# Nanopillars Photonic Crystal Waveguides

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**Abstract**

We present a novel type of a waveguide, which consists of several rows of periodically placed dielectric cylinders. In such a nanopillars photonic crystal waveguide, light confinement is due to the total internal reflection, while guided modes dispersion is strongly affected by waveguide periodicity. Nanopillars waveguide is multimode, where a number of modes is equal to the number of rows building the waveguide. We perform a detailed study of guided modes properties, focusing on possibilities to tune their frequencies and spectral separation. An approach towards the specific mode excitation is proposed and prospects of nanopillars waveguides application as a laser resonator are discussed.

## Section 1. Introduction

Photonic crystals (PhCs) are known for offering a set of unique options to control the flow of light by acting as waveguides, cavities, dispersive elements etc [1]. Photonic crystal waveguide (PCW) is one example of promising optical applications of PhCs at micron and submicron length-scales. In PCW, light confinement is due to a complete photonic bandgap (PBG). In this paper, we show that a finite system of periodically placed cylinders can also act as a waveguide (nanopillars PCW), effectively confining light. In such a structure, light confinement is due to the total internal reflection (TIR) at the effective waveguide boundary, while guided modes dispersion is strongly affected by waveguide periodicity.

In Section 2 of this paper, we show that a number of nanopillars rows can effectively confine light and therefore can be regarded as a PCW. The mode structure of nanopillars PCW is discussed afterwards. In Section 3, an influence of dielectric constant and radius of nanopillars, as well as, lattice geometry upon guided modes properties are analyzed. Finally, in Section 4, we report about excitation of only one mode in multimode region and propose a promising concept towards an application of a nanopillars PCW as a tunable laser resonator with ab-initio implemented distributed feedback. Section 5 concludes the paper.

## Section 2. Guided modes of a nanopillars PCW

In paper [2] it was found that a single row of periodically placed dielectric rods has two localized guided TM modes: the first one, fundamental mode, has an even symmetry and the second one -- an odd symmetry. The second mode splits from the upper continuum at the very end of the irreducible Brillouin zone (IBZ) leaving a wide gap between two modes. The waveguide is effectively single-mode in a wide frequency range.

Attaching one, two or more identical 1D periodic waveguides in parallel with the original one produces a coupled-waveguide structure. It is well known in optoelectronics that in the strong coupling regime, this leads to the splitting of the original modes into *n* modes, where *n* is a number of coupled waveguides [3]. In figure 1, TM-dispersion diagrams for 2-, 3-, 4- and 5-rows of 1D periodic array of dielectric rods are shown. All rods are placed in the square lattice vertices. We will refer to such structures as *nanopillar PCWs* and designate them as W2, W3, W4 and W5 correspondingly. Here it is assumed, that nanopillars PWCs are extended in *z* direction. Dielectric constant of rods is $\varepsilon = 13.0$ and their radius is $r = 0.3a$, where $a$ is a lattice constant of a square lattice. Dispersion diagrams were calculated using the plane-wave expansion method in 2D. To model nanopillars PCW the supercell method was employed. In all calculations, the supercell consists of one period in the *z* direction and 20 periods in the *x* direction, where *n* periods are occupied by dielectric rods.

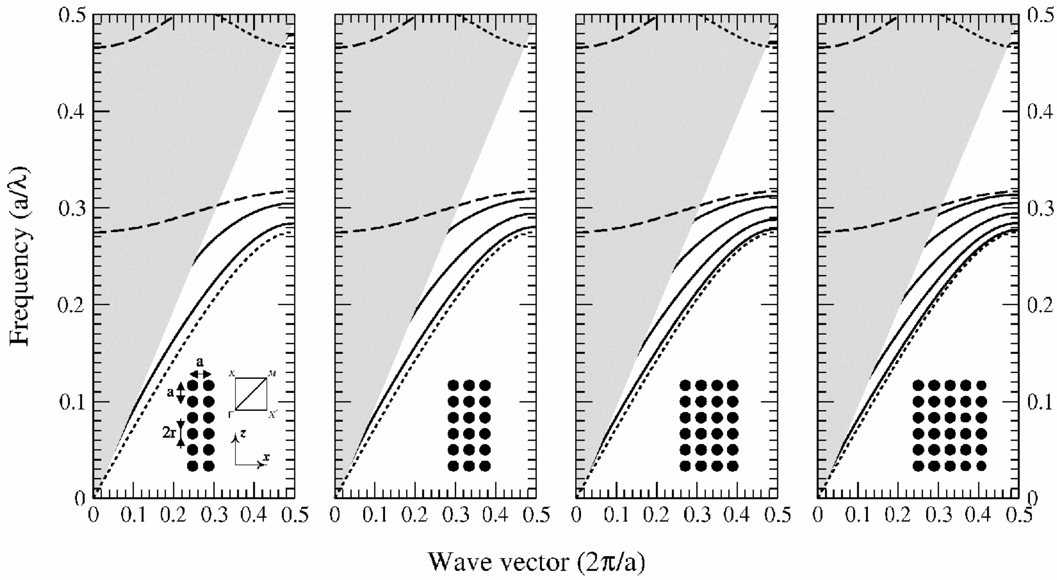


**Figure 1**. TM-dispersion diagrams for nanopillars PCWs with 2, 3, 4 and 5 rows. Insets show a sketch of the waveguides. Guided modes are shown in solid lines. Grey area shows a continuum of radiated modes lying above the light line. Dotted and dashed lines are the Γ-X and X-M dispersion curves.

W*n* waveguide is a multimode device with *n* modes grouped near the lowest original mode of a W1 nanopillar PCW. The group of *n* modes is separated from the higher frequency modes by a sizable bandgap. All *n* lowest guided modes are flat near the end of IBZ. This fact leads to almost equidistant distribution of flat tails of the modes for limiting values of wave vectors close to $k_z = 0.5$. In figure 2, field patterns for the four lowest modes of W4 waveguide are shown for this frequency range. Field patterns were calculated by 2D FDTD method. Monochromatic excitation with the corresponding mode symmetry was used. We applied periodic boundary conditions in the *z* direction and absorbing [perfect matched layers (PML)] boundary conditions in the *x* direction. The field patterns were plotted after the steady state regime had been reached. The field is effectively localized within the nanopillar PCW.

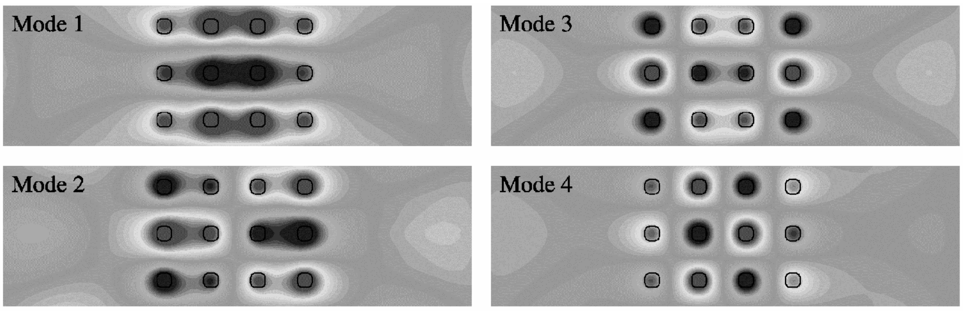


**Figure 2.** Field patterns of the 4 lowest guided modes of W4 PCW. Modes 1 and 3 are even, 2 and 4 are odd. $E_y$ component of the field is plotted.

Analyzing the dispersion diagrams in figure 1 it is noticeable that the *n* lowest guided modes of W*n* waveguide are localized in the certain regions of $\omega, k_z$ space. This can be understood using the following arguments. A surface truncation of an infinite 2D PhC imposes that modes of a semi-infinite crystal are modes of the infinite crystal, projected onto the direction of the crystal surface (in our case it is Γ-X direction) [1, 4]. In other words it means that for certain $k_z$ component of the wave vector all modes of the infinite crystal with allowed combinations of $(\omega, k_x)$ are supported by the truncated crystal. A continuous band of modes exists in a semi-infinite PhC and it is bounded by Γ-X (the dotted line in figure 1) and X-M (the dashed line in figure 1) dispersion curves of an infinite PhC. Truncation of the semi-infinite PhC from the second side, leaving only integer number of rows of pillars *n*, brings a new condition for the modes of the remaining system. Now, not all $(\omega, k_x)$ pairs for the particular $k_z$ are allowed in the system, but only those, which support the resonant conditions in transverse direction. The spectrum becomes discrete instead of continuous. Consequently, all dispersion curves of nanopillars PCW are localized between Γ-X and X-M bands of an infinite crystal and their number is equal to *n* (Fig. 1).

## Section 3. Modes dispersion engineering

It is well known that by varying the filling factor and dielectric constant of rods one can tailor the frequency range of the 2D PhC bands. In addition, the use a rectangular Bravais lattice [5] opens another possibility to affect the crystal band structure. Taking into account, that nanopillars PCW modes are bounded by Γ-X and X-M bands of an infinite crystal, these can be used for a proper adjustment of nanopillars waveguide modes, especially their flat tails near the edge of IBZ, on the spectrum.

First, decreasing the dielectric constant of the rods simply shrinks the gap uprising in frequency, so the flat *n*-modes bundle travels up and intersects with higher frequency modes. Second, by changing the crystal filling factor (the radius of the rods) the position of a bandgap is disturbed following the rule of a thumb [1]: the bigger the effective index, the lower the frequencies of the gap. Finally, changing the horizontal side of a square lattice in *m* times leads to the expansion or shrinkage of the frequency range of projected bands depending on whether coefficient $m>1$ or $m<1$. Examples are shown in figure 3 for the case of three Bravais lattices: square lattice ($m = 1.0$) and rectangular lattices with $m = 0.5$ and $m = 2.0$. Varying the coefficient *m* can control both the frequency separation and positions of waveguide modes.

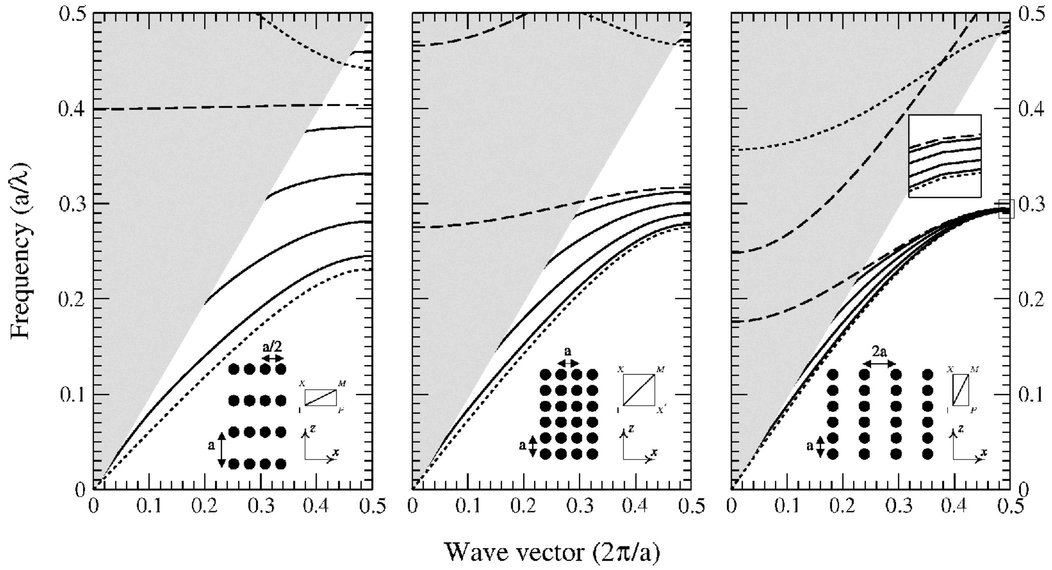


**Figure 3**. Dispersion diagrams for different rectangular Bravais lattices; $m = 0.5$ (left), 1.0 (center) and 2.0 (right). Insets show a sketch of the waveguides, the coordinate system and the quarter of the first Brillouin zone of the corresponding lattice. Grey area shows a continuum of radiated modes lying above the light line. Guided modes are shown in solid lines. Dotted and dashed lines are the Γ-X and X-M dispersion curves.

## Section 4. Given mode excitation

To analyze whether it is possible to excite the single mode of a nanopillars PWC, we calculated the transmission spectra of 20 periods long W4 waveguide. 2D FDTD method with PML boundary conditions at all sides and the resolution of 16 grid points per lattice constant was used. Modes were excited by a gaussian-shaped temporal impulse with initial spatial amplitude distribution reflecting the symmetry of a chosen mode (Fig. 2). Fields were monitored by input and output detectors and transmitted waves intensities were normalized by the ones of incident waves. In figure 4, transmission for different modes are compared with the dispersion diagram. The positions of the cut off frequencies for different modes are resembled by spectra. Intensive ripples on transmission curves are attributed to the Fabry-Perot resonance at the ends of the waveguide.

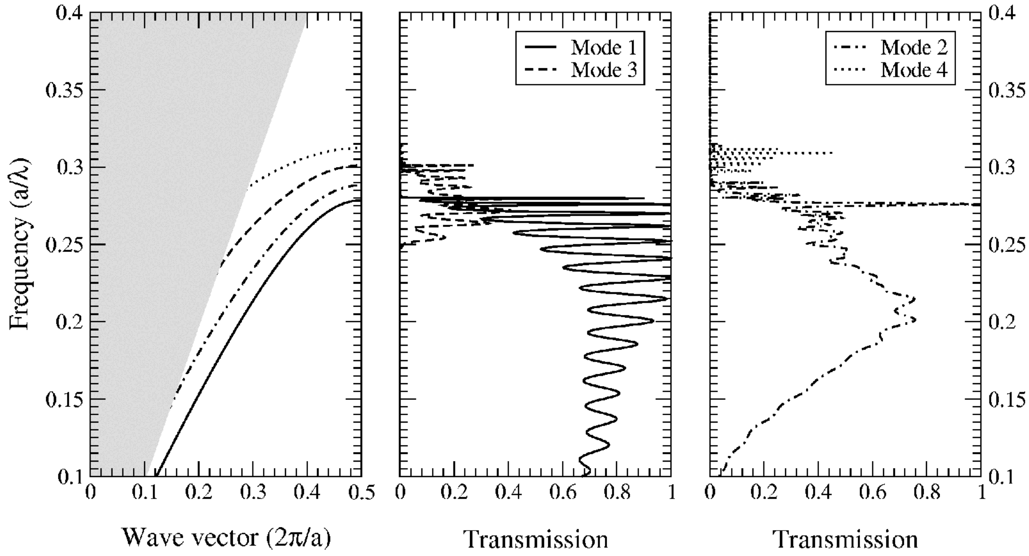


**Figure 4.** Dispersion curves (left) and transmission spectra for the modes 1- 4 (center and right) of W4 PCW.

Transmission spectra proved that the waveguiding effect in nanopillar PCW is promising for controlling the propagation of light. The final conclusion about transmission rates can be made only after full 3D FDTD calculation, which will be presented elsewhere. Nevertheless we can speculate that if nanopillars in Si, SIO or SiGe can be fabricated tall enough [6] to localize fields effectively in vertical direction our 2D results can be evaluated as realistic ones.

Flat tails of the nanopillars waveguide modes near the IBZ edge reflect a very low group velocity of these modes. Modes near flat tails should have a smallest energy decay rate in a finite waveguide. Thus, an excitation of a given single mode gives a possibility of tunable lasing in a nanopillars PCW. By simultaneously exciting only rods reflecting the symmetry of the requested mode the lasing frequency can be switched among *n* modes of the W*n* nanopillars waveguide. Choosing a proper material, lattice geometry and rods diameter can adjust lasing frequencies for a given spectral range and a given spectral resolution.

## Section 5. Conclusion

In conclusion we have proposed a novel type of 2D photonic crystal waveguides, comprising several rows of dielectric rods. Nanopillars waveguide possesses the system of localized modes separated nearly equidistantly at the boundary of the Brilloun zone. The factors playing the major influence upon modes dispersion have been analyzed. In spite of a multimode nature of the waveguide, transmission spectra prove the possibility of a single mode excitation by imposing specific symmetry conditions onto a field source. We believe in a great potential of nanopillars PCW as an effective laser resonator.

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