rather than having to use complex three dimensional structures to avoid signal crossings: the wavelength of the input Gaussian beams are $\lambda_1 = (1/0.25)\cdot a = 4\cdot a$, $\lambda_2 = (1/0.255)\cdot a = 3.9215\cdot a$ and $\lambda_3 = (1/0.251)\cdot a = 3.995\cdot a$ with a spectral width of 1.25·a.

We have to mention that because of the partial bandgap for the MΓ propagation direction, the corner mirror has to be placed on this direction (MΓ). First and second inputs beams suffer a 120° bend and the third one crosses the first (Fig. 6). This device requires an area spanning only (40×40)μm^2 and a single layer.

The second design consists in a rectangular lattice patterned with hexagonal air holes, air hole side is $(0.25\cdot a)/\sqrt{3}$. In this case – rectangular lattice – the invariance is with respect to the 90º rotation.



(a) (b)

Fig. 7: Rectangular lattice photonic crystal with 2D periodicity, hexagonal air hole in silicon, TM polarization: (a) photonic band diagram for air hole side $(0.35\cdot a)/\sqrt{3}$; (b) equifrequency contours for second band for air hole side $(0.25\cdot a)/\sqrt{3}$.

We calculate the equifrequency contours and we determine self-collimation effect spectral range (PWE method) - Fig. 7 (b): in this case, the contours have rectangular shape.

In order to design a structureless 90° bend waveguide, we implement a mirror based on bandgap of photonic crystals with 2D periodicity, rectangular lattice, hexagonal air holes in silicon background, but air hole side is $(0.35 \cdot a)/\sqrt{3}$ (Fig. 7 (a)).

As we can observe, the photonic bandgap for this structure extends between normalized frequencies [0.2466 – 0.2633] (Fig. 7 (a)) corresponding to the spectral range for self-collimation effect in the original photonic crystal (air hole side is $(0.25 \cdot a)/\sqrt{3}$) (Fig. 7 (b)).

The input Gaussian beams are $\lambda_1 = (1/0.255) \cdot a = 3.9215 \cdot a$, $\lambda_2 = (1/0.2552) \cdot a = 3.9184 \cdot a$ and $\lambda_3 = (1/0.2556) \cdot a = 3.9123 \cdot a$ with a spectral width of a. First signal (λ_1) suffers a 90° bend due to the reflection on the mirror. The second signal (λ_2) crosses the first and the third input signals without interference. Third signal (λ_3) crosses the reflection of the first input signal and the second one without interference (Fig.8).

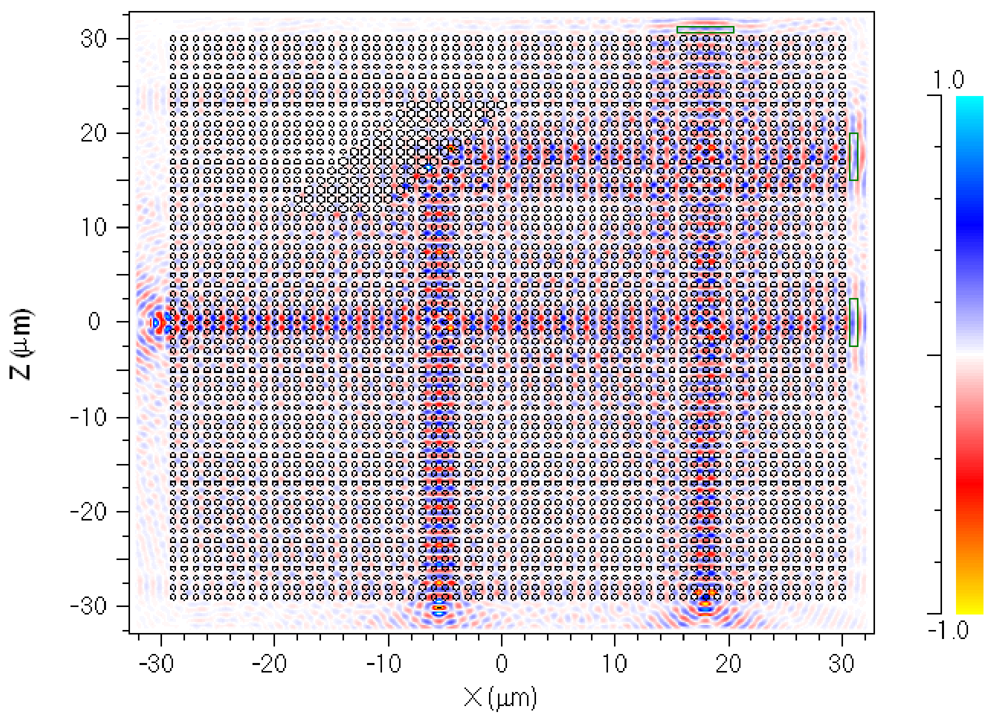


Fig. 8: FDTD simulation: H_y profile of three input Gaussian beams with different wavelengths routed within a single layer using the structureless photonic crystal waveguides based on self-collimation effect and photonic bandgap.

If the working wavelength is 1.55μm (third generation fiber optic system is based on 1.55μm window), then the lattice period is:

$$a = 1.55 \cdot 0.255\ \mu m = 395nm \quad (2)$$

and the air hole side is 57nm. These values are in the typical range of resolution of current lithographic process.

5. Conclusions

In this paper, we present a compact manner to route optical signal using different properties of photonic crystals with 2D periodicity – self-collimation and photonic bandgap. A few applications of self-collimated beams were demonstrated: 90°, 120° turns, mirrors, non-coupling intersections. For an optical interconnect layer, these applications present advantages over traditional index guided waveguides: the main advantage consists in the possibility of routing on one optical layer, requiring less area ((40x40)μm^2, respectively (60x60)μm^2) than their "classical" counterparts which could occupy few mm^2 or even cm^2 worth of area and at least two layers to accomplish the same task. The transmittance values are reasonable (around 40%). But this paper represents a qualitative study and optimization regarding the transmittance can still be done.

The novelty of our design represents the routing system based on photonic crystal with 2D periodicity, hexagonal air hole patterned in silicon background, rectangular lattice.

This routing system is demonstrated for three signals, but it can be extended to more input beams, using different numbers of mirrors depending on application requirements.

R E F E R E N C E S

[1] *O. Miţă, C. G. Bostan, P. Şchiopu*, "On chip optical signal routing based on self collimation effect in two-dimensional photonic crystals", International Semiconductor Conference (CAS), October 2008

[2] *I. O'Connor*, "Optical Solutions for System Level Interconnect", Laboratory of Electronics, Optoelectronics and Microsystems, Ecole Centrale de Lyon, 2004

[3] *C. G. Bostan*, "Design and fabrication of quasi – 2D photonic crystal components based on silicon - on – insulator technology", PhD thesis, University of Twente, Holland, 2005

[4] www.intel.com

[5] *O. Miţă, C. G. Bostan, P. Şchiopu*, "Self-collimation effect in hexagon-hole type photonic crystal slabs", International Conference "Advanced Topics in Optoelectronics, Microelectronics and Nanotechnologies", August 2010

[6] *K. S. Yee*, "Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media," IEEE Trans. on Antennas and Propagat., vol. 14, pp. 302-307, May 1966

[7] *Steven G. Johnson and J. D. Joannopoulos,* "Block-iterative frequency-domain methods for Maxwell's equations in a planewave basis," Optics Express 8, no. 3, 173-190 (2001)
[8] *Ardavan Farjadpour, David Roundy, Alejandro Rodriguez, Mihai Ibanescu, Peter Bermel, J. D. Joannopoulos, Steven G. Johnson, and Geoffrey Burr*, "Improving accuracy by subpixel smoothing in FDTD," Optics Letters 31 (20), 2972–2974 (2006).
[9] *B. Lombardet*, "Etude et realisation de cristaux photoniques pour l'optique integree", PhD Thesis, Ecole Polytechnique Federale de Lausanne", Suisse, 2005
[10] *T. Yamashita*, "Unravelling photonic bands: characterisation of self – collimation effects in two-dimensional photonic crystals", PhD Thesis, Georgia Institute of Technology, USA, August, 2005