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Andrei V. Lavrinenko, Peter I. Borel, Lars H. Frandsen, and Jacob Fage-Pedersen

COM·DTU, Department of Communications, Optics & Materials, NanoDTU, Technical University of Denmark,
345v, DK-2800, Kgs. Lyngby, Denmark
Tel: (45) 4525 6392, Fax: (45) 4593 6581, e-mail: ala@com.dtu.dk

ABSTRACT

We report on transmission, field mapping, and spectral dependence of the group index in the slow light regime, obtained by numerical modelling. The influence of a finite number of lattice periods on the observed properties is pointed out.

Keywords: Photonic crystal waveguides, slow light, transmission, group velocity.

1. INTRODUCTION

The area of the current research is the slow-light regime in photonic crystal waveguides (PCWs). This regime is interesting because modes with group velocity significantly smaller than the phase velocity in the bulk material have significantly enhanced light-matter interaction [1]. A number of publications have appeared about slow light applications for devices operating on photonic band gap effects since the first discussions [2-6]. The fact that nonlinear effects are effectively enhanced proportionally to the group index allows for a noticeable shrinkage of the size of photonic components. A lot of efforts are spent now to look for devices with large group indices of the propagating modes. Group velocities several hundreds times lower than the speed of light in vacuum have been reported recently by several groups [7-14]. Thus, the interest in utilizing slow light properties has been rising constantly.

We report in this paper on an investigation of PCW mode properties in the slow mode regime. The PCWs were made by removing one row of holes in the Γ–K direction of a triangular lattice of air holes etched in a dense dielectric like silicon ($n = 3.476$). Mode patterns and transversal and longitudinal energy flux profiles are addressed in Section 2. A closer look at the transmission properties of PCWs near the cutoff of the fundamental mode is made in Section 3. Here the data concerning the group index calculations are placed as well. Conclusions are finally given.

2. MODE PROFILES

We start with a comparison of the mode profiles in different parts of the fundamental band. In Figure 1 a typical band diagram for a W1 PCW (hole radius $r = 0.3a$, where a is the lattice constant) is presented together with mode maps for the component E_x of the electric field.
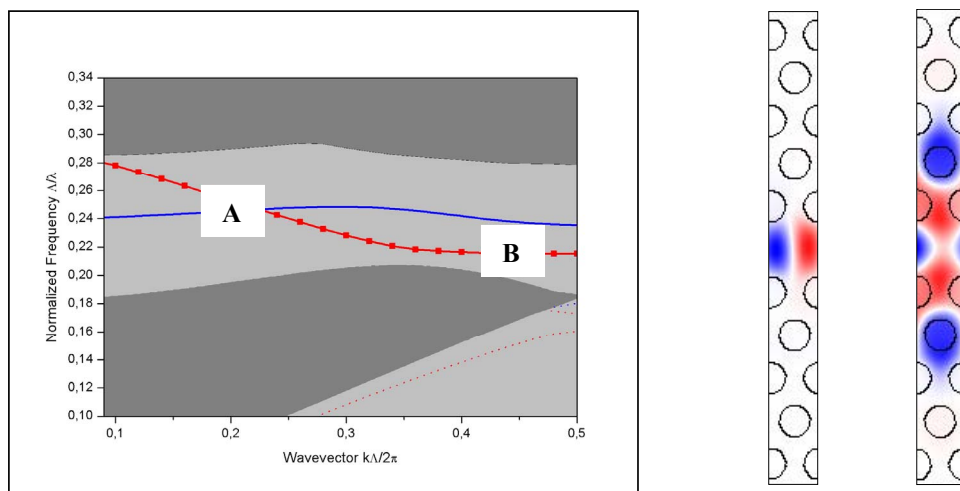

Figure 1. a) TE dispersion diagram for an infinite W1 PCW. The dark grey zones show continuum of photonic crystal modes. b) and c) The transverse profiles of the fundamental mode in points A and B, respectively.

The diagram was calculated with the 2D plane wave expansion method [15]. The fundamental band gap mode in the linear dispersion regime (point A) is confined within the waveguide core, as can be seen in Fig. 1*b*. However, in the slow-light regime where the dispersion curve is nearly flat (point B) the field spreads out of the core, occupying approximately the two nearest rows of holes on each side of the waveguide.

The mode profiles in the two different parts of a spectrum of a finite W1 PCW were also calculated with the 2D FDTD method. The PCW was 20 μm long, having $r = 0.3a$, and $a = 475$ nm. Results are shown in Fig. 2 for the electric field; the plots agree well with predictions for the infinite periodic structure made by the PWE method. The left-hand side picture is a steady state in the middle of the transmission window, corresponding approximately to point A in Fig. 1 ($\lambda = 2050$ nm). The right-hand side picture shows the slow-light mode spreading out from the core ($\lambda = 2203$ nm), corresponding to point B in Fig. 1. The hole pattern is shown with circles.
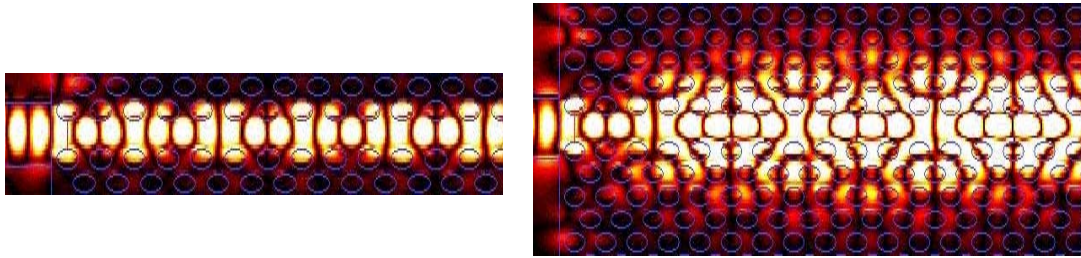

Figure 2. Same as Fig.1 right, but calculated by 2D FDTD for a 20-μm long PCW excited with a continuous-wave source. Left picture: in the linear dispersion regime, Right: in the slow mode regime.

To show the mode profiles in more detail, we have plotted the transverse profiles of the field intensity in the PCW in Figure 3. The profiles represent the two wavelengths of 2050 and 2203 nm, corresponding to high transmission and slow light near the cutoff, respectively. The fields were recorded by using 3-μm long transverse oriented detectors, and the zero coordinate is near the centre of the PCW channel.
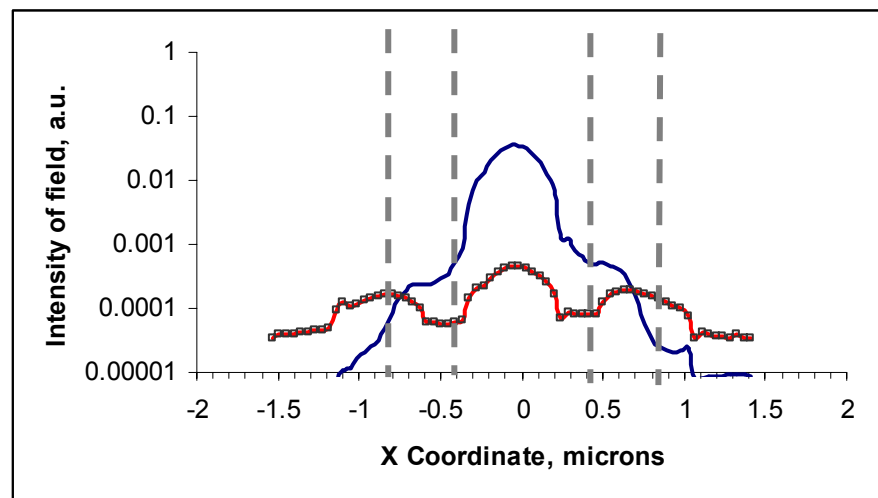

Figure 3. Intensities of the fields in a W1 PCW along a cross section of the core. The solid curve is for λ = 2050 nm, the curve with small squares is for λ = 2203 nm. The grey dashed lines show the positions of the two rows of holes nearest to the channel of the PCW.

We also placed a detector along the waveguide axis (*z*) to visualise the longitudinal profile of the mode. The observed intensity profiles are given in Figure 4a. Again, $\lambda = 2050$ nm and 2203 nm are investigated. The intensities were recalculated to be consistent within one graph. The PCW interface is at $z = 1$ μm.

We see that there is a transient region inside the PCW after which the fields reach maximum values. The region extends to approximately 1 μm from the interface at $\lambda = 2050$ nm. This distance increases up to 2 μm when approaching the cutoff wavelength. Such behaviour resembles to some extent that of field profiles calculated analytically for a 1D photonic crystal [16, 17], although in the cases treated in the references, a wave was used near the photonic band-edge wavelength (no defect modes in the 1D cases).

We analysed the profile of the energy flux. In the first section of the PCW, where the transient region occurs, the net flux in the middle of the channel has only positive values. This can be explained by strong scattering of the fields due to mode mismatch just at the entrance of the PCW, most pronounced for the slow-light mode. Near the peak value of the field, for a short distance the net flux of the slow-light mode becomes dominantly

negative in the centre of the channel. This is due to accumulation of the fields in the channel after intensive scattering at the entrance. After that, the usual oscillation of the sign of the net flux occurs in the PCW [16, 17]. In the transverse direction, the net flux as a function of x coordinate is shown in Fig. 4b. A 3-µm long detector had been placed 2 µm away from the input interface. In the linear dispersion regime the net flux is mostly confined within the channel (solid curve). In the slow-light regime there are two strong regions of backdraught with negative flux at the positions of the nearest rows of holes.
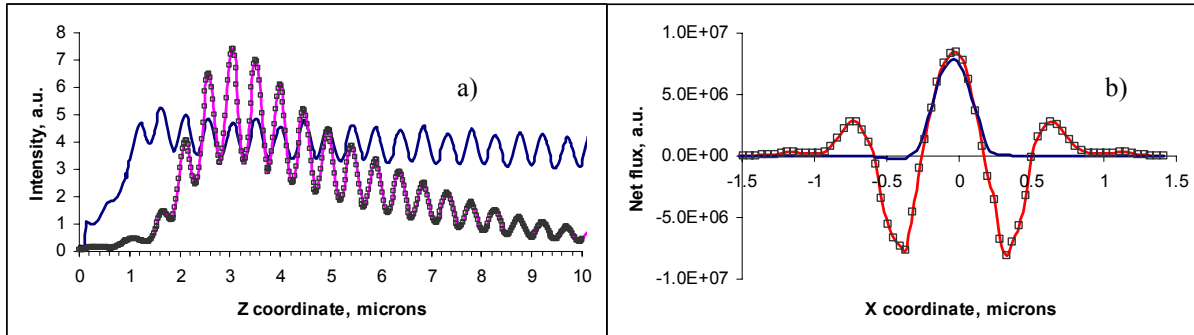

Figure 4. a) Field intensities along the waveguide axis of the W1 PCW, as a function of coordinate. b) Net energy flux inside the PCW, as a function of coordinate along the cross section. In both plots, the solid curve is for λ = 2050 nm and the curve with small squares is for λ = 2203 nm.

3. TRANSMISSION AND GROUP VELOCITY

An interesting issue is the behaviour of the transmission and group index close to the cutoff frequency. A time-of-flight technique was implemented by direct simulation of pulse propagation in the time domain. The method is described in details in ref. [12], where both 2D and 3D FDTD were employed. The pulse was formed with $1 \cdot 10^6$ time steps, providing a FWHM of approximately 0.36 nm. However, fast oscillations of the spectral curves that were observed in experiments called for a higher frequency resolution in the simulations. The simulations were repeated in 2D with pulses of $4 \cdot 10^6$ time steps. Such wide time envelope gives a 0.09-nm resolution in the frequency domain. This was sufficient to see sharp in-phase oscillations of transmission and group index. Results of the modelling are presented in Figure 5. Similar, distinct oscillations of the group index in experiments have been observed recently [12, 13]. The period of oscillations decreases monotonically when approaching the cutoff wavelength. The number of oscillations and their period is determined by the number of longitudinal lattice periods and is a signiture of the finite length of the PCW. In the 1D case the same effect was investigated in ref. [17].
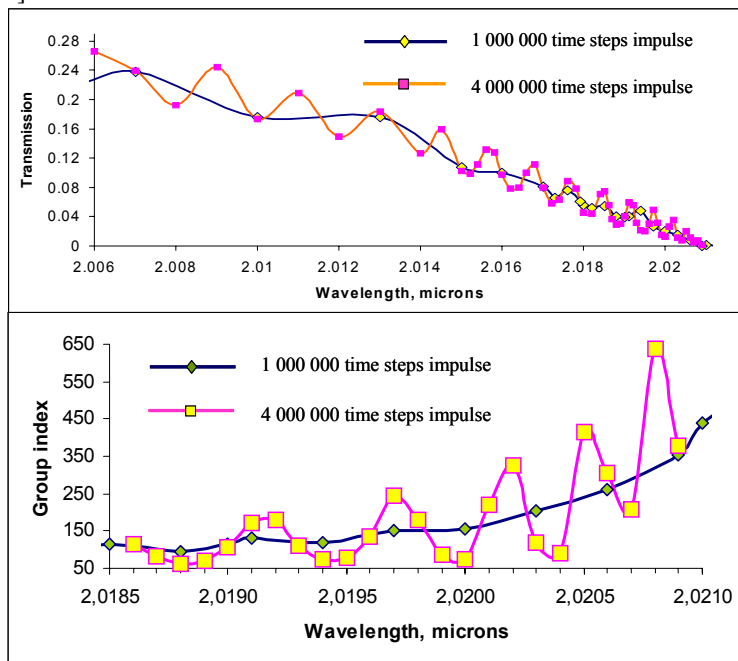

Figure 5. Transmission spectra (upper plot) and group index dependence on the wavelength (lower plot) close to the cutoff of a W1 PCW. The parameters of the waveguide are the same as in Ref.12.

4. CONCLUSIONS

We analysed the properties of guided modes in PCWs in the slow-light regime. The fields profiles show significant spreading of the fields out of the waveguide channel. This fact can be exploited to design structures with deliberate engineering of the slow-light behaviour, e.g. by changing parameters in the second nearest row of holes only. In this way, the properties of the modes propagating in the linear dispersion regime will remain unaffected. Field patterns, intensity profiles in the transverse and longitudinal directions, and diagrams of the net flux show significant differences for the slow-light behaviour in comparison with the ordinary linear dispersion regime. We found, e.g., the existence of zones with large negative net flux in the slow-light regime.

The spectral dependencies of the transmission and group index were calculated in the proximity of the fundamental mode cutoff. To observe rapid oscillations of waveguide characteristics in wavelengths, the frequency resolution of the time-of-flight method was increased four-fold. In analogy with the properties of 1D periodic stacks, the conclusion is made that the observed properties are dominantly governed by the finite length of the periodic lattice.

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