

## Fabrication and characterization of pillar-based photonic crystal waveguides

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*We present the fabrication and optical characterization of waveguides in photonic crystals based on pillars. The waveguides were integrated in a classical photonic integrated circuit in InP technology. Photonic crystal waveguides of varying lengths were fabricated and measured. From 2D band diagram simulations, two different defect radii were selected while keeping the background photonic crystal the same. The waveguide with the larger defect radius ( $r_{\text{defect}} = 210 \text{ nm}$ ) shows lower coupling losses than the waveguide with  $r_{\text{defect}} = 170 \text{ nm}$ . This is in agreement with simulations on the photonic crystal waveguides.*

### Introduction

Two-dimensional photonic crystals offer huge possibilities for devices with small footprints in integrated optical circuits. In these structures, the photonic band gap confines the light in the plane of the chip, whereas total internal reflection is exploited for confinement in the vertical dimension [1]. Photonic crystals based on pillars have several advantages. The layer stack of pillar PhCs is compatible with that of the classical photonic integrated circuits, and so is the fabrication technology. Furthermore, active pillar-based devices can be electrically contacted, inherently avoiding current spreading, and heat is efficiently dissipated to the substrate.

### Design

The pillar-based photonic crystal waveguides will be realized on an InP double hetero structure, consisting of an InP substrate ( $n = 3.169$  at a wavelength  $\lambda = 1550 \text{ nm}$  [2]) with an InGaAsP [Q(1.25  $\mu\text{m}$ )] guiding layer of 500 nm thickness ( $n = 3.364$ ), having an InP top cladding of 1  $\mu\text{m}$ . The optical circuit, as schematically shown in Fig. 1, on the chip consists of a 1.8- $\mu\text{m}$ -wide input ridge waveguide, followed by a  $1 \times 2$  multimode interference coupler (MMI) splitting the light into two branches [3]. In the reference branch, the light propagates through a classical ridge waveguide towards the output side of the chip. The other branch contains a photonic crystal waveguide. This configuration has two major advantages; first, the incoupling of light into the input waveguide can easily be optimized using the reference branch, even if the photonic crystal waveguide has high losses, and secondly, the transmission of the photonic crystal waveguide can directly be calculated from a comparison with the transmission of the reference arm.

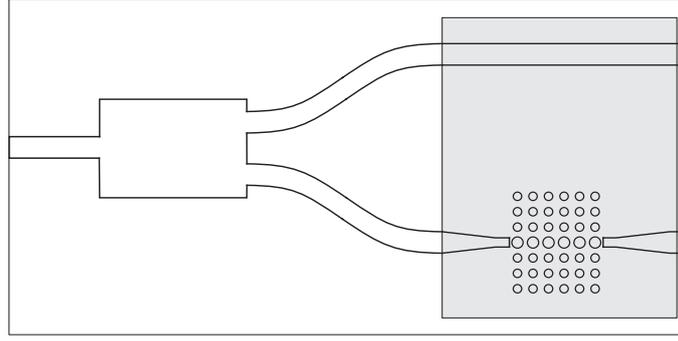


Figure 1: Schematic drawing of the chip layout, where the grey area is defined by e-beam lithography.

A PhC consisting of a square lattice of high-index pillars exhibits a large TM band gap [4]. This band gap is exploited to create a waveguide by introduction of a line defect of larger pillars. Since we aim for operation in photonic integrated circuits in the EDFA window (1530–1570 nm), the photonic crystal waveguides are designed for transmission around  $\lambda = 1550$  nm. A large photonic band gap is obtained for a pillar photonic crystal with a lattice constant  $a = 491$  nm and a pillar radius  $r = 123$  nm. Fig. 2 shows the calculated 2D band diagrams of line defects with two different radii of the defect pillars;  $r_{\text{defect}} = 170$  nm and  $r_{\text{defect}} = 210$  nm. To account for the third dimension in the calculations, an effective refractive index of the pillars is used. Within the band gap, the waveguide mode with a monotonically decreasing dispersion curve has an even mode profile, whereas the mode with the increasing dispersion curve has an odd symmetry. For the larger defect pillar radius, the frequencies of both the modes are reduced due to the higher average refractive index of the line defect.

Light is coupled from the ridge waveguide to the photonic crystal waveguide by first adiabatically tapering the ridge waveguide down to a width that matches the diameter of the defect pillars. The ridge waveguide is then placed in front of the photonic crystal waveguide [5], with a spacing that equals half of the distance between two adjacent defect pillars (i.e. a spacing of  $(a - 2r_{\text{defect}})/2$  between the end facet of the ridge and the first waveguide pillar). Since the ridge waveguide is placed symmetrically in front of the photonic crystal waveguide, we expect to excite mainly the even guided mode. Photonic crystal waveguides of 8, 16 and 32 periods length are designed on the chip.

## Fabrication

The ridge waveguides and the MMIs are defined by optical lithography, whereas the photonic crystal waveguides are defined by electron beam lithography. At the transition between the optically defined waveguides and the electron beam lithography areas, the waveguides have a width of  $0.8 \mu\text{m}$ . The waveguide pattern, including the photonic crystals, is first defined in a 50-nm-thick chromium masking layer using a lift-off process. This pattern is transferred into a silicon dioxide layer with a thickness of 430 nm by reactive ion etching (RIE) using a  $\text{CHF}_3$  chemistry. Finally, the deep etch to create the waveguides is performed by inductively coupled plasma (ICP) RIE using a  $\text{Cl}_2 : \text{Ar} : \text{H}_2$  chemistry [6]. Fig. 3(b) shows a SEM image of the photonic crystal waveguide after the ICP etch. The pillars are  $\sim 3.0 \mu\text{m}$  deep. According to simulations this should be enough

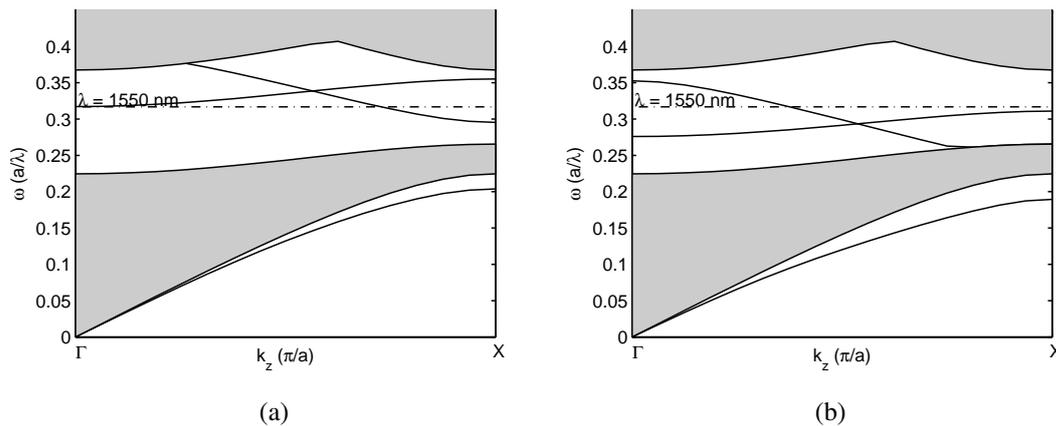


Figure 2: Band diagrams of a pillar photonic crystal waveguide with  $r_{\text{defect}}$  equals a) 170 nm and b) 210 nm. The shaded areas represent the cladding modes of the background photonic crystal.

to minimize coupling to the substrate modes.

### Transmission measurements

TM-polarized light from a tunable laser source is coupled into the input waveguide using a microscope objective. At the output side, the transmitted light is collected with a lensed fiber. The collected light is measured by a photoreceiver. The tunable laser scans the wavelength from 1530 to 1570 nm in steps of 0.1 nm. The cleaved facets of the chip introduce Fabry-Pérot fringes on the measured spectrum. These are averaged out by taking a running average over 10 data points of the spectrum. From the averaged spectra of both the branches, the transmission of the photonic crystal waveguide is determined. The transmission losses include the tapering of a waveguide from 0.8  $\mu\text{m}$  width down to the diameter of the defect pillars, the coupling to and from the photonic crystal waveguide and the propagation loss of the photonic crystal waveguide.

The measured transmission as a function of the length of the photonic crystal waveguides (in periods) is shown in Fig. 3(a). From this figure, it can be concluded that the propagation losses dominate over the coupling loss between both types of waveguide. Furthermore, the coupling loss for  $r_{\text{defect}} = 170$  nm seems to be slightly higher than in the case of  $r_{\text{defect}} = 210$  nm. This is in agreement with simulations, because the overlap between the Bloch mode of the line defect with  $r_{\text{defect}} = 170$  nm and the 340-nm-wide access ridge waveguide is smaller than the overlap of the Bloch mode of  $r_{\text{defect}} = 210$  nm with its corresponding access waveguide of 420 nm width. Also the reflections at the transition between both types of waveguides are predicted to be much higher in the case of  $r_{\text{defect}} = 170$  nm. The measured propagation losses are 1–1.5 dB/period for both photonic crystal waveguides.

### Conclusions

Pillar-based photonic crystal waveguides can successfully be integrated in photonic integrated circuits. Photonic crystal waveguides based on single line defects of different

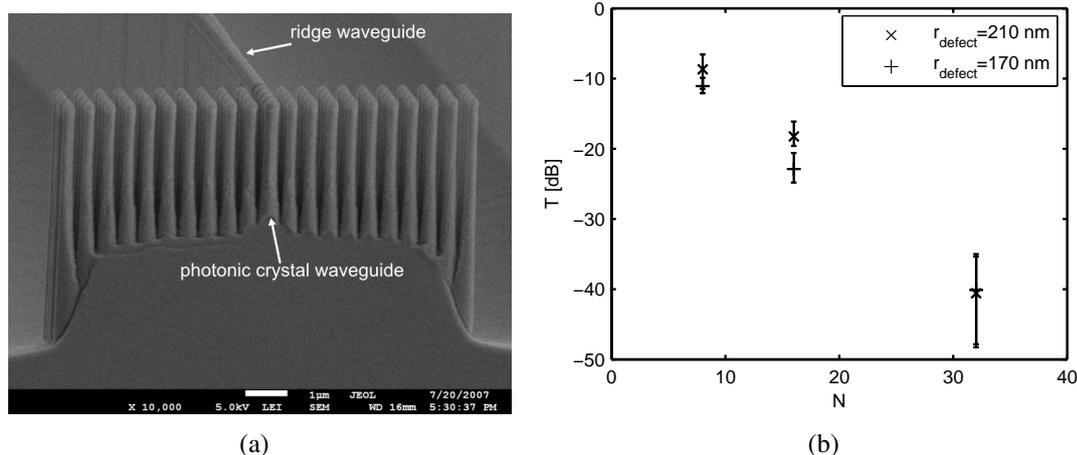


Figure 3: a) SEM image of a cross-section of a photonic crystal waveguide connected to a classical ridge waveguide on an InP substrate, and b) transmission of pillar photonic crystal waveguides as a function of the length of the waveguide in periods. In the characterized devices the silicon dioxide masking layer has been removed.

lengths are characterized and their behavior is in agreement with simulations. The propagation losses are 1–1.5 dB/period. These losses are too high for practical applications, however, we propose to implement a guiding polymer layer in between the pillars to reduce the propagation losses of the photonic crystal waveguides [7, 8].

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