Pillar photonic crystal for polarization filtering

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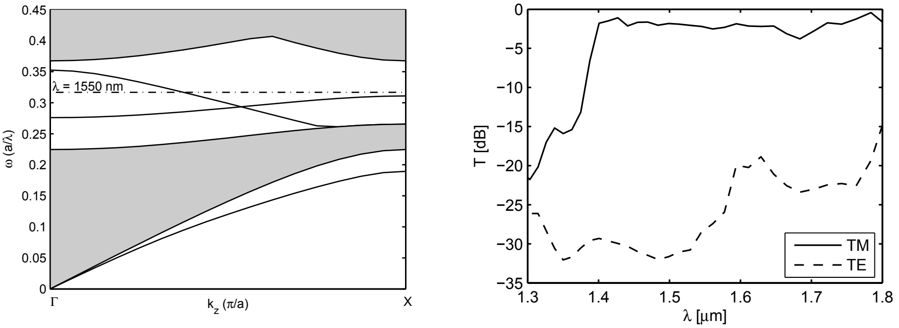
Abstract - *The strong polarization dependence of two-dimensional photonic crystals is exploited for polarization filtering. The device with a length of 3.9 μm is integrated in a photonic integrated circuit based on InP waveguide technology. The average transmissions in the EDFA-window are* -8.7 *dB for TM polarization and* -26.5 *dB for TE polarization.*

Introduction

Two-dimensional photonic crystals (2D PhCs) have been subject to extensive research in the past years, offering a huge potential for integration in photonic integrated circuits. They can be used to miniaturize existing integrated optical devices, e.g. bends, micro-cavities, add-drop filters and band edge lasers. Furthermore, their special properties can be used to design devices based on new principles. An example of such a device is a polarization filter. The polarization sensitivity of photonic crystals makes it possible to significantly reduce the foot print of polarization filters.
Photonic integrated circuits can be realized in different material systems, depending on the applications. However, indium phosphide (InP) technology is the only platform to monolithically integrate active and passive devices for use in the EDFA window (1530 – 1570 nm), the operating range for telecom applications. The classical waveguides of InP photonic integrated circuits are based on total internal reflection; light is confined to the indium gallium arsenide phosphide (InGaAsP Q[1.25]) core, which has a higher refractive index than the InP cladding layers ($n_{\mathrm{InGaAsP}} = 3.3640$ and $n_{\mathrm{InP}} = 3.1693$). In 2D PhCs, the in-plane confinement is created by the photonic band gap properties of the crystal, whereas the light is confined out-of-plane by total internal reflection.
TM-polarized light has its electric field vector parallel to the pillars, normal to the plane of the chip, and TE-polarization has its electric field vector in the plane of the chip. The strong polarization dependence of 2D photonic crystals ([1]) is used to investigate a TE polarization filter based on a pillar photonic crystal waveguide in a square lattice of high-index pillars. The device is integrated in a classical photonic integrated circuit on an InP substrate with a 500-nm-thick InGaAsP core layer and a 1-μm-thick InP top cladding. The layer stack of the pillar photonic crystal is compatible with that of the classical photonic integrated circuit, and so is the fabrication technology.

Design of the TE filter

A waveguide based on a line defect in a pillar PhC can serve as a TE filter if the TE polarized light does not couple into the PhC waveguide (either if this waveguide has a TE band gap or if the coupling efficiency for TE is very small) or if the TE polarized light is not confined by the crystal, in which case it radiates away from the line defect. The



(a) (b)

Figure 1: Modeling of a photonic crystal waveguide consisting of a line of larger pillars in a square lattice: a) band diagram showing the TM modes of the waveguide, where the lattice constant is 491 nm, the radius of the rods is 123 nm and that of the defect pillars is 210 nm, and b) the calculated transmission of an 8-period-long waveguide for both TM and TE polarization.

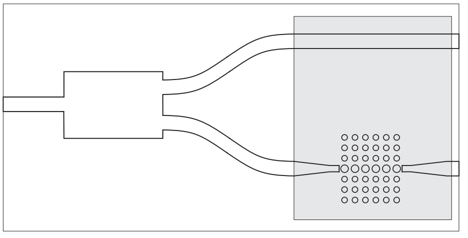
transmission of TM polarized light should be high. Therefore the line defect was first optimized for TM transmission.

Based on 2D band solver calculations, and using the effective index method to account for the third dimension, the background PhC was chosen to have a lattice constant $a = 491$ nm and a radius $r = 0.25a$. The introduction of a line defect of larger pillars along the ΓX-direction creates two guided TM modes inside the PhC band gap. Fig. 1(a) shows the projected band diagram of a PhC waveguide based on a line defect with radius $r_\mathrm{d} =$ 210 nm. The mode that increases in frequency, having a positive slope, is a mode with odd symmetry. The mode with a negative slope is a mode with even symmetry. At the wavelength of operation, i.e. in the range from 1530 to 1570 nm, the waveguide only supports the even symmetry mode.

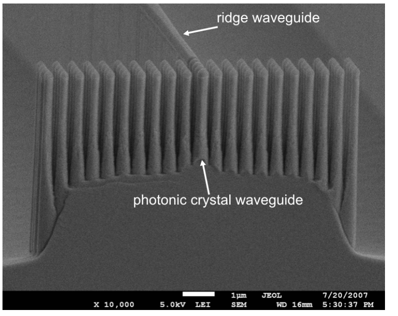
The light is coupled from a conventional ridge waveguide to the PhC waveguide and vice versa by placing the waveguides next to each other as is schematically shown in Fig. 2(a). The ridge waveguide is first adiabatically tapered down to a width that is equal to the diameter of the defect pillars, i.e. 420 nm. The gap between the end facet of the ridge waveguide and the first PhC pillar results in the highest transmission if it chosen in such a way that the ridge end facet is located exactly at the mirror plane between the first defect pillar and its virtual neighbor; this optimal gap is given by $g_\mathrm{opt} = 0.5(a - 2r_\mathrm{d})$.

In Fig. 1(b) the calculated transmission is shown for a PhC waveguide that is 8 periods long (based on a 3D FDTD calculation). The transmission for TM polarized light is -2.3 dB with an extinction ratio better than 25 dB around $\lambda = 1550$ nm. The good performance of this device is mainly due to a high coupling efficiency of the TM polarization at the transitions between the ridge waveguides and the PhC waveguide, while the TE polarization has a poor coupling from the access ridge waveguide to the PhC waveguide. The length of the polarization filter is only 3.9 µm (eight times the lattice constant).

The optical circuit design, as schematically shown in Fig. 2(a), on the chip consists of a 2-µm-wide input ridge waveguide, followed by a 1×2 multimode interference coupler



(a)



(b)

Figure 2: a) Schematic drawing of the chip layout, and b) SEM image of a cross-section of a photonic crystal waveguide connected to a classical ridge waveguide on an InP substrate.

(MMI) splitting the light into two branches. In the reference branch, the light propagates through a conventional ridge waveguide towards the output side of the chip. The other branch contains a PhC waveguide. This configuration has two advantages. First, the coupling into the input waveguide can easily be optimized using the reference arm, even if the PhC waveguide has high losses. Second, the transmission of the PhC waveguide can directly be calculated from a comparison with the transmission of the reference arm.

Fabrication

The ridge waveguides and the MMIs are defined by optical lithography, whereas the photonic crystals are defined by electron beam lithography to have sufficient control over the critical dimensions. At the transition between the optically defined waveguides and the e-beam lithography areas the waveguides are 0.8 µm wide. The waveguide pattern, including the PhCs, is first defined in a 50-nm-thick chromium masking layer by a series of lithography steps. This pattern is transferred into a 430-nm-thick silicon dioxide layer by reactive ion etching (RIE) using a CHF_3 chemistry. Finally, the deep etch to create the waveguides is performed by inductively coupled plasma (ICP) RIE using a $Cl_2 : Ar : H_2$ chemistry [2]. Fig. 2(b) shows a scanning electron microscope (SEM) image of the PhC structure after the ICP etch. The pillars are ~ 3.0 µm deep. According to simulations this should be enough to prevent the light from coupling to the substrate modes. Lateral dimensions of the PhC are well under control with this fabrication process [3].

Transmission measurements

Light from a tunable laser source is coupled into the input waveguide using a microscope objective. The polarization is fixed to TM or TE by use of a polarizer. At the output side, the transmitted light is collected with a lensed fiber. The collected light is measured by a photoreceiver. After optimization of the in- and outcoupling alignment at $\lambda = 1550$ nm, 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

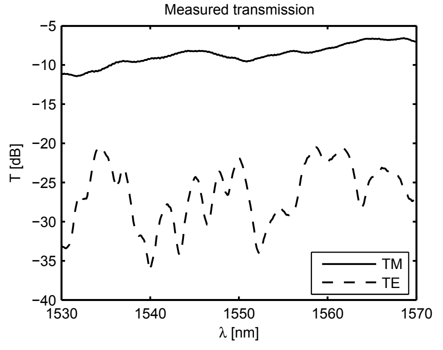


Figure 3: Measured transmission of a photonic crystal waveguide for both polarizations.

from 0.8 μm 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 for both TM and TE polarization is shown in Fig. 3. The average transmission for TM polarized light is −8.7 dB. The losses are higher than was calculated in the 3D simulation, probably due to scattering and to the non-vertical sidewalls of the pillars, which can cause large substrate leakage. Both can be reduced by an optimization of the fabrication technology. The TE transmission is −26.5 dB, which is in agreement with the simulated transmission. The modulation on the TE polarization is due to the reflections at the transitions between the ridge waveguides and the PhC waveguides, and to the reflections at the transitions between the optically defined waveguides and the e-beam defined ones. The latter reflections can be eliminated by adapting the design of the chip. The average transmission for TE polarization is −26.5 dB, whereas that of TM polarized light is −8.7 dB. This implies that an extinction ratio of about 18 dB should be feasible if the reflections are reduced.

Conclusions

A very short TE polarization filter can be realized in a pillar photonic crystal. The fabrication process is compatible with that of a photonic integrated circuit based on conventional waveguide technology. The device with a length of 3.9 μm has a transmission of −8.7 dB for TM polarization and −26.5 dB for TE polarization. The high losses are probably due to fabrication issues which can be solved by further optimization of the technology.

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