Efficient coupling structures for integration of pillar photonic crystals with ridge waveguides

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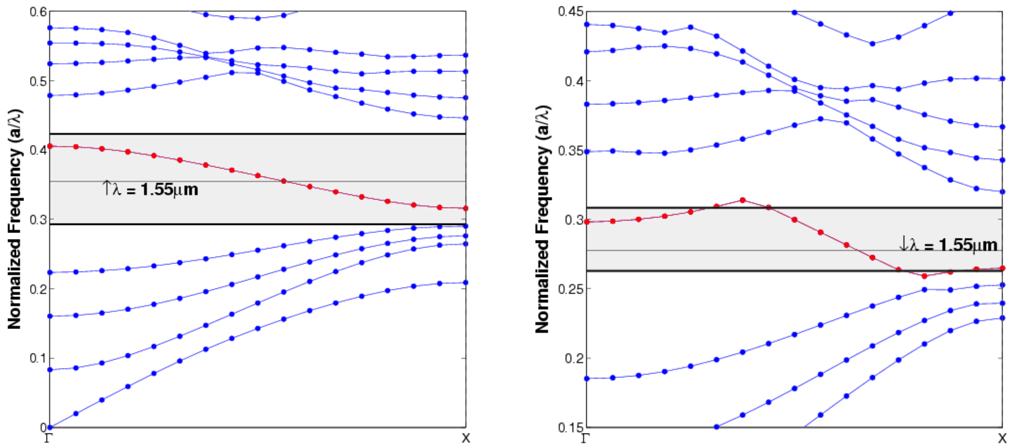
We present 2D FDTD simulations of the coupling from a conventional optical waveguide to a photonic crystal waveguide and vice versa. Firstly, the optimum radius of the waveguide rods is determined for pillar photonic crystals surrounded by air and with a polymer layer stack. Secondly, the transmission of the waveguides with the coupling structures is simulated. The bandwidth obtained at 95% transmission is $\simeq$ 20*nm for the pillars in air, increasing to* $\simeq$ 50*nm if the polymer layer stack is implemented.*

Introduction

Photonic crystals show a huge potential for decreasing the dimensions of planar photonic integrated circuits. However, photonic crystal-based components can only be successfully integrated with conventional optical integrated circuits if the losses are comparable or lower than those of existing components.
We aim for the integration of pillar photonic crystals in photonic integrated circuits based on InP/InGaAsP technology, operating around $\lambda = 1.55$ μm. A square lattice of high-index rods in a low-index medium gives rise to a large band gap for TM polarization. In order to reduce the losses of pillar photonic crystals in air, we implement a polymer layer stack between the rods. The core layer is a polyimide with a high refractive index, which is sandwiched between two polymer layers of low refractive index [1]. In this way we create optical guiding in between the semiconductor pillars, reducing the out-of-plane diffraction, and thus the propagation losses of the structure.
Furthermore, the losses can be significantly reduced by optimizing the coupling from the ridge waveguide to the photonic crystal waveguide and vice versa [2]. In this paper we present two-dimensional FDTD calculations of a simple butt coupler.

Photonic crystal waveguides

The conventional photonic integrated circuit imposes restrictions on the material system that is used for the photonic crystals. The substrate consists of InP with a refractive index of $n_{\mathrm{InP}} = 3.196$ and the guiding layer is InGaAsP, with an index of $n_{\mathrm{InGaAsP}} = 3.435$. The guiding layer is 500 nm thick, and it has an InP top cladding of 1 μm. The polymer layer stack that is implemented to create optical guiding between the pillars, consists of poly(hexafluoroisopropyl)methacrylate (PHFIPMA), with an index of $n_{\mathrm{PHFIPMA}} = 1.38$ and the polyimide PI2737, with an index of $n_{\mathrm{PI2737}} = 1.64$.
Full 3D simulations are necessary when designing photonic crystal-based devices, but these require substantial computational power. To get an indication of the influence of the different parameters, the first optimization is done in 2D. To account for the third dimension, the effective index method is applied. The effective index of the fundamental TM mode of the III-V layer stack is $n_{\mathrm{eff,III\text{-}V}} = 3.332$ and that of the polymer layer stack



(a) Pillars in air (b) Pillars in polymer

Figure 1: Band diagrams for photonic crystal waveguides; (a) for pillars in air, and (b) for pillars embedded in a polymer layer stack.

is $n_{\text{eff,polymer}} = 1.49$.
The largest possible band gap is obtained for $r/a = 0.20$ in the case of pillars in air, where r represents the pillar radius and a the lattice constant. The ratio increases to $r/a = 0.22$ if the polymer layer stack is implemented. From the center frequency of the band gap, and keeping in mind that the operating wavelength is 1.55 μm, the optimal lattice constant and the corresponding pillar radius are derived. For the lattice of pillars in air, this results in $a = 550$ nm and $r = 110$ nm, whereas in the case of pillars in polymers we derived $a = 430$ nm and $r = 95$ nm. The smaller dimensions of the latter crystal are due to the increase of the average refractive index, causing a decrease in the effective wavelength inside the structure.
Introducing a line defect in the photonic crystal, by changing the radius of a row of pillars, creates a guided mode inside the band gap. To choose the defect radius, we compared the calculated band diagrams in ΓX direction of varying defect radii. Fig. 1(a) shows the band diagram of the photonic crystal waveguide of pillars in air, with a defect radius of 175 nm. Fig. 1(b) show the analogue graph for pillars in a polymer stack, where the optimal defect radius is 170 nm. The optimal radii are chosen to have a steep but uniform slope around the wavelength of interest, which is indicated in the graphs as well. Note that in the case of pillars in polymers the guided mode of the line defect also exists outside 2D band gap.

Coupling structure

The simplest structure to couple light from a ridge waveguide into a photonic crystal waveguide, is to place the two types of guiding structures directly in front of each other. This configuration is depicted in Fig. 2. The input ridge waveguide is tapered down to the diameter of the line defect pillars and the output ridge waveguide can be tapered again to the width that is required in the photonic integrated circuit.
The transmission of this structure is calculated using the 2D FDTD method of Crystal-Wave, a commercially available software package. To calculate the transmission, we

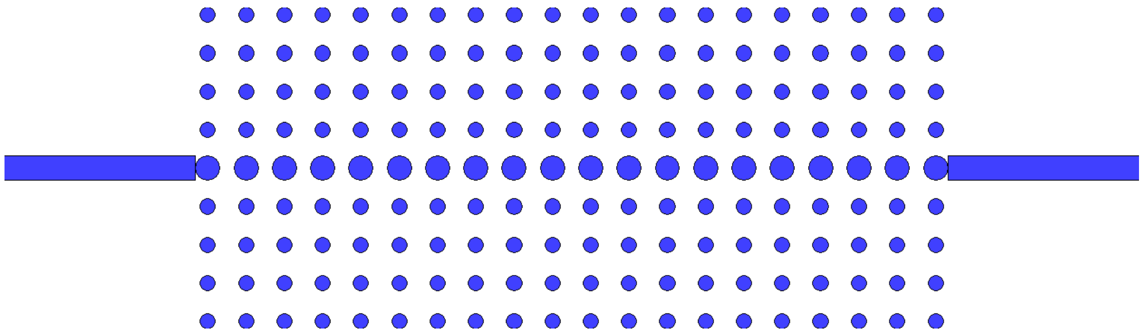
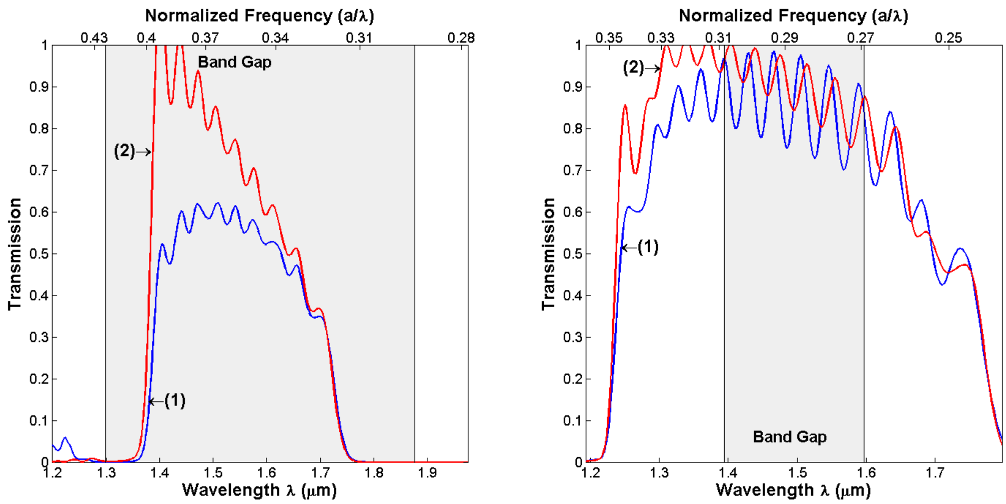


Figure 2: Top view of the coupling structure.

excite the fundamental mode of the input waveguide. By placing sensors in the ridge waveguides, we can extract the optical input and output powers. The transmission is given by dividing the optical power in the fundamental mode (propagating in forward direction) at the output waveguide sensor by that at the input waveguide sensor. The length of the photonic crystal waveguide is 20 periods, and the length of the input and output ridge waveguides corresponds to 5 times the lattice constant.

To optimize the transmission of the structures, the distance between the end facets of the ridge waveguides and the photonic crystal waveguide can be varied. Fig. 3(a) shows the transmission of the structure with pillars in air. In the graph, one curve shows the case where the ridge waveguide touches the first defect pillar. The second curve represents the optimal situation, with a distance of 100 nm between the ridge waveguide and the photonic crystal waveguide. For zero distance, the light couples directly to the first pillar of the photonic crystal waveguide. However, if we apply a gap between the two waveguide types, a cavity is created, making the coupling more wavelength-dependent. This effect is clearly visible in the transmission graph. The fact that the transmission exceeds 1 is due to the simulation method; the excitation is not exactly at the same location as the input sensor, so the output sensor might capture light that is not passing through the input sensor, e.g. because some light is reflected from the edges, back to the output sensor. It can be concluded that the distance between the ridge waveguides and the photonic crystal waveguide is an important parameter in the optimization of the coupling structure. The bandwidth at 95% transmission is in the order of 20 nm for a distance of 100 nm. Although we obtain a high transmission, the losses will increase when taking into account the third dimension.

The transmission of the photonic crystal waveguide of pillars embedded in a polymer layer stack is optimized following the same procedure. The transmission of that structure is shown in Fig. 3(b). Introducing the polymer layer stack increases both transmission and bandwidth considerably. The shifting of the modulation peaks when changing the distance between both types of waveguides in the coupler, indicates that they are due to Fabry-Pérot resonances. For the pillars in air, the guided mode extends outside the band gap, and this enables transmission outside the band gap. The bandwidth at 95% transmission is in the order of 55 nm for an optimized distance between the two types of waveguide of 45 nm.



(a) Pillars in air

(b) Pillars in polymer

Figure 3: Transmission for the butt coupler; (a) for pillars in air, and (b) for pillars embedded in a polymer layer stack. Curve (1) shows the transmission of the butt coupler with zero distance between ridge waveguide and photonic crystal waveguide, whereas curve (2) shows the result for optimized distance, being 100 nm for pillars in air and 45 nm for pillars in polymers.

Conclusions

We have determined the optimal geometrical parameters for a photonic crystal waveguide based on InP/InGaAsP pillars. To reduce the waveguide losses, a polymer layer stack is implemented. The transmission of a coupling structure from a conventional ridge waveguide to a photonic crystal waveguide and vice versa is optimized, based on 2D simulations. A high transmission is obtained, over a bandwidth that is sufficiently large for the application in photonic integrated circuits. Implementation of the polymer layer stack increases both transmission and bandwidth considerably.
Full 3D simulations are in preparation to complete the design of the photonic crystal waveguides. We are planning to fabricate the couplers and to compare transmission measurements to the simulation results.

Acknowledgement

This research is supported by NanoImpuls, a nanotechnology program of the Dutch Ministry of Economic Affairs. The authors would like to thank Dr. R.W. van der Heijden for his support.

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