ROYAL INSTITUTE
OF TECHNOLOGY

Two-Dimensional Photonic Crystals in InP-based Materials

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**Two-Dimensional Photonic Crystals
in InP-based Materials**

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Abstract

Photonic crystals (PhCs) are structures periodic in the dielectric constant. They exhibit a photonic bandgap, i.e., a range of wavelengths for which light propagation is forbidden. Engineering of defects in the PhC lattice offers new ways to confine and guide light. PhCs have been manufactured using semiconductors and other material technologies. This thesis focuses on two-dimensional PhCs etched in InP-based materials. Only recently, such structures were identified as promising candidates for the realization of novel and advanced functions for optical communication applications.

The primary focus was on fabrication and characterization of PhC structures in the InP/GaInAsP/InP material system. The demands on fabrication are very high: holes as small as 100-300 nm in diameter have to be etched at least as deep as 2 μm . Thus, different etch processes had to be explored and specifically developed for InP. We have implemented an etching process based on Ar/Cl₂ chemically assisted ion beam etching (CAIBE), that represents the state of the art PhC etching in InP.

Different building blocks were manufactured using this process. A transmission loss of 10 dB/mm for a PhC waveguide, a reflection of 96.5% for a 4-row mirror and a record quality factor of 310 for a 1D cavity were achieved for this material system. With an etch depth of 4.5 μm , optical loss was found to be close to the intrinsic limit. PhC-based optical filters were demonstrated using (a) a Fabry-Pérot cavity inserted in a PhC waveguide and (b) a contra-directional coupler. Lag effect in CAIBE was utilized positively to realize high quality PhC taper sections. Using a PhC taper, a coupling efficiency of 70% was demonstrated from a standard ridge waveguide to a single line defect PhC waveguide.

During the course of this work, InP membrane technology was developed and a Fabry-Pérot cavity with a quality factor of 3200 was demonstrated.

Descriptors: photonic crystals, photonic bandgap materials, indium phosphide, dry etching, chemically assisted ion beam etching, reactive ion etching, electron beam lithography, photonic integrated circuits, optical waveguides, resonant cavities, optical filtering.

I have little patience with scientists who take a board of wood, look for its thinnest part, and drill a great number of holes where drilling is easy.

Albert Einstein

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- J2 A. Berrier, **M. Mulot**, M. Swillo, M. Qiu, L. Thylén, A. Talneau and S. Anand, “Negative refraction at infra-red wavelengths in a two-dimensional photonic crystal,” submitted to *Phys. Rev. Lett.*, 2004.
- J3 S. de Rossi, I. Sagnes, A. Berrier, **M. Mulot**, S. Anand, J.-L. Gentner and A. Talneau, “Longitudinal mode selection in constricted photonic crystal guides and electrically injected lasers,” submitted to *IEEE J. Lightwave Technol.*, 2004.
- J4 A. Talneau, **M. Mulot**, S. Anand, S. Olivier, M. Agio, M. Kafesaki and C. M. Soukoulis, “Modal behavior of single-line photonic-crystal guiding structures on InP substrate,” to be published in *Photonics and Nanostructures - Fundamentals and Applications*.
- J5 A. Talneau, J.-L. Gentner, A. Berrier, **M. Mulot**, S. Anand and S. Olivier, “High external efficiency in a monomode full-photonic-crystal laser under CW electrical injection”, submitted to *Appl. Phys. Lett.*, 2004.

Acronyms

2D	two-dimensional
3D	three-dimensional
ABC	absorption boundary condition
CAIBE	chemically assisted ion beam etching
CPD	critical point drying
EBL	electron beam lithography
FDTD	finite difference time domain
FP	Fabry-Pérot
ILS	internal light source
MSB	mini stop-band
MOVPE	metalorganic vapor phase epitaxy
PhC	photonic crystal
PCIC	photonic crystal integrated circuit
PL	photoluminescence
PMMA	polymethylmethacrylate
PWE	plane wave expansion
RIE	reactive ion etching
RF	radio frequency
SEM	scanning electron microscope
TE	transverse electric
TM	transverse magnetic
UV	ultraviolet
QW	quantum well
WDM	wavelength division multiplexing

Notations

a	PhC lattice period
c	light velocity in vacuum
d	hole diameter
$\mathbf{D}$	displacement vector
$\mathbf{E}$	electric field
f	air-filling factor
$\mathbf{H}$	magnetic field
$\mathbf{j}$	current density
$\mathbf{k}$	wavevector
k_x	propagation constant in a PhC waveguide
L	mirror loss
L_{decay}	decay length of the electric field in the substrate
L_p	optical penetration depth inside a PhC mirror
ℓ, ℓ_i	cavity length
n	refractive index
n_{core}	refractive index in the core layer
n_{clad}	refractive index in the cladding layer
n_{eff}	effective refractive index of the planar waveguide
n_g	group index of the fundamental mode in a PhC waveguide
n_g^m	group index of m^{th} order mode in a PhC waveguide
Q	quality factor of a resonant cavity
P_{in}	input power
P_{out}	output power
P_{ref}	reference power
$\langle P_{ref} \rangle, \langle P_{out} \rangle$	average power
q	ion charge
R, R_i	mirror reflection
$\mathbf{r}$	position vector
t	transmission of a PhC structure
T, T_i	mirror transmission
T_c	cavity internal transmission
u	normalized frequency ($= a/\lambda$)

$u_{\mathbf{k}}$	Bloch function
W	mirror spacing of a 1D cavity
v_g	group velocity
V_{bias}	self-induced bias in RIE
V_-, V_+	electric potentials of the grids of the CAIBE system
α_c	cone angle of a PhC hole
α, α_i	optical absorption/loss coefficient
$\Delta\epsilon$	difference in the dielectric constant between core and cladding layer
ϵ, ϵ'	dielectric constant
$\bar{\epsilon}$	complex dielectric constant
ϵ''	loss parameter (imaginary part of $\bar{\epsilon}$)
ϵ''_{int}	intrinsic loss parameter
ϵ''_{ext}	extrinsic loss parameter
Γ_{core}	confinement factor in the core layer
κ_x	normalized propagation constant in a PhC waveguide ($= ak_x/2\pi$)
λ	optical wavelength
μ'	magnetic permeability
η_{in}	coupling efficiency
η_{out}	collection efficiency
ω	optical frequency
ϕ, ϕ_i	phase shift
σ	electric conductivity
ζ	vertical field profile

Chapter 1

Introduction

The field of photonics is rapidly developing. Photonics is used in several day to day applications, such as compact disc and DVD players, office printers and supermarket checkouts to mention a few. Most important of all, it is the underlying technology supporting today's worldwide optical communication network. New applications are emerging in the field of optical computing, biotechnology and sensors. In spite of the recent developments, photonics is still far from electronics in maturity in the sense of integration of devices: current photonic integrated circuits are still expensive, relatively large and integrate only few basic functions. **Photonic crystals** have, over the past few years, received a dramatically increased attention, since these novel materials could bring photonics on the way to higher integration and better performance.

Photonic crystals (PhCs) were first described in 1987 as an artificial material allowing inhibition of spontaneous light emission [1] and photon localization [2]. PhCs exhibit a photonic bandgap, i.e., a range of optical wavelengths for which light is unable to propagate [1, 2]. The most common photonic bandgap material consists of a periodic dielectric media. The periodicity can be in one, two or three dimensions.

Due to this periodicity, certain analogies can be drawn between the behaviour of light in PhCs and that of electrons in a semiconductor crystal. In semiconductors, the periodic potential of the crystal lattice affects the dispersion relation of the free electrons. As a result, a band structure appears in the energy spectrum of the electrons. The energy gaps between the bands correspond to forbidden energy ranges for electrons. In PhCs, the periodic variation of the dielectric constant is at the origin of the band structure observed in the optical spectrum.

Two-dimensional (2D) and three-dimensional (3D) PhCs are an important extension of the well-known (1D) Bragg grating to higher dimensions and offer a lot of possibilities. By engineering of defects in the otherwise periodic PhC lattice, it is possible to tailor the optical density of states and to control the propagation of light at desired wavelengths [3]. The applications of defect engineering are numerous: for instance, single-defect resonant cavities can be used

Figure 1.1. (a) Schematic of the Yablonovite. (b) The “woodpile” structure (courtesy of Sandia National Laboratories). (c) Representative examples of manufactured 2D PhC structures in InP/GaInAsP/InP.

for low threshold lasing or enhancement of the light-matter interaction [4–7]. Line defects in PhCs are also interesting since they have the ability to guide light [8–12]. Frequency selective coupling between waveguides and cavities can be used to make compact optical filters [13–16]. More advanced applications of PhCs involve non-linear materials for the realization of optical switches [17] or frequency converters [18]. One should mention that even perfectly periodic PhCs can be utilized in various domains, such as light extraction enhancement in light emitting diodes [19], or band-edge lasers [20]. The exceptional dispersion properties of PhC lattices, such as the superprism effect and the negative refraction can be also used for beam shaping or filtering applications [21–26]. Thus, the potential of PhCs is enormous and still needs to be explored.

The first artificial PhC with full photonic bandgap (i.e., a bandgap that exists regardless of the direction in which light propagates) was made in 1991 by the group of Yablonovitch. The “Yablonovite” is produced by drilling an array of holes in plexiglas (Fig. 1.1(a)). The first Yablonovite exhibited a photonic bandgap between 13 and 15 GHz [27]. This first demonstration generated interest among researchers and triggered a race for the first PhC working at shorter wavelengths.

Figure 1.2. Schematic sketch of a 2D PhC with vertical confinement by index guiding.

The fabrication of PhCs for infrared or optical wavelengths is a challenging task. One of the conditions to obtain a photonic bandgap at a given wavelength λ dictates that the periodicity of the structure must be in the same order of magnitude as λ . Nanotechnologies are therefore required. A further condition concerns the refractive index variation between the low index and the high index regions in the PhC: this difference should be large enough for a photonic bandgap to appear. This limits the range of materials that can be used.

Under such constraints, a Yablonovite working in the mid-infrared regime is not the easiest solution from the point of view of fabrication [28]. Therefore, other types of 3D PhC structures were proposed and realized: for instance, the “woodpile” structure (Fig. 1.1(b)), that is a multilayered example made by stacking patterned dielectric layers [29–31]. Opals are PhCs manufactured by self-organization of submicron-sized dielectric spheres [32–34]. Other solutions based on micromanipulation [35, 36], autocloning [37], glancing angle deposition [38], laser rapid prototyping [39] and interferometric lithography [40] were also reported.

Although feasible, 3D PhCs are difficult to engineer. A lot of research was, therefore, oriented towards 2D PhCs, that are easier to manufacture. Although their bandgap is incomplete, 2D PhCs exhibit most of the properties of their three-dimensional counterparts [3, 41].

In order to compensate for the absence of photonic bandgap in the vertical direction, light can be confined to a dielectric layer embedded between two layers with lower refractive index (Fig. 1.2). Such a confinement scheme is called **index guiding** or **total internal reflection**. The first 2D PhC with index guiding was demonstrated in 1996 by Krauss et al. in a GaAs-based structure [42].

Semiconductor materials appear like a natural material platform for the realization of 2D PhCs. They have indeed relatively high dielectric constants and high quality materials can be epitaxially grown or deposited. From the processing point of view, a wide range of sophisticated tools and techniques of direct relevance to PhC fabrication such as sub-micron patterning technologies (for example, electron beam lithography), advanced plasma methods for deposition

and etching, wafer-bonding, etc. Thus, the available semiconductor technology is a very attractive platform that is not only appropriate but also can be modified or developed further for PhCs.

For active PhC devices, appropriate materials that can emit light at the desired wavelengths have to be used, which implies direct bandgap III-V semiconductors. On the other hand, for passive functions, silicon can also be used and silicon-on-insulator has emerged as the preferred choice [12, 43, 44]. With III-Vs, it is, however, possible to realize both active and passive functions at the same time. The active sections are realized by embedding optical emitters into the structure, such as quantum wells or quantum dots. Due to their versatility, PhCs in III-V semiconductors have attracted a lot of interest and significant efforts are being made to identify key applications.

This thesis is concerned with PhCs in InP-based materials. These materials are the most suitable of III-V semiconductors for photonic applications in the 1.2 - 1.7 μm wavelength range. Fabrication of high quality PhCs in InP is a critical issue, since it directly dictates ultimate utility of InP-based PhCs in practical device applications. One solution to make InP-based PhCs consists in etching a periodic array of air holes into an InP/GaInAsP/InP structure (Fig. 1.1(c)). The demands on fabrication of 2D PhCs in such a material system are very high: holes with a diameter as small as 100-300 nm have to be etched at least as deep as 2 μm . Thus, different etch processes have to be explored and specifically developed for InP. This was one of the objectives of this thesis. In particular, two etch processes, Ar/CH₄/H₂ RIE and Ar/Cl₂ CAIBE, were investigated and compared for PhC etching. This led to the identification of Ar/Cl₂ CAIBE as a suitable etch process. This work addresses the critical etching parameters and their optimization for high quality PhC etching. Using Ar/Cl₂ CAIBE, several building blocks and device concepts such as cavities, mirrors, mode converters and filters were implemented and characterized.

InP-based suspended membranes represent another technology platform for 2D PhCs. A primary advantage of such a system is lower optical loss compared to InP/GaInAsP/InP. In the course of this work, a PhC-based Fabry-Pérot cavity etched in an InP membrane was investigated as a step towards realization of a high-Q resonant cavity.

The thesis is organized as follows: Chapter 2 gives the necessary background on light propagation and optical losses in 2D PhCs. The InP/GaInAsP/InP system is described here as well. Chapter 3 gives a description of the PhC patterning process. In Chapter 4, the two methods used for optical characterization of PhCs are presented. In Chapter 5, the results obtained on mirrors and 1D cavities are discussed, while Chapter 6 focuses on waveguides. Chapter 7 contains an overview of existing PhC-based filters and present both designs investigated in this work. Chapter 8 summarizes the work that was achieved on InP membranes. Finally, Chapter 8 gives some conclusions as well as a list of possible extensions of this work.

Chapter 2

Properties of a 2D photonic crystal lattice

In this chapter, some basic concepts about light propagation in periodic media are given. Subsequently, some properties of a perfectly periodic 2D PhC lattice relevant to this work are described. The InP/GaInAsP/InP structure is introduced.

2.1 The Maxwell equations

The description below follows the treatment given in [3]. Light propagation is described in any linear, isotropic and macroscopic medium by the following form of the Maxwell equations (in CGS units):

$$\nabla \cdot \mathbf{H} = 0 \quad (2.1)$$

$$\nabla \cdot \mathbf{D} = 4\pi\rho \quad (2.2)$$

$$\nabla \times \mathbf{E} = -\mu' \frac{1}{c} \frac{\partial \mathbf{H}}{\partial t} \quad (2.3)$$

$$\nabla \times \mathbf{H} = \frac{4\pi}{c} \mathbf{j} + \frac{1}{c} \frac{\partial \mathbf{D}}{\partial t} \quad (2.4)$$

The vectors $\mathbf{H}(\mathbf{r})$ and $\mathbf{E}(\mathbf{r})$ are the magnetic and the electric field, respectively. The electric displacement $\mathbf{D}(\mathbf{r})$ is equal to $\epsilon'(\mathbf{r})\mathbf{E}(\mathbf{r})$, with $\epsilon'(\mathbf{r})$ the dielectric constant. $\rho(\mathbf{r})$ is the density of charge and $\mu'(\mathbf{r})$ the permeability. The local current density $\mathbf{j}(\mathbf{r})$ is equal to $\sigma(\mathbf{r})\mathbf{E}(\mathbf{r})$, with $\sigma(\mathbf{r})$ the electric conductivity.

The materials we are interested in are non-magnetic ($\mu' \equiv 1$) and have a negligible density of charge ($\rho \equiv 0$). The Maxwell equations can then be simplified into:

$$\nabla \cdot \mathbf{H} = 0 \quad (2.5)$$

$$\nabla \cdot (\epsilon' \mathbf{E}) = 0 \quad (2.6)$$

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{H}}{\partial t} \quad (2.7)$$

$$\nabla \times \mathbf{H} = \frac{4\pi\sigma}{c} \mathbf{E} + \frac{\epsilon'}{c} \frac{\partial \mathbf{E}}{\partial t} \quad (2.8)$$

We assume that $\mathbf{H}$ and $\mathbf{E}$ have a harmonic time dependence:

$$\mathbf{H}(\mathbf{r}, t) = \mathbf{H}(\mathbf{r}) e^{i\omega t} \quad (2.9)$$

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r}) e^{i\omega t} \quad (2.10)$$

If we insert these expressions into the two curl equations (Eq. 2.7 and 2.8), we find:

$$\mathbf{H} = -\frac{c}{i\omega} \nabla \times \mathbf{E} \quad (2.11)$$

$$\mathbf{E} = \frac{c}{i\omega(\epsilon' - i\frac{4\pi\sigma}{\omega})} \nabla \times \mathbf{H} \quad (2.12)$$

From Equation 2.12, we can define a complex dielectric constant $\bar{\epsilon} = \epsilon' - i\epsilon''$, the imaginary part ϵ'' being equal to $4\pi\sigma/\omega$. ϵ'' is related to the optical absorption in the medium.

Combining equations 2.11 and 2.12 allows for an elimination of the electric field $\mathbf{E}$:

$$\nabla \times \left(\frac{1}{\bar{\epsilon}} \nabla \times \mathbf{H} \right) = \left(\frac{\omega}{c} \right)^2 \mathbf{H} \quad (2.13)$$

This equation is known as the **master equation**. The master equation informs us that the magnetic field $\mathbf{H}$ is an eigenvector of the Maxwell operator Θ , defined as:

$$\Theta = \nabla \times \left(\frac{1}{\bar{\epsilon}} \nabla \right) \times \quad (2.14)$$

2.2 Scalability of the master equation

Let us consider a PhC structure A and another PhC structure B that is obtained by multiplying the physical dimensions of A by a factor s . The optical modes of the PhC B can be deduced from those of A by rescaling the wavelength λ to $s\lambda$. This interesting property comes from the fact that the master equation is independent from the length scale.

The scalability of the master equation can be demonstrated as follows: to rescale a PhC with a scaling factor s is equivalent to performing the variable change from $\mathbf{r}$ to $\mathbf{r}' = s\mathbf{r}$ in the master equation (Eq. 2.13). In the new coordinate system the nabla operator is $\nabla' = \nabla/s$:

$$s\nabla' \times \left(\frac{1}{\bar{\epsilon}(\mathbf{r}'/s)} s\nabla' \times \mathbf{H}(\mathbf{r}'/s) \right) = \left(\frac{\omega}{c} \right)^2 \mathbf{H}(\mathbf{r}'/s) \quad (2.15)$$

We introduce $\epsilon'(\mathbf{r}') = \bar{\epsilon}(\mathbf{r}'/s)$, $\mathbf{H}'(\mathbf{r}') = \mathbf{H}(\mathbf{r}'/s)$, $\omega' = \omega/s$ and divide out the s 's so that the equation becomes:

$$\nabla' \times \left(\frac{1}{\epsilon'(\mathbf{r}')} \nabla' \times \mathbf{H}'(\mathbf{r}') \right) = \left(\frac{\omega'}{c} \right)^2 \mathbf{H}'(\mathbf{r}') \quad (2.16)$$

Consequently, if $\mathbf{H}(\mathbf{r})$ is a solution of the original master equation for the frequency ω , then $\mathbf{H}'(\mathbf{r}) = \mathbf{H}(\mathbf{r}/s)$ is a solution of the rescaled master equation for the frequency ω/s . In section 4.3, we will explain how we take advantage of the scalability property in the optical characterization of PhCs.

2.3 Computational methods

The different methods used to model the propagation of electromagnetic waves in PhCs are derived from classical methods used in electromagnetism or solid state physics. Among these methods, one can cite the plane wave expansion [45, 46], the block-iterative frequency-domain [47], the finite difference time domain [48], the transfer matrix [49], the tight-binding [50] or the diffraction grating methods [51]. The first two methods are briefly described below, since they are used in this thesis.

2.3.1 The plane wave expansion method

The plane wave expansion (PWE) method is applicable in the case of strictly 2D or 3D PhC structures, where the complex dielectric constant $\bar{\epsilon}$ is a periodic function of space. In virtue of the Bloch theorem, one can expand $\mathbf{H}$ into a sum of plane waves defined as follows:

$$\mathbf{H}_{\mathbf{k}} = e^{i\mathbf{k} \cdot \mathbf{r}} \mathbf{u}_{\mathbf{k}}(\mathbf{r}) \quad (2.17)$$

where $\mathbf{u}_{\mathbf{k}}$ is a Bloch function, i.e., a periodic function with the same periodicity as the PhC lattice, and $\mathbf{k}$ is a wavevector within the first Brillouin zone of the reciprocal lattice. The PWE method consists in defining a basis of plane waves and solve the master equation with the help of standard matrix diagonalization methods.

The PWE method is well suited for band structure calculations in perfectly periodic PhCs. However, it cannot be used when the Bloch theorem does not apply, i.e., when the structure is far from a perfect periodicity or when finite size

or boundary conditions begin to dominate. Nevertheless, it is possible to simulate cavities or straight waveguides by implementation of the supercell method [52].

2.3.2 The finite difference time domain method

Since the first algorithm, written by Yee in 1966 [53], the finite difference time domain (FDTD) method has been extensively used in electromagnetism. Its success is attributed to its flexibility in simulating almost any kind of geometry. This method based on finite element calculation, consists in dividing the space as well as the time into a mesh of nodes. The Maxwell equations are replaced by finite difference equivalents that relate the fields at each mesh point to the fields at neighbouring points. The difference equations are then solved under the constraint of boundary and initial conditions.

The FDTD method can provide exact solutions of the Maxwell equation provided that the mesh is dense enough. Moreover, it allows for the introduction of absorbing boundary conditions (ABCs) to eliminate spurious reflections at the boundaries of the simulation domain. The ABC that was implemented in all FDTD calculations in this thesis is the perfectly matched layer condition [54].

The FDTD method can be used to obtain the photonic band structure. It is, however, mostly used to simulate light propagation in PhC-based structures, thereby calculating the time evolution of the electromagnetic field. The spectral behaviour of the structure is deduced from the time evolution by Fourier transformation.

2.3.3 The effective refractive index approximation

Strictly two-dimensional PhCs can be simulated by two-dimensional computational models. The case of 2D PhCs etched into a semiconductor structure is, however, more delicate since the problem becomes three-dimensional. 3D simulations are time consuming and require a lot of computer memory, therefore it is a great benefit if one can solve 3D problems by means of 2D modelling.

Thanks to the **effective index approximation**, it is possible to approximate 2D PhCs with a purely two-dimensional structure. The effective index approximation consists in replacing the planar waveguide with a homogeneous dielectric material having an effective refractive index n_{eff} defined as:

$$n_{eff} = \int_{-\infty}^{+\infty} \zeta(z)n(z)dz \quad (2.18)$$

$\zeta(z)$ is the vertical field distribution and $n(z)$ is the vertical refractive index profile in the planar waveguide.

The effective index approximation can be applied in combination with the PWE or the FDTD method [55]. This implementation is widely used in this thesis for simulation of 2D PhCs etched into InP-based materials.

Figure 2.1. Schematic of the InP/GaInAsP/InP planar waveguide structure. Also shown is the vertical profile of the electric field for the TE polarization.

2.4 The InP/GaInAsP/InP planar waveguide

Two-dimensional (2D) PhCs possess a two-dimensional periodicity in the dielectric constant, which is at the origin of a two-dimensional photonic bandgap. In order to integrate 2D PhCs in planar optical circuits, optical confinement in the third dimension is necessary. This is accomplished in conventional optical circuits, where light is confined in the vertical direction by a planar waveguide structure.

The InP/GaInAsP/InP planar waveguide is a three-layer system. The structure is grown on an InP substrate by metalorganic vapor phase epitaxy (MOVPE). It consists of a core layer embedded between two cladding layers with slightly lower refractive index (Fig. 2.1). Light is, therefore, confined in the core layer by index guiding. The cladding layers are made of InP (refractive index $n_{clad} = 3.17$ at $\lambda = 1.55 \mu\text{m}$). The thickness of the top cladding is 200 nm. The lower cladding is the InP substrate itself. The core layer is made of $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ ($x = 0.24$, $y = 0.52$) lattice-matched to InP. The refractive index of this material is $n_{core} = 3.35$ and its absorption edge λ_{gap} is equal to $1.22 \mu\text{m}$. The thickness h_{core} of the core layer is typically 420 nm. Only one vertical mode can fit in the planar waveguide for wavelengths above $1.28 \mu\text{m}$. All layers are nominally undoped.

The electromagnetic field in the vertical waveguide can be separated into two polarizations: the **transverse electric** (TE) polarization, corresponding to the components (E_x, E_y, H_z) and the **transverse magnetic** (TM) polarization, corresponding to (E_z, H_x, H_y) . TE and TM modes are sometimes referred to as H- and E-mode, respectively. Fig. 2.1 shows the vertical profile of the electric field intensity $\zeta(z) = |\mathbf{E}(z)|$ in the planar waveguide for the wavelength $\lambda = 1.55 \mu\text{m}$ and for the TE polarization.

Due to the small refractive index difference between the core layer and the substrate, the decay of $\zeta(z)$ is smoother in the substrate than in the top cladding

Figure 2.2. The triangular lattice.

where the proximity of the air layer improves the confinement ($n_{air} = 1$). In the substrate we have:

$$\zeta(z) = A \exp(z/L_{decay}) \quad (2.19)$$

L_{decay} is the decay length of the field in the substrate:

$$L_{decay} = \frac{\lambda}{2\pi} \cdot \frac{1}{\sqrt{n_{eff}^2 - n_{clad}^2}} \quad (2.20)$$

where n_{clad} is the refractive index in the cladding and n_{eff} the effective refractive index of the structure for the considered wavelength. For our structure (Fig. 2.1), n_{eff} and L_{decay} are equal to 3.24 and 370 nm, respectively, at a wavelength of $1.55 \mu\text{m}$.

The poor confinement of the vertical mode has a significant impact on the design of PhCs. PhCs have, indeed, to be etched at least $2 \mu\text{m}$ deep into the planar waveguide in order to minimize light scattering at the bottom of the holes. We will return to this point in section 2.8.

For our InP/GaInAsP/InP planar waveguide structure, the 2D FDTD model applied with an effective refractive index $n_{eff} = 3.24$ is consistent with 3D simulations over a wide frequency range [55].

2.5 The 2D photonic crystal lattice

The PhC pattern etched into the planar waveguide is a triangular lattice of cylindrical air holes (Fig. 2.2). The triangular lattice offers the highest possible symmetry order (six-fold symmetry), which is favourable for the isotropy of the optical properties and opening of a photonic bandgap [1]. a is the lattice period, i.e., the distance between two neighbouring holes. The reciprocal lattice is also a triangular lattice. The first Brillouin zone in the reciprocal space is a hexagon. The points M and K at the edge of the Brillouin zone are high symmetry points of the reciprocal lattice.

Figure 2.3. Map of photonic bandgaps for a triangular lattice of cylindrical holes etched in InP/GaInAsP/InP. The bandgap calculations were made using the PWE method.

For PhCs working in the $1.5\,\mu\text{m}$ wavelength range, the lattice period a lies between 200 and 600 nm. The air-filling factor f , i.e., the ratio between the volume of air and the volume of dielectric (semiconductor) in the PhC, is a function of d/a , where d is the diameter of the air holes:

$$f = \frac{\pi}{2\sqrt{3}} \left(\frac{d}{a} \right)^2 \quad (2.21)$$

The position of the photonic bandgap in the optical spectrum, as well as the optical loss, depend on the air-filling factor (cf. 2.6 and 2.8).

2.6 The photonic gap map

Fig. 2.3 shows the photonic bandgap(s) depending on the air-filling factor f . Such a diagram is called a **gap map**. The simulations were done using the PWE method with an effective refractive index $n_{\text{eff}} = 3.24$. As explained in section 2.2, the scalability of the optical properties allows the use of normalized frequency $u = a/\lambda$ in place of the frequency ω . First, one notices that for most values of f there is not one, but several photonic bandgaps. The first photonic bandgap is the most interesting since it is the widest. The bandgaps for TE and TM polarization overlap only for $f > 0.60$. Such high air-filling factors are not desirable since the optical losses in the PhC increase when f increases. This statement will be justified in the following sections. It is therefore preferable to limit the bandgap to the TE polarization and work with moderate air-filling factors ($0.3 < f < 0.5$). For an air-filling factor of 0.4, the relative width $\Delta u/u$ of

Figure 2.4. Calculated dispersion diagram for a triangular lattice of cylindrical holes etched into InP/GaInAsP/InP ($f = 0.40$). Only TE polarized modes are represented. Calculations are based on 2D PWE with an effective index $n_{eff} = 3.24$.

the TE photonic bandgap is approximately 40%. This corresponds to a bandgap width of 600 nm at $1.5 \mu\text{m}$.

2.7 The band structure

Fig. 2.4 displays the dispersion diagram for a PhC etched in InP/GaInAsP/InP. It was rendered using 2D PWE ($n_{eff} = 3.24$), for an air-filling factor $f = 0.40$ and for the TE polarization only. Due to the six-fold symmetry of the reciprocal lattice, the PhC modes need to be calculated only for $\mathbf{k}$ -vectors belonging to the irreducible Brillouin zone, which is defined by the triangle ΓMK in Fig. 2.2. Only the $\mathbf{k}$ -vectors along the edges of the irreducible Brillouin zone are taken into account to draw the dispersion diagram.

As in semiconductor physics, the permitted bands above and below the photonic bandgap are commonly called **conduction** and **valence bands**, respectively. The PhC modes in the conduction band concentrate more of their energy in the air holes compared to the modes in the dielectric band. This is why the valence and the conduction bands are also referred to as **dielectric** and **air band**, respectively.

2.8 Optical losses

Part of the light that propagates in a PhC will be lost by scattering. One distinguishes **intrinsic losses**, that are inherent to the PhC structure and **extrinsic losses**, that are related to imperfections in the fabrication.

2.8.1 Intrinsic losses

At a given lattice period a and air-filling factor f , the optical loss in a 2D PhC is expected to be minimum if the air holes are infinitely deep and perfectly cylindrical [56, 57]. Even in this hypothetical case, the structure may not be lossless: the presence of the air holes alters the confinement properties of the planar waveguide structure.

In terms of optical modes, out-of-plane scattering can be understood as a coupling between the PhC modes and the radiation modes of the planar waveguide. By definition, radiation modes are not confined in the core layer: instead, they form a standing wave in the substrate and/or in the air. Depending on its position in the dispersion diagram with respect to the air and the substrate line (Fig. 2.4), a PhC mode is coupled to different types of radiation modes. The equation of the **substrate line** can be approximated by:

$$u = \frac{a}{2\pi} \frac{|\mathbf{k}|}{\langle n_{sub} \rangle} \quad (2.22)$$

where $\langle n_{sub} \rangle$ is the average refractive index *below* the core layer. Under the assumption that the air holes are infinitely deep:

$$\langle n_{sub} \rangle = (1 - f)n_{clad} + fn_{air} \quad (2.23)$$

where $n_{clad} = 3.17$ and $n_{air} = 1$. The **air line** is defined by:

$$u = \frac{a}{2\pi} \frac{|\mathbf{k}|}{n_{air}} = \frac{a}{2\pi} |\mathbf{k}| \quad (2.24)$$

All the PhC modes that lie between the substrate line and the air line are coupled to radiation modes that decay exponentially in the air and form a standing wave below the core layer. In other words, these modes are radiated into the substrate only. All the PhC modes that lie above the air line are radiated both into the air and into the substrate. A PhC mode needs to be below the substrate line in order to be lossless. For 2D PhCs etched into InP/GaInAsP/InP, the quasi totality of the photonic bandgap lies above the substrate line. Any defect mode in the photonic bandgap is therefore susceptible to out-of-plane loss.

2.8.2 Extrinsic losses

In manufactured 2D PhC structures, **extrinsic losses** add up to the intrinsic loss. Extrinsic losses include the extra out-of-plane scattering resulting from a

non-ideal hole shape. To minimize out-of-plane scattering, it is essential that the depth of the PhC holes is large enough to overlap completely with the vertical profile of the guided mode [57]. A high etch depth is, however, still not sufficient. The holes should also be as cylindrical as possible [58].

Fluctuations of the hole position or the hole diameter as well as fabrication-related material damage are further sources of loss.

2.9 The loss parameter model

A conventional two-dimensional modelling of the PhC does not allow estimation of the optical losses caused by out-of-plane scattering by the air holes. In the case of low index contrast confinement, however, the phenomenon of scattering can be reproduced by introducing a fictitious absorption in the holes. This involves attributing a complex dielectric constant $\bar{\epsilon}_{air}$ to the air holes forming the PhC lattice:

$$\bar{\epsilon}_{air} = \epsilon'_{air} - i\epsilon''_{air} = 1 - i\epsilon''_{air} \quad (2.25)$$

The semiconductor medium surrounding the holes is assumed to be lossless. Therefore we can write the phenomenological parameter ϵ''_{air} simply ϵ'' without ambiguity. ϵ'' is commonly called the **loss parameter**. It is a widely used figure of merit for PhCs.

ϵ'' is the sum of two components:

$$\epsilon'' = \epsilon''_{int} + \epsilon''_{ext} \quad (2.26)$$

ϵ''_{int} and ϵ''_{ext} are the loss parameters quantifying the intrinsic and the extrinsic losses, respectively. Thus, this type of empirical approach can be used to model optical loss in 2D PhCs. It can be implemented in the 2D FDTD model [59]. In the following, we present a semi-analytical model for evaluation of the loss parameter.

2.9.1 The intrinsic loss parameter

If the material absorption is neglected, the intrinsic loss is purely radiative. The radiation from the holes of a PhC can be viewed as the radiation from an electric dipole placed in each hole. Using a perturbative approach [56], one can show that, in the case of infinite cylindrical holes, the volume V of the emitting dipole corresponds to the intersection between the core layer of thickness h_{core} and the volume of an air hole of diameter d :

$$V = \frac{\pi}{4} h_{core} d^2 \quad (2.27)$$

The power P_{rad} radiated by one dipole is given by [60]:

$$P_{rad} = \epsilon_0 \Delta\epsilon \langle |\mathbf{E}| \rangle_V V \quad (2.28)$$

with ϵ_0 the permittivity of free space, $\Delta\epsilon = n_{core}^2 - n_{clad}^2$ the difference in the dielectric constant between the core and the cladding layer and $\langle |\mathbf{E}| \rangle_V$ the average electric field in the dipole. A fraction η of the dipole radiation escapes from the PhC structure, whereas the remaining power is recaptured by the vertical waveguide. η can be approximated by

$$\eta = \sqrt{1 - \left(\frac{n_{clad}}{n_{core}} \right)^2} \quad (2.29)$$

Supposing that the emission of the dipoles is incoherent, a semi-quantitative expression of ϵ''_{int} can be formulated:

$$\epsilon''_{int} \approx \frac{h_{core} n_{core}}{\lambda} (u^2 f) (\Delta\epsilon)^2 \eta \Gamma_{core}(\lambda) \quad (2.30)$$

where u is the normalized frequency, f is the air-filling factor and $\Gamma_{core}(\lambda)$ is the confinement factor inside the core layer:

$$\Gamma_{core}(\lambda) = \frac{\int_{core} \zeta^2(z) dz}{\int_{-\infty}^{+\infty} \zeta^2(z) dz} \quad (2.31)$$

$\Gamma_{core}(\lambda)$ is a decreasing function of the wavelength. According to Equation 2.30, for a given material system and slab structure, the intrinsic losses become more significant as the air-filling factor increases. This is why it is more advantageous to work with moderate air-filling factors.

For PhCs etched in InP/GaInAsP/InP, ϵ''_{int} lies in the range 0.01-0.02 ($f = 0.30$ and $\lambda = 1.5 \mu\text{m}$) [58].

2.9.2 Extrinsic losses: influence of the hole shape

Extrinsic losses are caused both by the irregularities due to fabrication (e.g. sidewall roughness, deviations in the lattice period or in the hole diameter) and by a non-perfect hole morphology. We focus, below, on the impact of the hole depth and the hole shape on the extrinsic loss parameter.

Using the same perturbative approach as for the calculation of ϵ''_{int} , an semi-analytical expression of ϵ''_{ext} in the case of a cylindrical hole with finite etch depth $|z_0|$ can be calculated [56, 57]:

$$\epsilon''_{ext} = C \Gamma(z_0, \lambda) (uf)^2 \exp(-|z_0|/L_{decay}) \quad (2.32)$$

C is a constant that depends only on the characteristics of the planar waveguide. $\Gamma(z_0, \lambda)$ is the fraction of the electric field that is located under the depth $|z_0|$ of the holes.

Figure 2.5. The truncated cylindroconical profile.

$$\Gamma(z_0, \lambda) = \frac{\int_{-\infty}^{z_0} \zeta^2(z) dz}{\int_{-\infty}^{+\infty} \zeta^2(z) dz} \quad (2.33)$$

$\Gamma(z_0, \lambda)$ is an increasing function of the wavelength λ . A considerable work was dedicated to the optimization of the fabrication techniques in order to reduce ϵ''_{ext} at least to the same level as the intrinsic loss parameter.

In reality, state of the art fabrication methods for PhCs in InP-based materials produce air holes that are cylindrical in their top section and conical towards the bottom section [58]. The model described above can be extended to the case of a truncated cylindroconical profile (Fig. 2.5). This profile is defined by three geometrical parameters: the total etch depth $|z_0|$, the cone angle α_c and the length $|z_b|$ of the cylindrical section. As represented in Fig. 2.5, we assume that the cylindrical section extends from the surface until the bottom of the core layer. This assumption is consistent with what is commonly observed on scanning electron micrograph of holes etched in InP-based materials. Using the perturbative approach, one can show that a truncated cylindroconical hole induces always more optical loss than a cylindrical hole with comparable etch depth [58].

The graph on Fig. 2.6 displays the calculated dependence of ϵ''_{ext} on the cone angle α_c for various etch depths $|z_0| > 2 \mu\text{m}$ and for a hole diameter $d = 330 \text{ nm}$. On the same graph we included the special case where the hole is conical without truncation (black curve). Here, the depth is defined by the cone angle. One can distinguish two regimes:

- for $\epsilon''_{ext} > 0.02$, the loss parameter is independent on the etch depth and depends only on the cone angle α_c . This is the **cone regime**.
- for $\epsilon''_{ext} < 0.02$, the loss parameter depends both on α_c and $|z_0|$. This is the **truncated cone regime**.

Figure 2.6. Theoretical dependence of the extrinsic loss parameter ϵ''_{ext} on the cone angle α_c for different hole depths. These curves were calculated for a hole diameter $d = 330$ nm.

More generally, for a loss parameter ϵ''_{ext} that is superior to the intrinsic loss parameter ($\epsilon''_{int} = 0.01-0.02$ for $f = 0.30$), there is no significant dependence of the optical loss on the etch depth as long as the etch depth is larger than $2 \mu\text{m}$. The tilt angle of the walls, nevertheless, determines the loss level. Efforts should, therefore, be focused on making the air holes as cylindrical as possible.

Chapter 3

Patterning of photonic crystals

Electron beam lithography and subsequent etching of the PhC pattern are the most critical steps in the PhC fabrication. These techniques are described here. In the section 3.2 on dry etching, some conclusions from Paper A and B are reported.

Fabrication of 2D PhCs into InP/GaInAsP/InP is based on a two-mask process. The lower mask is a dielectric mask deposited on the semiconductor sample by plasma enhanced chemical vapor deposition. The upper mask is an electron sensitive resist that is spun on top of the dielectric mask. The PhC pattern is first written in the resist using electron beam lithography. Thereafter, the pattern is transferred into the dielectric mask by CF_4 or CHF_3 based reactive ion etching. Finally, the patterned dielectric layer is used as a mask to etch the semiconductor material. Before optical characterization, the sample still needs to be cleaved and mounted.

3.1 Electron beam lithography

The fabrication of PhCs working in the telecommunication wavelength range requires high resolution lithography. Innovative techniques such as deep-UV lithography [61] or imprint lithography [62] are under development. However, **electron beam lithography** is still most popular since it is flexible and is a well established method for nanofabrication.

Electron beam lithography (EBL) involves exposing an electron sensitive resist by means of a focused electron beam. The electrons are extracted from a hot filament and then accelerated under a high voltage (Fig. 3.1). Several electromagnetic lenses focus the beam on the sample surface. An adjustable aperture screens the external part of the electron beam in order to improve the focusing. A beam blanker cuts off the electron beam each time the beam needs to be

Figure 3.1. Schematic of the electron gun of the Raith Turnkey 150 electron beam lithography system.

moved from one exposure area to another. Beam deflectors are used to nudge the focused beam onto the sample surface with high precision. The displacement range achievable by beam deflection is typically $500\text{ }\mu\text{m}$. Larger displacements require the use of a movable stage. The movements of the stage are monitored by an interferometric positioning system with a precision of typically 20 nm . Both the beam blaster and the deflectors are controlled by fast electronics in order to maintain a high writing speed.

The pattern to be exposed, that is drawn using a dedicated software, is split into several square areas called **writing fields**. During the lithography, the writing fields are exposed one after another. Within one writing field, the focus point of the electron beam is scanned over the region to be exposed by means of the beam deflectors. When all the features within one writing field are exposed, the sample is moved to the next writing field using the movable stage. These sample displacements are not as precise as the beam deflections. Therefore mismatches can occur between two writing fields. These stitching errors can alter the functioning of the final component if they are located in critical areas.

The resolution of the EBL system is mainly limited by electron scattering in matter. These scattering processes are at the origin of the so-called **proximity effect**, where some energy is deposited around the region that is intentionally exposed. The outcome of the proximity effect is that the exposed features are finally larger than the size specified in the EBL file. This distortion becomes more significant as the density of the exposed patterns increases. The amplitude of the electron scattering is less significant at low acceleration voltages ($< 10\text{ kV}$).

Yet, the penetration depth of low energy electrons into the resist is relatively short, so it may be difficult to expose thick resist layers. On the other hand, when the acceleration voltage is increased, the average distance crossed by an electron before being scattered increases. If the acceleration voltage is large enough (typically > 50 kV), scattering mainly takes place below the resist, which reduces the proximity effect.

The electron beam patterning for some of the PhC structures was provided by the Laboratory of Photonics and Nanostructures (CNRS/LPN) in Marcoussis, France and by Universität Würzburg, Germany. Both laboratories use an acceleration voltage of 100 kV and polymethylmethacrylate (PMMA) as the resist. For some other structures, a Raith Turnkey 150 system (Nanofabrication laboratory, KTH) was used, with ZEP520A as the resist.

3.2 Dry etching

After the definition of the etch mask follows the etching of the PhC pattern into the semiconductor material. For PhCs etched in low index contrast planar waveguides, the demand on fabrication is stringent since the etched holes (100-300 nm in diameter) have to be etched deeper than $2\text{ }\mu\text{m}$ in order to minimize leaking of the PhC modes into the substrate (cf. 2.8). In addition to this, lateral etching must be minimal in order to avoid hole widening or hole distortion during the etching. The fabrication of PhCs requires consequently a highly anisotropic etch process.

Dry etching is an appropriate method for PhC etching. A common difficulty encountered in dry etching of InP-based materials is the difference of sputtering yield between indium and phosphorus. In pure sputtering processes, the imbalance between indium and phosphorus on the surface brings about surface roughening [63, 64]. The excess indium atoms tend to diffuse and form indium clusters that mask the surface and increase roughness. To avoid indium enrichment, the removal of indium is often enhanced by a chemically reactive etch mechanism.

3.2.1 Methane based reactive ion etching

Methane based reactive ion etching (RIE) is a classical etching process for etching of InP. It provides a reasonable etch rate (40 nm/min) and smooth surfaces on micrometer-scale patterns.

Fig. 3.2 is a schematic of an RIE chamber. The plasma is generated by application of a radio frequency (RF) voltage between two parallel electrodes. The RF generator is capacitively coupled to the bottom electrode. Due to the larger mobility of electrons compared to ions, a self-induced negative bias $-V_{bias}$ builds up on the bottom electrode when the plasma is ignited. The positively charged ions are accelerated by the self-induced bias and hit the substrate with an energy qV_{bias} , q being the electric charge of an ion. The self-induced bias

Figure 3.2. Schematic of a RIE system with parallel plate design.

Ar flow	5 sccm
CH ₄ flow	7 sccm
H ₂ flow	35 sccm
Process pressure	1.5×10^{-2} Torr
Process temperature	16°C
RF power	150 W
RF frequency	13.56 GHz
Electrode potential	565

Table 3.1. Process parameters for the Ar/CH₄/H₂ RIE process.

cannot be controlled independently, but depends on process parameters such as RF power, gas type and pressure.

The process gases are Ar, H₂ and, of course, methane (CH₄). The CH₄ molecules dissociate in the plasma to form mostly CH₃ radicals [65]. These radicals combine with indium atoms to form In_xCH₃ compounds. PH₃ is the other major etch product [66]. Argon is added to the mixture in order to increase the etch rate by enhancing physical sputtering of the sample surface [67]. The presence of hydrogen gas reduces the formation of CH₂ and CH radicals [68]. These radicals are undesirable since they tend to combine with each other and form polymer chains that contaminate the sample surface [69].

The RIE process was tested on PhC patterns (cf. Fig. 3.3 and Paper A). The process conditions are summarized in Table 3.1. A strong dependence of the etch depth on the hole diameter is observed (Fig. 3.4). This phenomenon is referred to as **RIE lag** [70]. The conical shape of the holes clearly suggests the presence of a strong etch limiting mechanisms. Even if, for the moment, we ignore this, a consequence of the lag effect is that the etch duration required to etch 2 μm deep holes is prohibitive (4h for a hole diameter of 300 nm). This process is, therefore, clearly not suitable for deep etching into InP-based materials.

Figure 3.3. Cut view of a photonic crystal etched 1h long with Ar/CH₄/H₂ RIE (Paper A).

Figure 3.4. Ar/CH₄/H₂ RIE: dependence of the hole depth on the hole size after 1h etching (Paper A).

3.2.2 Chlorine based chemically assisted ion beam etching

Ar/Cl₂ chemically assisted ion beam etching (CAIBE) consists in bombarding the sample with an argon ion beam under a chlorine atmosphere. Chlorine (Cl₂) reacts with the sample surface and increase the etch rate.

CAIBE was performed with a Nordiko 3000 ion beam etching system, equipped with a two-grid ion gun. In this system, the plasma is generated by inductive coupling of RF power through a dielectric window by way of a flat coil antenna (Fig. 3.5). A set of two perforated grids is used to extract the ions from the plasma and accelerate them towards the sample. The positive grid, as

Figure 3.5. Schematic of the Nordiko 3000 CAIBE system.

well as the walls of the plasma chamber, are at the potential V_+ . The negative grid is isolated from the chamber and has a negative potential V_- . The distance between the two grids is approximately 1 mm. The ions emanating from the plasma impinge on the positive grid with low energy (a few eV). The ions that diffuse through the openings of the positive grids are then accelerated by the potential difference between the grids. Since the openings of both grids are aligned, bombardment of the negative grid is minimal [71]. After the acceleration phase, the ions acquire an energy qV_+ . Since the sample holder is grounded, this is the energy with which the ions impinge on the sample. Unlike RIE with parallel plate design, the ion energy can be controlled independently from the other process parameters.

Chlorine based CAIBE takes advantage of the high chemical reactivity of halogen chemistries. In the Ar/ Cl_2 CAIBE process, the preferential removal of phosphorus by argon sputtering is compensated by the chemical etching of indium by chlorine. Chlorine is introduced into the chamber through a gas ring surrounding the sample holder (Fig. 3.5) and reacts with indium on the surface to form InCl_x compounds [72, 73]. InCl_x have a relatively low vapor pressure at room temperature [74]. Although the desorption of the InCl_x compounds is enhanced, to some extent, by ion sputtering [71, 75], the sample temperature needs to be increased before they can desorb efficiently. According to Ref. [76], a process temperature above 225°C results in good anisotropy. That is why the sample is heated by a halogen lamp. The process temperature is adjusted by varying the intensity of the lamp illumination. The influence of temperature on InP etching is described in Paper A and B.

Ar/ Cl_2 CAIBE applied to micrometer size patterns in InP leads to smooth profiles, a fast etch rate and vertical etch walls [76–78]. Etching of PhC structures

Table 3.2. Typical process parameters for the Ar/Cl₂ CAIBE process.

Ar flow	1-5 sccm
Cl ₂ flow	< 1.5 sccm
Positive grid voltage V ₊	400 V
Negative grid voltage V ₋	-100 V
Process pressure	$1 - 3 \times 10^{-4}$ Torr
Process temperature	250 – 280°C
RF power	25-80 W
RF frequency	13.56 GHz
Maximal etch rate (InP)	100 nm/min
Selectivity (InP/SiO ₂)	25:1

Figure 3.6. Dependence of the hole depth on the hole diameter for Ar/Cl₂ CAIBE.

is of course more complex, due to the small diameter of the holes (100-300 nm). Our early experiments showed that a divergence of the ion beam results in a conical hole shape. The ion beam needs, therefore, to be collimated with the help of a diaphragm in order to reduce beam divergence (Fig. 3.5). Apart from the diaphragm, an electron gun is also used to neutralize the ions in the beam and reduce thereby the beam divergence generated by Coulomb repulsion between ions.

The process parameters used for PhC etching are listed in Table 3.2. One can note that the process pressure in CAIBE is two orders of magnitude lower than in methane based RIE. A low process pressure is advantageous for the desorption of the etch products from the sample surface.

As already observed for RIE, the depth of CAIBE-etched holes decreases when the hole diameter decreases (Fig. 3.6). The CAIBE lag is, however, less severe than the RIE lag: holes with a diameter as small as 250 nm can be etched, indeed, as deep as 3.5 μm. This makes Ar/Cl₂ CAIBE one of the most successful etching processes for the fabrication of PhCs in InP-based materials.

It is interesting to note that widening of the SiO₂ mask during Ar/Cl₂ etching is negligible. Moreover, scanning electron microscope investigations of etched

Figure 3.7. Cut view of a photonic crystal etched in InP/GaInAsP/InP using Ar/Cl₂ CAIBE. On this micrograph, the etch depth is approximately 2.8 μm for a hole diameter of 300 nm.

PhCs show that a uniform widening of the hole occurs during the CAIBE etching, probably due to lateral chemical etching by chlorine. The corresponding increase of the hole diameter is approximately 40 nm for all hole sizes after 45 minutes of etching with Ar/Cl₂ CAIBE.

Fig. 3.7 shows a cut-view of a PhC etched with CAIBE. Ar/Cl₂ CAIBE does not result in perfectly cylindrical holes. Rather, the top section of the hole is nearly cylindrical, while the bottom-most part is conical (Fig. 3.7). The tilt angle α_c of the sidewall in the top section decreases when the etch depth is increased from 2.5 to 4.5 μm (Paper D). Having in mind the negative impact of a large value of α_c on the optical loss (cf. 2.8), this observation justifies the efforts invested into increasing the etch depth.

As for the sidewall roughness, one can observe sidewall corrugation on micrometer-sized patterns etched by Ar/Cl₂ CAIBE. Nevertheless, the sidewalls of PhC holes etched with the same process appear smooth, when observed by scanning electron microscope. It is therefore reasonable to assume that the light scattering induced by the sidewall roughness is negligible compared to the influence of the hole shape.

3.2.3 Other processes

Other research groups have investigated different types of chlorine based etching processes for the etching PhCs in InP. In particular, mention should be made of SiCl₄ inductively coupled plasma etching [79, 80] and Cl₂ electron resonance coupling reactive ion etching [58]. These processes achieve etch depth similar to Ar/Cl₂ CAIBE although PhCs etched with Ar/Cl₂ CAIBE exhibit better optical properties in the photonic bandgap (cf. Paper D). More recently, an Ar/Cl₂

CAIBE with very high ion beam energies ($\sim\text{keV}$) has been used to obtain similar etch depths [81]. In this case, ion bombardment induced hardening of the dielectric mask was shown to improve mask selectivity.

Chapter 4

Optical characterization

Two different methods were used to determine the optical characteristics of PhC samples. The **internal light source method** uses photoluminescence from embedded quantum wells as the light source to probe the sample. Paper C presents the first measurements on InP-based PhCs performed with this method. The **end-fire method**, on the other hand, uses an external light source to characterize structures that can then be optically passive. This method was used in several of the papers.

4.1 The internal light source method

The internal light source (ILS) measurements presented in this work were carried out at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. EPFL's ILS setup was inspired by the original setup presented in Ref. [82].

The photoluminescence (PL) from two GaInAsP quantum wells (QWs) embedded in the core layer of the planar waveguide is used as the build-in light source. The emission of the QWs covered the wavelength range 1470-1570 nm. The photoluminescence is excited by focusing the emission from a He-Ne laser ($\lambda = 633$ nm) on the sample surface (Fig. 4.1). The excitation spot is at a distance d from the cleaved facet. The PhC structure under characterization lies between the excitation spot and the cleaved facet. Part of the PL signal generated at the excitation spot is guided along the planar waveguide and reaches the PhC structure. The light transmitted through the PhC propagates further along the planar waveguide until it emerges from the cleaved facet. The light beam emitted from the cleaved facet is collected by a perfectly achromatic $\times 36$ Cassegrain objective and guided through a multimode fiber to a spectrum analyzer. The objective aperture limited the collected rays to an incidence angle of 6° compared to the normal direction to the facet, so that, in a first approximation, only the light impinging the cleaved facet at normal incidence is detected. For a more detailed description of the ILS setup, we refer to Paper C.

Figure 4.1. Experimental configuration for a PhC transmission measurement with the internal light source method (Paper C and D).

The distances d and d' are two important parameters of the measurement (Fig. 4.1). The guided signal is reabsorbed by the QWs, therefore d and d' should be as small as possible in order to maximize the intensity of the collected signal. d should, however, be at least $100\ \mu\text{m}$ in order that the light radiated into the air and into the substrate from the excitation spot is out of focus for the collection objective. d' should be larger than $30\ \mu\text{m}$ to limit the influence of the multiple reflections between the PhC structure and the cleaved facet. Typically, d and d' are equal to $100\ \mu\text{m}$ and $60\ \mu\text{m}$, respectively.

The determination of the absolute transmission $t(\lambda)$ through the PhC structure requires a reference measurement. The reference intensity $I_1(\lambda)$ is measured in an unpatterned region of the sample located near the PhC field under test. The excitation spot is placed at the same distance d from the cleaved edge. The measured intensity $I_2(\lambda)$ for the PhC structure is given by $I_2(\lambda) = t(\lambda)I_1(\lambda)$. Therefore the ratio $I_2(\lambda)/I_1(\lambda)$ yields the absolute transmission spectrum $t(\lambda)$ of the PhC structure.

The ILS method is useful to investigate the optical properties of reflecting PhC structures (Paper C and D). Characterization of PhC waveguides is also possible under the condition that the guiding channel is wide enough to allow a good light incoupling. Last but not least, ILS enables characterization of cavities, although the performance of such structures are penalized by the QW absorption.

Figure 4.2. Schematic of the setup for end-fire measurements with a tunable laser source (Paper I).

4.2 The end-fire method

A schematic of the end-fire setup is shown on Fig. 4.2. Unlike samples characterized by ILS, the sample tested by the end-fire method is optically passive. The probing light is, therefore, provided by external sources: a tunable laser emitting in the wavelength range 1480-1580 nm (Paper I) and an amplified spontaneous emission source with an emission spectrum spanning from 1520 to 1620 nm (Paper B and H). The PhC device is inserted between two ridge waveguides. The ridge waveguides are defined by two parallel trenches etched at the same time as the PhC. The guiding channel between the trenches is $1.2\ \mu\text{m}$ wide. The total length of the structure is at least 1 mm, which is long enough for cleaving at both ends. Light is injected into the input ridge waveguide and the transmitted light is collected from the other facet.

TE polarization of the input light is insured by a Panda polarization maintaining fiber or by a polarization filter. The light is focused on the cleaved edge of the input ridge waveguide by a Selfoc cylindrical lens. The TE polarized fundamental mode of the ridge waveguide is predominantly excited. The light emitted from the exit ridge waveguide is collected by a $\times 63$ microscope objective and is focused onto a multimode fiber with a core diameter of $64\ \mu\text{m}$. This fiber is connected to an InGaAs photodiode. In order to filter out any remaining TM polarization component at the exit port, a Glan-Thompson prism is added to the setup as an analyzer. For direct observation of the output facet, a fraction of the output light is deflected using a beam splitter and redirected to an infrared Vidicon camera.

The transmission spectrum from a single ridge waveguide etched on the same sample can be taken as reference to deduce the absolute transmission of the PhC device under test (cf. 6.5).

The end-fire method configured appropriately can in principle be used for

all types of PhC devices. This is, in particular, a good alternative to ILS for characterization of passive devices. One difficulty of the end-fire method is the incoupling of light that must be carried out with high precision in order to insure reproducibility of the measurement.

4.3 Lithographic tuning

For both end-fire method and internal light source method, the spectral bandwidth of the available light sources is not sufficient to characterize PhCs both inside and outside the bandgap. The scalability principle (cf. **2.2**) tells us, however, that the transmission t can be plotted as a function of the normalized frequency a/λ . If the λ -range is limited, we consequently still have the possibility to combine spectra from samples with different periods a in order to widen our investigation range. This scheme is called **lithographic tuning**. In the case of our ILS samples, periods between 240 nm and 600 nm with a step of 20 nm were necessary to be able to visualize both the dielectric band and the air band.

Chapter 5

Photonic crystal mirrors

In this chapter, some of the results concerning ILS characterization of mirrors and 1D cavities are presented. These results are reported in Paper C and D.

A simple PhC field made of a few rows of air holes has the property to reflect wavelengths within the photonic bandgap. At the difference of Bragg gratings, light beams are reflected irrespective of the incident angle. Besides their applications as reflectors for resonant cavities, PhC mirrors are interesting objects to investigate the optical properties of the PhC lattice both inside and outside the photonic bandgap.

At this point, it is important to point out that in the same way as a conventional Bragg grating, a PhC field can diffract light in multiple directions of the plane. For a normalized frequency u smaller than $1/n_{eff} \approx 0.31$, however, no in-plane diffraction in oblique directions takes place [83]. Since the normalized frequency range in the present work extends from 0.15 to 0.35, only a small part of the spectrum in the high frequency domain is affected by in-plane diffraction.

In this chapter, the properties of PhC mirrors at normal incidence are addressed. PhC mirrors oriented either in the ΓM or the ΓK direction of the lattice were characterized (Fig. 5.1). Characterization was performed with the ILS method.

The spectra of different samples with different hole profiles and air-filling factors are compared. Both samples were etched with Ar/Cl₂ CAIBE:

- Sample *A* and *B* have a maximum etch depth of $2.5\ \mu\text{m}$. The air-filling factors of Sample *A* and *B* are 0.25 and 0.30, respectively. The characterization results are reported in Paper C.
- Sample *C* has a maximum etch depth of $4.5\ \mu\text{m}$ and an air-filling factor of 0.40. The results are described in detail in Paper D.

Figure 5.1. Photonic crystal mirrors. Left: ΓM orientation, right: ΓK orientation (Paper C and D).

Table 5.1. Results of the ILS measurements on PhC mirrors for Sample *B* and *C*. For Sample *C*, the largest lattice periods were not available for the ΓK orientation. Consequently, the air band could not be characterized.

Sample		f	ϵ''_{diel}	ϵ''_{air}
<i>B</i>	ΓM	0.30	0.04	0.08
	ΓK	0.32	0.06	0.16
<i>C</i>	ΓM	0.40	0.04	0.08
	ΓK	0.40	0.08	-

5.1 Single mirrors

Transmission spectra through PhC slabs along the ΓM crystal orientation for TE polarization and two different air-filling factors are shown in Fig. 5.2. A well-defined photonic bandgap appears in each spectrum; the dielectric and the air bands are also seen. The fringes on the experimental curves are due to multiple reflections between the PhC mirror and the sample facet.

Experimental curves are fitted with theoretical curves simulated by 2D FDTD. The position of the band edges and the width of the photonic bandgap depend on the air-filling factor f . In accordance with the theoretical photonic gap map (Fig. 2.3), the width of the photonic bandgap increases when f increases.

5.1.1 Optical losses

The loss parameters and air-filling factors estimated from the transmission measurements through PhC mirrors are presented in Table 5.1. Apart from the material loss, that has been eliminated by normalization, the extrinsic loss is

Figure 5.2. Transmission through 10-row PhC mirrors measured by ILS for TE polarization and ΓM orientation. Sample *B* was manufactured with a larger air-filling factor than Sample *A* (Paper C).

the preponderant source of loss in the samples. According to Equation 2.32, the extrinsic loss parameter ϵ''_{ext} increases with the normalized frequency u . Consequently, out-of-plane losses are expected to be more significant in the air band (high u) than in the dielectric band (low u). This is indeed what we observe experimentally on Fig. 5.2: for an average transmission of 80% in the dielectric band, the transmission in the air band is not larger than 60%. Different ϵ'' values are, therefore, used to fit the dielectric and the air band edge.

Although Sample *C* has a higher air-filling factor than Sample *B*, both samples have similar loss parameters, which proves that the deeper holes of Sample *C* have a positive impact on the loss figure.

5.1.2 Bandgap transmission

For a 10-row mirror, a transmission of 3 to 5% is observed in the bandgap, although the 2D FDTD simulation predicts a bandgap transmission smaller than 0.01% (cf. FDTD fit on Fig. 5.2). This discrepancy is typical for PhCs etched in InP/GaInAsP/InP and is not observed in the GaAs/AlGaAs system [82]. It is interpreted as a consequence of light transmission *below* the PhC field. A full understanding of this peculiarity would require more experiments with different sample designs. Some experiments are currently underway.

5.2 1D Fabry-Pérot cavities

The investigated PhC based 1D cavities (Paper C and D) are Fabry-Pérot (FP) cavities formed by two PhC mirrors of 4 rows each placed at a distance W from each other (Fig. 5.3). Such objects are particularly useful test structures to investigate the properties of PhCs *inside* of the photonic bandgap [84]. It gives access, in particular, to the mirror loss L , a parameter that cannot be deduced by in-plane characterization of simple mirrors.

A wave packet entering the input mirror at normal incident is partly reflected by the input mirror. The transmitted light travels back and forth in the cavity. At each round trip, a fraction of light is transmitted through the mirrors. The phase shift 2ϕ after one round-trip in the cavity is given by:

$$2\phi = \frac{2\pi n_{\text{eff}} W'}{\lambda} \quad (5.1)$$

with $W' = W + 2L_p$ the actual length of the cavity taking into account of the penetration depth L_p of the light into the PhC mirrors. Resonance is reached when the round-trip phase 2ϕ in the cavity is equal to $2m\pi$ with m an integer. When this condition is fulfilled, a standing wave builds up in the cavity. The light escaping from the cavity by transmission through the input mirror interferes destructively with the input light.

Fig. 5.4 shows a transmission spectrum through a 1D FP cavity with a spacing W defined by $W/a = 1.7$. We observe a resonance peak inside the photonic bandgap for $u = 0.28$. The transmission T of the mirror can then be fitted with the Airy function [60]:

$$t = \frac{T_c T^2}{|1 - RT_c \exp(2i\phi)|^2} \quad (5.2)$$

where T and R are the transmission and reflection coefficients for a single PhC mirror and T_c is the internal transmission of the cavity, i.e., the fraction of light transmitted across the distance W in the cavity. T_c is smaller than 1 due to light absorption by the QWs. According to the Lambert-Beer law, T_c decreases exponentially with the cavity length W :

Figure 5.3. Scanning electron micrograph of a 1D Fabry-Pérot cavity. The lattice period a is 440 nm and the spacing W between both mirrors is equal to $1.7a$ (Paper D).

Figure 5.4. Transmission spectrum of a 1D Fabry-Pérot cavity for Sample *C* (Paper D).

$$T_c = \exp(-\alpha W) \quad (5.3)$$

α is the linear absorption coefficient of the cavity expressed in m^{-1} . α is

estimated experimentally by measuring the transmission through the bare slab without PhC with the excitation spot at different distances from the cleaved facet. α is in the order of 100 cm^{-1} (cf. Paper C). Since the cavity length W is small, T_c is very close to 1 and Eq. 5.2 can be rewritten as:

$$t \approx \frac{T^2}{|1 - RT_c \exp(2i\phi)|^2} \quad (5.4)$$

$$= \frac{T^2}{1 + (RT_c)^2 - 2RT_c \cos(2\phi)} \quad (5.5)$$

Fitting of the resonance peak of Fig. 5.4 results in a reflection of 96.5% and a transmission of approximately 2.5%. From these values, the mirror loss L can be obtained:

$$L = 100\% - R - T \approx 1\% \quad (5.6)$$

The mirror loss includes out-of-plane as well as in-plane loss.

5.2.1 Quality factor

The **quality factor** Q of a resonant cavity at a resonance frequency ω_0 is a dimensionless number defined as:

$$Q = \omega_0 \mathcal{E}_{cav} / \dot{\mathcal{E}}_{loss} \quad (5.7)$$

where $\mathcal{E}_{cav}$ is the energy stored in the cavity and $\dot{\mathcal{E}}_{loss}$ is the energy loss per unit of time in the cavity due to out-of-plane scattering or transmission through the mirror. One can prove that:

$$Q = \Delta\omega / \omega_0 = \Delta u / u_0 \quad (5.8)$$

with $u_0 = a\omega_0/2\pi c$ and Δu the full width of the resonance peak at half maximum. Equation 5.8 suggests that the bandwidth of a filter based on a resonant cavity is inversely proportional to the quality factor of the cavity. Therefore, the quality factor is an important figure of merit of a cavity.

Transmission through 1D Fabry-Pérot cavities reveals a significant difference between the two samples (Table 5.2). The bandgap transmission is indeed much lower for Sample *C*, which results in a much higher quality factor. The Q value of 310 obtained for Sample *C* is the highest reported so far in InP for this kind of structure.

As a conclusion, a deeper etch depth and an improved hole shape allow achieving PhC mirrors with lower losses and higher reflection. The loss level achieved for Sample *C* is close to the intrinsic limit.

Table 5.2. Results of ILS measurement on 1D FP cavities for Sample *B* and *C*.

Sample	$T(\%)$	$R(\%)$	$L(\%)$	Q
<i>B</i>	14	64	22	28
<i>C</i>	2-3	96.5	0.5 - 1.5	310

Chapter 6

Photonic crystal waveguides

This chapter describes some of the properties of PhCs and summarizes the results obtained in Paper B. Also the mode converters of Paper E and F are presented.

Waveguiding in PhCs can be achieved by removing rows of holes from the lattice (Fig. 6.1). Waveguides are essential building blocks of a photonic crystal circuit. Unlike classical ridge waveguide, they are able to guide light along tight bends [8, 9, 11, 85–89]. Besides acting as interconnects, PhC waveguides exhibit interesting properties that can be exploited in optical filters, splitters or lasers. PhC waveguides are also used as test structures in order to assess the quality of PhC fabrication. Most of the discussions and results presented pertain to the InP/GaInAsP/InP structure studied in this work.

6.1 Confinement mechanism

Wn are the PhC waveguides obtained by removal of n rows of holes. All Wn waveguides are multimode in the photonic bandgap, except the $W1$ waveguide that is monomode in a specific wavelength range. In the following sections, we will describe the $W3$ waveguide as an example of a multimode PhC waveguide with symmetric boundaries.

The dispersion diagram in Fig. 6.2(a) shows the eigenfrequencies of the guided modes in a $W3$ waveguide with an air-filling factor $f = 0.48$. Only TE modes are taken into consideration. Each state on the dispersion diagram is defined by its normalized frequency u and its propagation constant k_x , which is the component of the wavevector $\mathbf{k}$ along the central axis of the waveguide. Because of their periodic boundaries, PhC waveguides are classified as **corrugated waveguides**. The period of the axial index modulation of a PhC waveguide oriented in the ΓK direction is a (Fig. 6.1). Therefore, only values of the propagation constant k_x between $-\pi/a$ and π/a are relevant. Since each state (k_x, u) has a corresponding state $(-k_x, u)$ propagating in the opposite direction, it is sufficient to trace the dispersion diagram for $k_x > 0$. Finally, rather than k_x , we use the normalized

Figure 6.1. A W3 PhC waveguide oriented in the ΓK direction of the PhC lattice. A W3 waveguide is obtained by removing 3 rows of holes from a perfect PhC lattice (Paper B).

Figure 6.2. Eigenfrequencies of the guided modes in a W3 waveguide with $f = 0.48$. (a) is with mode coupling, (b) is without mode coupling. In (b), the solid lines represent the index-guided modes, whereas the dotted lines represent the bandgap modes (Paper B).

propagation constant $\kappa_x = ak_x/2\pi$. The gray areas contain leaky modes of the waveguide and modes of the PhC that are not coupled to the waveguide.

In Fig. 6.2(a), the different guided modes of the waveguide are difficult to identify as the dispersion curves are strongly influenced by mode coupling. For clarification, the dispersion diagram without mode coupling is shown on Fig. 6.2(b). Following the description in Ref. [90], the guided modes are labelled

by two integers $[m, n]$. m is called **mode order**. n gives the propagation direction of the mode: if $\kappa_x > -n$ the mode propagates forward, whereas $\kappa_x < -n$ corresponds to backward propagation. Equivalently, in the dispersion diagram, the sign of the slope of the dispersion curve indicates the direction of propagation: positive and negative for a forward and a backward propagating mode, respectively.

Two types of guided modes can propagate in PhC waveguides: index-guided modes and bandgap modes.

6.1.1 Index-guided modes

Index-guided modes are confined to the waveguide channel by index guiding, i.e., total internal reflection. Index guiding in PhC waveguides is made possible by a higher *average* refractive index in the waveguide channel, compared to the PhC boundaries. The average refractive index in the PhC region can be approximated by $f n_{air} + (1 - f) n_{eff}$, with $n_{air} = 1$ and n_{eff} the effective refractive index of the planar waveguide (cf. **2.3.3**). Index guiding becomes ineffective above the photonic bandgap, as light escapes from the waveguide channel by diffusing between the boundary holes.

In a W3 waveguide, the 1^{st} , 2^{nd} and 3^{rd} order modes are index-guided modes (Fig. 6.2(a)). The 1^{st} order mode, also called the fundamental mode, has a field profile similar to that the guided mode in a standard ridge waveguide. This is why coupling from a ridge waveguide into a PhC waveguide predominantly excites the fundamental mode of the PhC waveguide.

In the long wavelength limit ($\lambda \gg a$) the fundamental mode exhibits a linear dispersion relationship:

$$u(\kappa_x \rightarrow 0) = \frac{\kappa_x}{n_g} \quad (6.1)$$

n_g is the group index of the fundamental mode in the long wavelength limit. A general definition of the group index n_g is:

$$n_g = c \left(\frac{d\omega}{dk_x} \right)^{-1} \quad (6.2)$$

$$= \left(\frac{du}{d\kappa_x} \right)^{-1} \quad (6.3)$$

$1/n_g$ in Equation 6.1 is the slope of the dispersion curve next to the origin in diagram 6.2. A linear dispersion curve is a characteristic of purely index-guided modes like, for example, guided modes in ridge waveguides. In the case of index-guided modes in PhC waveguides, however, the slope of the dispersion curves for all index-guided modes decreases when the frequency increases. It can be seen clearly for the mode $[1, 0]$ and $[2, 0]$. This is the result of the light diffraction at the photonic crystal boundaries improving the lateral confinement of index-guided modes. In particular, within the photonic bandgap, diffraction

improves light transmission through tight bends, where index guiding becomes inefficient.

6.1.2 Bandgap modes

Bandgap modes are confined in the PhC waveguide by Bragg reflection at the PhC boundaries. These modes can exist only in the photonic bandgap. Their dispersion is similar to that of a guided mode in a metallic waveguide. At the cut-off frequency of a bandgap mode, the x -component k_x of the propagation constant, as well as the group velocity, are equal to zero. This corresponds to a Fabry-Pérot resonant mode oscillating in the y -direction between the PhC boundaries.

In Fig. 6.2(a), the 4th, 5th and 6th order modes are bandgap modes.

6.2 Transmission loss

On Fig. 6.2, one can observe that for frequencies inside the photonic bandgap, all the guided modes in a W3 waveguide lie above the substrate line. Thus, all the guided modes are susceptible to out-of-plane losses (cf. 2.8). This is the case for all PhC waveguides in InP/GaInAsP/InP. Since out-of-plane radiation originates from the air holes, losses are larger for a mode whose field profile expands further from the waveguide channel into the PhC boundaries. In brief, poor lateral confinement favours transmission losses.

The empirical loss parameter ϵ'' can be included in the 2D FDTD modelling of a PhC waveguide in order to simulate the losses (cf. 2.8). We represented in diagram 6.3 the dependence of the transmission loss in a PhC waveguide at a wavelength of 1.55 μm .

This diagram shows that the transmission loss depends on the order of the guided mode and on the channel width of the waveguide.

6.2.1 Modal dependence

Among all waveguide modes, the fundamental mode exhibits the best lateral confinement. In comparison, the field distribution of higher order modes stretches further into the PhC boundaries. As a consequence, at similar wavelengths, high order modes suffer more out-of-plane losses compared to the fundamental mode.

6.2.2 Channel width dependence

In narrow PhC waveguides such as W1, the guided modes are less confined to the waveguide channel than in wider waveguides. This explains the high propagation loss for the fundamental mode calculated for W1 compared to W3 in Fig. 6.3. The possibility to achieve low propagation losses with wide PhC waveguides makes them attractive for integrated optics applications, although they are not strictly monomode.

Figure 6.3. Calculated transmission loss at $1.55\ \mu\text{m}$ depending on the loss parameter ϵ'' in a PhC waveguide with air-filling factor $f = 0.47$ and lattice period $a = 480\ \text{nm}$. The calculations were made by 2D FDTD.

6.2.3 State of the art

In Paper B, a minimum transmission loss of 10 dB/mm was measured in a W3 waveguide etched in InP/GaInAsP/InP. Later on, the fabrication process for PhCs was improved and lower loss parameter could be achieved. For example, in Paper G, we measured a loss parameter $\epsilon'' = 0.10$, which corresponds to a transmission loss of 5 dB/mm. The lowest achievable transmission loss is limited by the intrinsic loss in the planar waveguide structure (cf. 2.8) and is estimated to be 2 dB/mm for a W3 waveguide.

In spite of the advances in fabrication techniques, it is doubtful whether the transmission loss in narrow-channel PhC waveguides etched into InP/GaInAsP/InP will ever be as low as in conventional ridge waveguides (a few dB/cm). Such a comparison is strictly not meaningful since PhC devices are typically much shorter (about $100\ \mu\text{m}$) and in this sense, it may still be worthwhile to tolerate the loss level provided unique functionalities and/or compactness are achieved.

6.3 Mode coupling

For specific values of the propagation constant k_x , the periodic boundaries of PhC waveguides induce a distributed back-reflection of the guided mode. This phenomenon can be described as the coupling of the guided mode into a mode propagating in the opposite direction.

Fig. 6.2(b) represents the dispersion diagram of a W3 waveguide *without* mode coupling. In this diagram, mode coupling may occur where two dispersion curves intersect. At the intersection point, both modes propagate with the same

Figure 6.4. Mini stop-bands and simple crossings in the dispersion diagram of a W3 waveguide.

phase velocity, but in opposite direction. The identical phase velocity favours the interaction between both modes. Mode coupling takes place in a given wavelength range around the intersection point and gives rise to a so-called **mode gap** or **mini stop-band** (MSB) [91, 92].

In spite of an identical phase velocity, some modes do not couple to each other. In order to list out the allowed couplings, we need to define the **mode parity**. **Even modes** have an odd mode order and their field profile is symmetric with respect to the central axis of the waveguide. **Odd modes** have an even mode order and their field profile is antisymmetric. In a PhC waveguide with axial symmetry like W1 or W3, mode coupling occurs only between modes of the same parity. In antisymmetric waveguides such as W2 or W4, mode coupling occurs only between modes of opposite parity. In the dispersion diagram 6.4 we emphasize mode couplings in a W3 waveguide. Mode coupling can occur at the edge of the Brillouin zone between modes of the same order, or in the middle of the Brillouin zone between modes of different orders. Note the MSBs at the intersection of the dispersion curves for the modes $[5, 0]$ and $[1, -1]$ and the simple crossing between modes $[5, 0]$ and $[4, -1]$: $[5, 0]$ and $[1, -1]$ have the same parity, whereas $[4, 0]$ and $[1, -1]$ have opposite parity.

If light is injected into a PhC waveguide with a frequency and a propagation constant corresponding to a mini stop-band, the light intensity decreases exponentially along the direction of forward propagation, due to the mode cou-

Figure 6.5. (a) Calculated and measured transmission through a 120-row long W3 PhC waveguide with $f = 0.48$. The theoretical curves were calculated by 2D FDTD. (b) Dispersion diagram in the same normalized frequency range as the transmission spectrum. The bold line represents the fundamental mode.

pling. A MSB appears, therefore, as a dip in the transmission spectrum of the waveguide. As an example, the transmission measurements for a W3 waveguide is discussed below (Paper B). The light gray curve in Fig. 6.5(a) is the theoretical transmission through the W3 waveguide excited with a ridge waveguide. The transmission was calculated by 2D FDTD for the TE polarization *without* out-of-plane loss. Two mini stop-bands can be observed. The mini stop-band at $u = 0.275$ corresponds to the coupling between the fundamental mode and the 5th order mode, while the mini stop-band at $u = 0.33$ corresponds to the coupling with the 3rd order mode (Fig. 6.5(b)).

The black curve in Fig. 6.5(a) is a transmission curve measured on a W3 waveguide using the end-fire method. This experimental curve was fitted with an FDTD simulation including out-of-plane loss (dark gray curve). The loss

Figure 6.6. SEM top view of a manufactured PhC mode converter showing the tapered transition between a $1.2\mu\text{m}$ wide ridge waveguide and a W1 PhC waveguide (Paper E).

parameter $\epsilon'' = 0.18$ produces the best fit. The shape of the MSB dips changes in presence of out-of-plane losses. In Paper B, we show that the position of the MSB dip depends largely on the air-filling factor, whereas its width and depth are strongly influenced by the out-of-plane losses. This property is used in Paper B in order to assess the air-filling factor and the loss parameter in PhCs.

6.4 Mode conversion

The W1 waveguide is monomode over a narrow wavelength range inside the photonic bandgap. In device applications, monomode transmission is essential for two main reasons: (a) the transmission of high order modes is low compared to that of the fundamental mode and (b) mode conversion is detrimental for device cascability.

In simple waveguiding applications, it is, however, preferable to use a multi-mode waveguide such as the W3 waveguide. The benefit is two-fold: (a) The W3 waveguide has a lower transmission loss compared to a W1 waveguide and (b) the coupling between a W3 waveguide and a conventional ridge waveguide with a typical width of $1.2\mu\text{m}$ is larger than 95% [90], which is advantageous for the integration of PhC-based devices into conventional InP-based photonic circuits.

Thus, a PhC integrated circuit made in InP/GaInAsP/InP must combine both W3 and W1 waveguides for optimal performance. This implies that one must be able to couple light from a W3 (or a ridge waveguide) to a W1 waveguide with minimal loss and minimal reflection. One elegant way to do this is to use a PhC-based mode converter [93–95]. Paper E and F deal with such mode converters based on a PhC taper. This taper utilizes a gradual increase of the hole diameter and the hole size from a W3 into a W1 waveguide (Fig. 6.6). In order to insure minimum reflection, the very first holes of the tapered section should be as small and as shallow as possible [95]. The minimal hole diameter

is limited by the resolution of the electron beam lithography system, while the etch depth is determined by the etch process. As underlined in section 3.2, holes etched with Ar/Cl₂ CAIBE have different etch depth depending on hole diameter (CAIBE lag). Thus, CAIBE lag, here, is beneficial for the fabrication of a mode converter. In Paper E, the first hole of the tapered section has a diameter of 180 nm, which results in a transmission of 50%. When the diameter of the first hole is reduced to 100 nm, a coupling efficiency of 70% is measured (Paper F). The measurement method used to estimate the taper transmission is described below.

6.5 Optical characterization

The characterization of PhC waveguides was done by the end-fire method. A schematic of the characterized sample is shown in Fig. 6.7. The short PhC section is inserted between two long ridges that deal as waveguides for light in- and out-coupling. A reference without PhC waveguide is necessary to estimate the transmission loss in the ridge waveguides.

In general, the interfaces between the PhC and the ridge waveguides exhibit a parasitic reflection R_2 and R_3 (Fig. 6.7). These parasitic reflections as well as the reflections R_1 and R_4 at the cleaved facets define a set of three coupled Fabry-Pérot cavities $\mathcal{C}1$, $\mathcal{C}2$ and $\mathcal{C}3$. The central cavity $\mathcal{C}2$ is the PhC waveguide itself. Each cavity $\mathcal{C}i$ is defined primarily by its physical length ℓ_i and its group index n_i .

In the following we will describe two different methods to extract the absolute transmission of the PhC waveguide from raw data collected by the end-fire method.

6.5.1 The single cavity measurement

In the case where the transmission between the ridge waveguide and the PhC waveguide is nearly 100%, the sample can be viewed as a single cavity with the cleaved facets as mirrors. This is true, for instance, for a W3 waveguide inserted between two 1.2 μm wide ridge waveguides. The parasitic reflections R_2 and R_3 are then smaller than 5% [90].

The transmission of a single Fabry-Pérot cavity is given by the Airy formula:

$$P_{out} = P_{in} \frac{\eta_{in}\eta_{out}T_4e^{-\alpha\ell}}{1 + R_1R_4e^{-2\alpha\ell} - 2\sqrt{R_1R_4}e^{-\alpha\ell}\cos(2\phi)} \quad (6.4)$$

with P_{in} the output power of the external light source, η_{in} the fraction of the probing light that is coupled into the input waveguide (coupling efficiency) and η_{out} the collected fraction of the light escaping from the output facet (collection efficiency). The phase shift ϕ in the cavity $\mathcal{C}i$ is defined as:

Figure 6.7. Schematic of a sample for end-fire measurement on a PhC waveguide. Two standard ridge waveguides enable light in- and out-coupling. The different internal cavities are also represented.

$$\phi = \frac{2\pi}{\lambda}(n_1\ell_1 + n_2\ell_2 + n_3\ell_3) + \phi_{mirrors} \quad (6.5)$$

where $\phi_{mirrors}$ is the sum of all the phase shifts introduced by each mirror of the sample. The total physical length ℓ is given by:

$$\ell = \ell_1 + \ell_2 + \ell_3 \quad (6.6)$$

The total loss coefficient α is defined by:

$$\alpha\ell = \alpha_1\ell_1 + \alpha_2\ell_2 + \alpha_3\ell_3 \quad (6.7)$$

The cosine term in Equation 6.4 is responsible for the high-frequency fringes observable on the transmission spectra. These fringes can be suppressed either by filtering out the high frequency components of the transmission spectrum, or by an averaging over a spectral window of at least 1 nm while recording the spectrum. The smoothed output spectrum $\langle P_{out} \rangle$ can be described by the following relation:

$$\langle P_{out} \rangle = P_{in} \frac{\eta_{in}\eta_{out}T_4 e^{-\alpha\ell}}{1 - R_1 R_4 e^{-2\alpha\ell}} \quad (6.8)$$

In the same way, one can show that the smoothed output spectrum from the reference waveguide is given by:

$$\langle P_{ref} \rangle = P_{in} \frac{\eta_{in} \eta_{out} T_4 e^{-\alpha_r \ell}}{1 - R_1 R_4 e^{-2\alpha_r \ell}} \quad (6.9)$$

All ridge waveguides on the sample can be assumed to be identical and have, therefore, the same linear loss coefficient:

$$\alpha_1 = \alpha_3 = \alpha_r \quad (6.10)$$

The measured value of α_r is of the order of 1-1.5 dB/mm, which is negligible compared to the expected linear loss coefficient for the PhC waveguide:

$$\alpha_2 \gg \alpha_r \quad (6.11)$$

This leads to a useful approximation of $\alpha \ell$:

$$\alpha \ell = \alpha_r \ell + (\alpha_2 - \alpha_r) \ell_2 \quad (6.12)$$

$$\approx \alpha_r \ell + \alpha_2 \ell_2 \quad (6.13)$$

We calculate next the ratio $\langle P_{out} \rangle / \langle P_{ref} \rangle$:

$$\frac{\langle P_{out} \rangle}{\langle P_{ref} \rangle} = \frac{1 - R_1 R_4 e^{-2\alpha_r \ell}}{1 - R_1 R_4 e^{-2\alpha \ell}} \exp((\alpha_r - \alpha) \ell) \quad (6.14)$$

$$\approx (1 + \epsilon_{err}) e^{-\alpha_2 \ell_2} \quad (6.15)$$

With reflections R_1 and R_4 being equal to approximately 35%, the error ϵ_{err} is in the range $[0, 0.1]$ for all values of $\alpha_r \ell_r$ and $\alpha_2 \ell_2$. Besides, ϵ_{err} is below 2% for $e^{-\alpha_2 \ell_2} > 0.8$ and below 1% for $e^{-\alpha_2 \ell_2} > 0.9$. Thus:

$$\alpha_2 \approx -\frac{\ln(\langle P_{out} \rangle / \langle P_{ref} \rangle)}{\ell_2} \quad (6.16)$$

This approximation was used in Paper B to estimate the transmission in W3 waveguides.

6.5.2 The compound cavity measurement

In the general case, the reflections R_2 and R_3 at the interface between the PhC and the ridge waveguides are moderate and the loss coefficient α_2 of cavity C2 containing the PhC waveguide is relatively high. One can consequently assume that the average transmission $\langle P_{out} \rangle$ through the sample is independent on the multiple internal reflections:

$$\langle P_{out} \rangle \approx \eta_{in} \eta_{out} T_2 T_3 T_4 P_{in} \quad (6.17)$$

Fig.6.8 illustrates an example of a transmission through a W1 waveguide connected to the surrounding ridge waveguides with the PhC taper presented in the previous section.

Figure 6.8. Transmission spectrum of a W1 waveguide inserted between two ridge waveguides measured using the end-fire method (Paper E). The coupling between the ridge waveguides and the PhC waveguide is insured by mode converters made of a 4-row long PhC tapered sections (Paper F).

The Fourier analysis of the transmission signal allows for the separation of the different cavity contributions to the overall signal. By this method, internal reflections inside of the sample as well as the transmission loss of individual cavities can be determined. The Fourier analysis was used at CNRS/LPN to estimate the transmission of PhC mode converters (Paper E and F).

Before performing the Fourier transform, the transmission spectrum is split in several wavelength domains $\Delta\lambda$. On the one hand, $\Delta\lambda$ should be small enough so that the variations of the loss coefficients and the group index dispersion can be neglected on each wavelength domain. On the other hand, $\Delta\lambda$ should be large enough to include a few oscillations of the transmission signal. For a total sample length of 1 mm, $\Delta\lambda$ is typically 15 nm. Through its dependence on the phase shifts ϕ_i , P_{out} is a function of $x = 4\pi/\lambda$. The Fourier transform $\mathcal{F}_{\lambda,d\lambda}$ of the function $f(x) = P_{out}(4\pi/x)$ between $x_1 = 4\pi/(\lambda + \Delta\lambda)$ and $x_2 = 4\pi/\lambda$ is defined as:

$$\mathcal{F}_{\lambda,d\lambda}(L) = \left| \int_{x_1}^{x_2} P_{out}(4\pi/x) e^{-iLx} dx \right| \quad (6.18)$$

where L is a quantity having the dimension of a length. $\mathcal{F}_{\lambda,d\lambda}$ is a set of peaks, each peak being attributed to the resonance of a cavity in the sample (Fig. 6.9). Due to the relatively high transmission loss and to the moderate values of reflections R_2 and R_3 , not all the cavities of the sample appear in the Fourier spectrum. A list of the cavities that have the strongest resonance is given in the appendix. According to [96], the signature of a cavity with an optical length ℓ_{opt} in the Fourier spectrum is a series of peaks at positions ℓ_{opt} , $2\ell_{opt}$, $3\ell_{opt}$ and the following harmonics. As another consequence of the high

Figure 6.9. Fourier transform of the transmission spectrum of Fig. 6.8 in the wavelength range between 1425-1440 nm.

transmission loss, for each cavity, only the first of the peaks appears clearly in the spectrum.

The next step of the Fourier analysis consists in mathematically filtering out all the peaks in the Fourier spectrum except that of cavity $C5$ (Fig. 6.7). The average power level is unaffected by this operation provided that the approximation 6.17 can be made. The length of cavity $C5$ is the total length ℓ of the sample, and its phase shift ϕ is detailed in Equation 6.5. The internal transmission in the cavity is equal to $e^{-\alpha_5 \ell}$. α_5 can be expressed as follows:

$$e^{-\alpha_5 \ell} = T_2 T_3 \exp(-\alpha_1 \ell_1 - \alpha_2 \ell_2 - \alpha_3 \ell_3) \quad (6.19)$$

$$= T_2 T_3 e^{-\alpha \ell} \quad (6.20)$$

The inverted transform of the filtered Fourier spectrum can be approximated by the Airy function of cavity $C5$:

$$P_5 = \frac{(1 - R_1 R_4 e^{-2\alpha_5 \ell}) \langle P_{out} \rangle}{1 + R_1 R_4 e^{-2\alpha_5 \ell} - 2\sqrt{R_1 R_4} e^{-\alpha_5 \ell} \cos(2\phi)} \quad (6.21)$$

One can easily check from this expression that the average value of P_5 is equal to the average power $\langle P_{out} \rangle$ through the sample. P_5 is a function of λ oscillating between a minimal and a maximal value $P_{5,min}$ and $P_{5,max}$, respectively:

$$P_{5,min} = \frac{(1 - R_1 R_4 e^{-2\alpha_5 \ell}) \langle P_{out} \rangle}{(1 + \sqrt{R_1 R_4} e^{-\alpha_5 \ell})^2} \quad (6.22)$$

$$P_{5,max} = \frac{(1 - R_1 R_4 e^{-2\alpha_5 \ell}) \langle P_{out} \rangle}{(1 - \sqrt{R_1 R_4} e^{-\alpha_5 \ell})^2} \quad (6.23)$$

the fringe contrast θ_5 is defined as:

$$\theta_5 = \sqrt{P_{5,min}/P_{5,max}} \quad (6.24)$$

θ_5 fulfills the following condition:

$$\ln\left(\frac{1-\theta_5}{1+\theta_5}\right) = \frac{1}{2} \ln(R_1 R_4) + \ln(T_2 T_3) - \alpha \ell \quad (6.25)$$

Both facets have the same reflection ($R_1 = R_4$). Moreover, both ends of the PhC waveguide are identical, so that $T_2 = T_3$. An approximation of α is given in Equation 6.13.

$$\ln\left(\frac{1-\theta_5}{1+\theta_5}\right) \approx \ln R_1 + 2 \ln T_2 - \alpha_r \ell - \alpha_2 \ell_2 \quad (6.26)$$

ℓ and ℓ_2 are easily estimated by optical microscope inspection of the sample. The facet reflection R_1 and the ridge linear loss coefficient α_r are deduced from the measurement on the reference ridge.

One method to determine T_2 and α_2 consists in characterizing two identical PhC waveguides with different lengths [97]. This is the **Fabry-Pérot resonance method**. It is also possible to isolate other cavities from the Fourier spectrum. For instance, one can measure the fringe contrast θ_1 of cavity $\mathcal{C}1$ and use the following relation to calculate R_2 :

$$\ln\left(\frac{1-\theta_1}{1+\theta_1}\right) = \frac{1}{2} \ln(R_1 R_2) - \alpha_1 \ell_1 \quad (6.27)$$

Therefore:

$$R_2 = \frac{1}{R_1} \cdot \left(\frac{1-\theta_1}{1+\theta_1}\right)^2 e^{2\alpha_1 \ell_1} \quad (6.28)$$

Due to out-of-plane scattering at interface between the PhC and the ridge waveguide, the sum $R_2 + T_2$ is not necessarily equal to 100%. A third equation is then necessary to calculate T_2 and α_2 . The fringe contrast θ_4 of cavity $\mathcal{C}4$ can be used to this purpose:

$$\ln\left(\frac{1-\theta_4}{1+\theta_4}\right) = \frac{1}{2} \ln(R_1 R_2) + \ln(T_2) - \alpha_r \ell_1 - \alpha_2 \ell_2 \quad (6.29)$$

Combining equations 6.29 and 6.26 gives access to the transmission T_2 between ridge and PhC waveguide and the linear loss coefficient α_2 .

This method is referred to as **compound cavity measurement**. In Paper E, it is shown that compound cavity measurements are consistent with result obtained with the Fabry-Pérot resonance method. As a conclusion, this method is useful for the determination of internal reflections and transmission in a multi-cavity sample. It is particularly well suited for the characterization of PhC mode converters (Paper E and F).

Chapter 7

Photonic crystal based optical filters

This chapter begins with a review of PhC-based optical filters. Subsequently, the filter designs published in Paper G and H are introduced.

Wavelength Division Multiplexing (WDM) is a common method to increase capacity in optical communication networks, by transmitting data simultaneously at multiple carrier wavelengths. Optical filters are one of the most critical components in WDM systems. The usual add/drop filters, such as grating filters, Fabry-Pérot filters and array waveguide gratings, are relatively large, typically several millimeters. Compact filters well below millimeter size, while still highly efficient, are in demand for integrated optical circuits.

PhCs enable optical filters with smaller footprint and narrower bandwidth. Designs for such a component depend on which properties of the PhCs the filter relies on.

7.1 Superprisms

2D PhCs can exhibit an exceptionally high dispersion in a frequency range outside the photonic bandgap [23, 98]. **Superprisms** use efficiently this property to separate different wavelengths in a light beam [22, 24, 25]. The superprism effect was, for instance, demonstrated in a silicon-based 3D PhC: two beams, one at a wavelength of $0.99\ \mu\text{m}$, the other at $1.00\ \mu\text{m}$, could be separated by an angle of 50° , which is two orders of magnitude higher than what can be achieved with conventional prisms or gratings [22]. Also, an angular dispersion of $0.5^\circ/\text{nm}$ is demonstrated in a 2D PhC superprism etched in a GaAs-based structure [24].

Figure 7.1. Principle of a drop filter using microcavity and a waveguide. Courtesy of S. Noda, University of Kyoto.

7.2 Microcavities

Microcavities, or **defect point cavities** are obtained by removing or modifying the size of a single hole in the PhC lattice. Microcavities can only support one degenerate mode at the resonant frequency f_0 [3]. If a microcavity is carved in the vicinity of a PhC waveguide, light from the waveguide is able to couple into the microcavity in a narrow wavelength range around f_0 [13]. This property can be used to realize a drop filter. The two existing configurations for PhC filters based on microcavities are described below.

7.2.1 Out-of-plane dropping

In Ref. [14], a drop filter based on the lateral coupling between a PhC waveguide and a microcavity is demonstrated. In this design, the light trapped in the microcavity is collected perpendicularly to the sample surface by an optical fiber (Fig. 7.1). This configuration takes advantage of the out-of-plane scattering from the cavity, which is inherent to all 2D PhCs.

7.2.2 Resonant tunneling

Fig. 7.2(a) shows the concept of a resonant tunneling filter. At the resonance frequency f_0 , light from the input channel tunnels into the drop channel through the optical resonator. Two designs based on PhCs were proposed [13, 16]. In both

Figure 7.2. (a) The principle of a resonant tunneling filter. (b) Design of a planar PhC filter working by resonant tunneling. This design proposed in Ref. [16] was optimized for the InP/GaInAsP/InP material system. The optical resonator consists of two microcavities (larger holes). The holes encircled in black are made smaller in order to shift the resonant wavelength of the microcavities.

designs, the optical resonator consists of two identical microcavities separated by a certain number of holes (Fig. 7.2(b)). In most cases, the light trapped in the microcavities couples back into the four channels of the filter. The distance between the microcavities can be adjusted, however, so that their emissions interfere destructively in the “input” and the “add” channel whilst constructively in the “output” and “drop” channels.

Besides having a size of only a few microns, resonance tunneling filters offer a drop efficiency close to 100 %. They are, nonetheless, very sensitive to out-of-plane losses and require extremely high precision in their fabrication.

7.3 Fabry-Pérot cavities in W3 waveguide

In Paper G, we present a planar filter design utilizing a Fabry-Pérot (FP) cavity inserted into a PhC waveguide. The FP cavity is formed by inserting two mirrors into a W3 waveguide (Fig. 7.3). Although they are multimode, W3 waveguides are more advantageous compared to W1 waveguides from the point of view of transmission loss (cf. 6.2).

the round trip phase 2ϕ of the cavity is given by:

$$2\phi = \frac{4\pi n_g \ell'}{\lambda} \quad (7.1)$$

n_g is the group index in the cavity. The length ℓ' is defined by:

$$\ell' = \ell + 2L_p \quad (7.2)$$

with ℓ the physical length of the cavity as measured from Fig. 7.3 and L_p the optical penetration depth into the mirrors. The cavity is at resonance when the round trip phase 2ϕ is a multiple of 2π , i.e.,

Figure 7.3. Scanning electron micrograph of a resonant cavity inserted in a W3 waveguide.

$$2\phi = 2m\pi \quad (7.3)$$

with m an integer. Thus, the resonance wavelength λ_m of order m is given by:

$$\lambda_m = \frac{2n_g\ell'}{m} \quad (7.4)$$

Only the resonance wavelengths λ_m of the FP cavity are transmitted, while the other wavelengths are reflected by the cavity. In a complete filter design, a circulator, or a beam splitter, is necessary upstream of the cavity in order to isolate the reflected signal from the input signal.

Fig. 7.4 illustrates a transmission spectrum through the device of Fig. 7.3. The spectrum was obtained by the end-fire method. An appreciably high quality factor of 470 was measured.

The transmission spectrum was fitted with an Airy function:

$$t(\lambda) = \frac{T^2 e^{-\alpha\ell}}{1 + R^2 e^{-2\alpha\ell} - 2R e^{-\alpha\ell} \cos(4\pi n_g \ell' / \lambda)} \quad (7.5)$$

with R, T the reflection and the transmission of the mirrors, α the linear loss coefficient in the cavity. Since the mirror are short compared to the total length cavity, ℓ can be approximated by ℓ' in Equation 7.5. α and n_g depend on which guided mode propagates inside the cavity. For the device shown on Fig. 7.3, simulations of the modal field inside and outside the cavities at resonance show that the third order mode is predominant inside the cavity possibly due to the V-shape of the mirrors. The spectrum was fitted by an 2D FDTD simulation using the loss parameter model (cf. Paper G). The resulting loss parameter ϵ'' is equal to 0.10, which is equivalent to $\alpha = 95 \text{ dB/mm}$ for the third order mode.

Figure 7.4. Transmission spectrum of the Fabry-Pérot resonance cavity shown on Fig. 7.3.

The optical length $n_g \ell'$, as well as R and T , can then be deduced from the Airy function fit: $n_g \ell' = 27.35 \mu\text{m}$, $R = 95.5\%$ and $T = 2\%$. The loss L in one mirror reads:

$$L = 1 - R - T = 2.5\% \quad (7.6)$$

As a conclusion, losses in the device are mostly due to out-of-plane scattering in the cavity region. These losses could be reduced by suppressing mode conversion by the mirror.

7.4 Waveguide coupling

Optical filters can be made based on waveguide coupling, which is a wavelength selective phenomenon in which light is exchanged between two waveguides brought next to each other. One inconvenience of such filters is their relative large size compared to filters based on resonant cavities. It is because a large waveguide length may be necessary to couple a sufficient amount of light from a waveguide to the other. It is possible, however, to increase the coupling by adding a grating between the coupled waveguides. One can differentiate two types of grating-assisted waveguide coupling: the **co-directional** and the **contra-directional** coupling. In the case of a co-directional coupling, the coupled optical modes travel in the same direction, whereas for contra-directional coupling, they travel in opposite directions (Fig. 7.5).

Due to their periodic boundaries, two PhC waveguides brought close to each other are naturally grating-assisted waveguide couplers. PhC-based co-directional couplers have already been demonstrated [99, 100].

Figure 7.5. Grating-assisted co-directional and contra-directional coupling.

In Paper H we present a filter based on a contra-directional PhC waveguide coupler. The design layout of the filter is shown in Fig. 7.6. The two PhC waveguides are chosen as a W1 waveguide and a W0.8 waveguide, for which the channel width is 80% that of a W1 waveguide.

7.4.1 Design

The contra-directional coupling occurs between the fundamental modes of the two waveguides. Modelling was done with 2D FDTD for an air-filling factor $f = 0.45$. The calculated center frequency for the coupling is at the normalized frequency $u = a/\lambda_0 = 0.33$, thus the lattice period $a = 530$ nm is used to ensure an operation wavelength λ_0 around 1550 nm. The diameter of the air holes deduced from Equation 2.21 is equal to 370 nm. For more details about the modelling of the device, we refer to Paper H and Ref. [101].

From the coupled mode theory, the filter bandwidth $\Delta\lambda$ is approximately [102]:

$$\Delta\lambda = \frac{2\lambda_0^2\kappa}{\pi\left(\frac{c}{v_g^+} + \frac{c}{v_g^-}\right)} \quad (7.7)$$

where κ is the coupling coefficient. v_g^+ and v_g^- are the group velocities of the guided modes. κ depends on the distance between both waveguides. If this distance is small, the coupling is strong and the bandwidth is wide. Consequently, a weak coupling, i.e., a large distance between the waveguides is favourable to the spectral characteristics of the filter.

The drop efficiency D is defined as the ratio between the dropped power and the output power at the resonance wavelength λ_0 . Provided that the device is lossless, D is given by [103]:

$$D = \tanh^2(\kappa\ell) \quad (7.8)$$

where ℓ is the length of the waveguides. According to this expression, at a constant coupling coefficient, the drop efficiency increases steadily when the length of the device is increased. In order to keep the device compact, the coupling coefficient κ should therefore be large. We have seen earlier, however, that a strong coupling results in a wide bandwidth. Consequently a trade-off must be made between a narrow bandwidth and a short device length.

One way to circumvent this problem is to take advantage of guided modes with a small group velocity. Such slow modes were evidenced experimentally in PhC waveguides etched in a silicon membrane [104]. According to Equation 7.7, sufficiently small group velocities could compensate for a large coupling coefficient κ , which would result in a narrower bandwidth.

7.4.2 Characterization results

The transmission through the device is measured using the end-fire method. The input, output and drop ports of the filter are prolonged by $1.2\,\mu\text{m}$ wide ridge waveguides (Fig. 7.6). The $100\,\mu\text{m}$ long tapered sections facilitate the coupling between the ridge waveguide and the PhC waveguide (Fig. 7.6). A bend with a radius $> 100\,\mu\text{m}$ is used to bring the drop port on the same side as the output port, in order to facilitate the optical characterization.

For the center wavelength of $1585\,\text{nm}$, we measure a drop efficiency is approximately 18%. The bandwidth is $10\,\text{nm}$. Only around 5% of the light finally reaches the detectors on the output channel side due to the strong out-of-plane losses in the W0.8. A significant part of the loss also comes from the tapered section of the ridge waveguides.

As a conclusion, we demonstrated experimentally a wavelength drop function based on a contra-directional coupling between two PhC waveguides. A possible design improvement would consist in taking advantage of slow propagating modes in order to reduce the overall size of the device.

Figure 7.6. Design layout and scanning electron micrographs of the add-drop filter based on contra-directional coupling between two PhC waveguides. The lattice period is 530 nm and the hole diameter is 370 nm (Paper H).

Chapter 8

Photonic crystals etched in InP membrane

In this chapter, the InP membrane system is introduced and the results from Paper I are commented.

8.1 The high index contrast system

The optical loss in 2D PhCs is strongly influenced by the difference of dielectric constant $\Delta\epsilon$ between the core layer and the claddings of the planar waveguide. 2D PhC etched in a **low index contrast** system, like, for instance, InP/GaInAsP/InP ($\Delta\epsilon = 1.17$) are intrinsically liable to loss. This is explained by the fact that the quasi totality of the photonic bandgap is situated above the substrate line in the dispersion diagram. Defect modes in the bandgap are, consequently, all coupled to radiation modes (cf. **2.8**).

2D PhCs etched into planar waveguides with **high index contrast** can, on the contrary, support modes below the substrate line. These modes are not subject to radiation losses, provided that the PhC lattice is perfect. The

Material system	core	bottom cladding	$\Delta\epsilon$
Silicon on insulator (SOI) [12, 43, 44]	silicon (n=3.5)	SiO ₂ (n=1.45)	10.1
GaAs on Al ₂ O ₃ [105]	GaAs (n=3.37)	Al ₂ O ₃ (n=1.61)	8.8
GaAs membrane [106]	GaAs (n=3.37)	air (n=1)	11.4
InP membrane [107, 108]	InP (n=3.17)	air (n=1)	10.0
GaInAsP membrane [4, 7, 109]	GaInAsP (n=3.4)	air (n=1)	11.6

Table 8.1. Examples of high index contrast planar waveguides. $\Delta\epsilon$ is the difference between the dielectric constant in the core layer and the dielectric constant in the bottom cladding.

larger $\Delta\epsilon$ is, the more modes exist below the substrate line [110, 111]. Table 8.1 summarizes some of the commonly used high index contrast material systems.

Low-loss modes below the substrate line can be used efficiently to realize high transmission waveguides as well as microcavities with high quality factors. A W1 waveguide made in silicon-on-insulator with a transmission loss of only 0.76 dB/mm has been reported [112]. As for microcavities, quality factors larger than 10000 were predicted by 3D FDTD calculations [6, 109]. Quality factors of approximately 2000 were obtained experimentally for microcavities etched in GaInAsP membranes [7, 113]. More recently, the Q values have been tremendously increased [114].

One promising high index system for the realization of low-loss waveguides and high- Q microcavities at optical communication wavelengths is the InP membrane. As a first step towards the fabrication of low-loss PhC structures, we investigated PhC-based FP filters etched in an InP membrane (Paper I). We describe below the fabrication of the samples and the results from the end-fire measurements.

8.2 Fabrication

8.2.1 Epitaxial structure

The epitaxial structure was grown by MOVPE on InP substrate [115]. It consists of a 300 nm thick layer of InP on top of the 600 nm thick layer of InGaAs. The InGaAs layer is the **sacrificial layer** that will be selectively wet-etched to form the air gap. The top InP layer will form the membrane.

An InP membrane is monomode at $\lambda = 1.5 \mu\text{m}$ when its thickness is below 260 nm. A 300 nm-thick InP membrane supports two vertical modes: the fundamental mode is symmetric with respect to the membrane plane, whereas the higher order mode is antisymmetric. Thicker membranes are advantageous from the point of view of mechanical stability. Moreover, since the horizontal symmetry of the membrane is conserved in our device, the fundamental mode remains predominant.

8.2.2 Lithography and etching

Electron beam lithography was performed with a Raith Turnkey 150 EBL system at the KTH Nanofabrication Laboratory. The electron beam energy used was 30 keV.

The semiconductor material is etched by Ar/Cl₂ CAIBE. The etch mask is a 100 nm thick layer of SiO₂. In principle, only the top InP layer needs to be etched. But in reality we etch almost through the InGaAs layer, to ease the next process step, namely **selective wet etching**.

Figure 8.1. SEM micrograph showing a tilted view of the cleaved facet of a W1 waveguide in an InP membrane after selective wet etching. Note the 300 nm thick air gap below the suspended InP membrane

8.2.3 Selective wet etching

After etching of the PhC pattern and cleaving of the sample, the InGaAs sacrificial layer is locally removed by selective wet etching. FeCl_3 diluted in water ($\text{FeCl}_3:\text{H}_2\text{O}$ 1:3) is used as an etch solution. This etch solution is highly selective against InGaAs in favour of InP. The etch solution finds its way to the InGaAs layer from the facets of the sample and through the holes of the PhC. An etch duration of 1 minute is sufficient to remove all the InGaAs material below the PhC area.

After the selective wet etching, the sample is rinsed in water and acetone. At this stage, we cannot let the sample dry in the atmosphere as the capillary forces induced by surface tension of the acetone may cause the freestanding structure to collapse at the bottom of the gap. Thus, the acetone has to be removed by a technique called **critical point drying (CPD)**. In the first step of the CPD process, the acetone in which the sample is immersed is replaced by liquid CO_2 in a pressurized chamber. The temperature and the pressure are then increased until they reach the values of 31.34°C and 72.92 atm , respectively, which is the critical point of CO_2 . Above the critical point, CO_2 is a **supercritical fluid**. Supercritical fluids have a low surface tension compared to liquids. Therefore CO_2 can be vaporized without risk of damaging the membrane structure. Fig. 8.1 is a scanning electron micrograph of the W1 waveguide in the InP membrane after selective wet etching. The membrane is patterned with a W1 PhC waveguide.

Figure 8.2. SEM top view of a PhC-based Fabry-Pérot cavity in an InP membrane.

8.3 Experimental results

We manufactured and characterized PhC Fabry-Pérot (FP) cavities etched in an InP membrane (Paper I). The FP cavity is integrated within a W1 PhC waveguide. The PhC is a triangular array of air holes with period $a = 450$ nm and a hole size of 270 nm, resulting in an air-filling factor of 35%. The cavity is formed by providing air holes as mirrors (Fig. 8.2). The length of the cavity is 60 PhC periods, which corresponds to about $27 \mu\text{m}$.

Quality factors around 3000 were measured for such structures. In Paper G we demonstrated a quality factor of 470 in $7.0 \mu\text{m}$ long PhC cavities etched in the low index contrast structure InP/GaInAsP/InP. The values cannot be compared directly since the quality factor Q of a Fabry-Pérot cavity depends the cavity length. An expression of Q can be derived using the Airy function in Equation 5.2:

$$Q = \frac{2\pi n_g \ell}{\lambda_0} \cdot \frac{1}{\arccos\left(1 - \frac{(1 - Re^{-\alpha\ell})^2}{2Re^{-\alpha\ell}}\right)} \quad (8.1)$$

where n_g is the group index, ℓ the cavity length, and λ_0 the resonance wavelength. By means of this expression and the experimental data listed in section 7.3, a quality factor of approximately 600 can be extrapolated for a $27 \mu\text{m}$ long FP cavity etched in InP/GaInAsP/InP. The improvement from 600 to 3000 is a consequence of the higher waveguide transmission in the membrane case.

Inspection of the sample surface with an infrared Vidicon camera equipped with a microscope objective shows intense radiation coming from the cavity mirrors (Paper I). The confinement in the cavities, as well as the overall transmission, are penalized by this out-of-plane radiation. This radiation cannot be avoided,

since a PhC waveguide etched in a high index system must have a translational symmetry in order to be able to sustain Bloch modes devoid of loss. The cavity mirrors break this symmetry and favour, therefore, the coupling of the guided modes to radiative modes [116]. The radiation can, however, be reduced by replacing the 1-hole and 2-hole mirrors by a distributed Bragg mirror made of a series of smaller holes.

As a conclusion, 2D PhCs etched into InP membranes represent clearly a low-loss alternative to the InP/GaInAsP/InP system. However, a few difficulties still need to be overcome before high-performance devices can be demonstrated: first, a PhC etched into an InP membrane is difficult to integrate with a conventional photonic circuit based on a low index contrast planar waveguide. Second, the realization of metal contacts for carrier injection in electrically pumped lasers or in electrically tunable devices is complex. Finally, the poor heat conductivity of the InP membrane system is a severe issue for the realization of active devices [4].

Chapter 9

Guide to the papers

PAPER A: Dry etching of photonic crystals in InP based materials

This paper focuses on dry-etching of PhCs in InP-based materials. At the time when this paper was published, there were only few publications on this subject. Two different etching processes are compared: Ar/CH₄/H₂ RIE and Ar/Cl₂ CAIBE. With the RIE process, we obtained PhCs with smooth profiles. However, the strong RIE lag makes the process unsuitable for etching of deep holes in InP/GaInAsP/InP. As for Ar/Cl₂ CAIBE, the sample temperature is identified as an important parameter of the process. After optimization, an etch depth of 2.4 μm is achieved for a hole diameter as small as 210 nm. The same process was used for fabrication of the samples presented in Paper B and C. After this initial work, Ar/Cl₂ CAIBE was improved further and used for etching of different types of PhC structures.

Contribution of the author: fabrication, characterization, interpretation and writing.

PAPER B: Low-loss InP-based photonic-crystal waveguides etched with Ar/Cl₂ chemically assisted ion beam etching

This paper summarizes one of the first experimental results on PhC waveguides in the InP-based low index contrast system. W3 PhC waveguides were etched into an InP/GaInAsP/InP structure using Ar/Cl₂ CAIBE. The quality of the PhCs etched in two different process conditions is compared by using the shape and the position of one of the mini stop-bands as an assessment tool. For

an etch depth of $1.5\ \mu\text{m}$, the minimum transmission loss measured in the W3 waveguide is 60 dB/mm. The corresponding value for an etch depth of $2.4\ \mu\text{m}$ is 10 dB/mm. This value was, at the time of publication, the lowest reported for this kind of structure. This result confirmed that Ar/Cl₂ CAIBE is a promising process for PhC etching in InP.

Contribution of the author: fabrication, data analysis and writing.

PAPER C: Optical study of two-dimensional InP-based photonic crystals by internal light source technique

This paper describes the first ILS measurements performed on InP-based PhCs. Mirrors and 1D cavities etched by Ar/Cl₂ CAIBE in InP/GaInAsP/InP were characterized. Due to the CAIBE lag, the etch depth varies from 1.5 to $2.5\ \mu\text{m}$ for a hole diameter in the range 240-500 nm. The photonic bandgap widens when the air-filling factor is increased from 0.25 to 0.30, which is consistent with theoretical predictions. The transmission outside the photonic bandgap was found to be limited by out-of-plane scattering. A minimum loss parameter of 0.04 is measured in the dielectric band of a 10-row mirror. This value is close to the intrinsic limit. A transmission of 3 to 5% was measured in the bandgap for the 10-row mirrors. One possible explanation for this is light propagation below the PhC field. A maximum quality factor of 28 was measured in 1D cavities. Better performance can be obtained within and outside the bandgap if the hole shape and the hole depth are improved. This paper was followed up by Paper D.

Contribution of the author: fabrication, geometrical analysis. Participation in writing and optical analysis.

PAPER D: Fabrication of 2D InP-based photonic crystals by chlorine based chemically assisted ion beam etching

In this paper, improvements in the optical properties of PhC mirrors and 1D cavities are reported. The samples were etched with an etch process that was further optimized compared to what was presented in Paper C. The characterization is done using the ILS method. The air-filling factor of the PhC is approximately 0.40. Even though this value is larger than in Paper C, the same loss parameter are obtained in the dielectric and the air band, which suggests an improved hole shape. This is confirmed by measurements on 1D cavities: the reflection of the 4-row mirror is improved from 64% to 96% compared to

Paper C, while the quality factor of the cavity reaches a value of 310, which is a record for this material system.

Contribution of the author: fabrication, internal light source characterization, analysis, writing.

PAPER E: Compound cavity measurement of transmission and reflection of a tapered single-line photonic-crystal waveguide

This paper presents a demonstration of improved light coupling between a $1.2\,\mu\text{m}$ -wide ridge waveguide and a W1 PhC waveguide by the way of a PhC mode converter. The mode converter consists in a tapered PhC section. The taper is 10-row long and the diameter of the first hole is equal to 180 nm. The transmission of the manufactured mode converters is measured by the end-fire method. The experimental data were processed using both the Fabry-Pérot resonance method and compound cavity measurements. Both methods give similar results. It was found that the coupling between a conventional ridge waveguide and a W1 waveguide without mode converter is only 25%, while it is 50% with mode converter. The performance of the mode converter can be improved by reducing the size of the smallest hole of the taper section. This paper was followed up with Paper F.

Contribution of the author: fabrication. Participation in analysis and writing.

PAPER F: High bandwidth transmission of an efficient Photonic-Crystal mode converter

In this paper, improvements in the performance of a mode converter based on a PhC tapered section are reported. The tapered section is 4-row long and the diameter of the very first hole of is 100 nm. A coupling efficiency of 70% over a 80 nm bandwidth is measured between a standard ridge waveguide and W1 waveguide. The improvement compared to Paper E is explained by the smaller diameter of the first hole of the tapered section. A double bend including this specific taper design for both bends demonstrates only 3 dB additional losses when compared to a straight deep ridge. This result is an important step towards low-loss PhC integrated circuits.

Contribution of the author: fabrication. Participation in analysis and writing.

PAPER G: In-plane resonant cavities with photonic crystal boundaries etched in InP-based heterostructure

The aim of this paper is to demonstrate experimentally the feasibility of a FP filter inserted in a W3 waveguide. The PhC pattern is etched by Ar/Cl₂ CAIBE. The etch depth is close to 3 μm . The transmission spectra are measured using the end-fire method. The loss parameter in the PhC is estimated by fitting the experimental curves with 2D FDTD simulations. A loss parameter of 0.10 is obtained, which corresponds to a minimum transmission loss of 5 dB/mm in the W3 waveguide. The increased hole depth explains the considerable improvement compared to the 10 dB/mm obtained in Paper B. A quality factor of 460 is measured for a 6.2 μm long cavity. This value decreases to 330 for a 3.4 μm long cavity. The high transmission loss through the device is explained by mode conversion at the PhC mirrors. Lower out-of-plane loss and higher quality factors can be obtained provided that a specific mirror design is implemented.

Contribution of the author: fabrication, writing. Participation in optical characterization and analysis.

PAPER H: Photonic crystal optical filter based on contra-directional waveguide coupling

Unlike PhC filters based on resonant cavities, PhC optical filters based on waveguide coupling are expected to be less sensitive to radiation loss and more fabrication-tolerant. In the present paper, the principle of a filter based on contra-directional coupling between two PhC waveguides is validated experimentally. Contra-directional coupling occurs between a W1 and a W0.8 waveguide. Light in- and out-coupling is insured by ridge waveguide tapers and a ridge waveguide bend. A drop efficiency of 18% and a bandwidth of 10 nm are demonstrated. The measured drop efficiency is smaller than the 42% calculated by means of the 2D FDTD method, probably due to optical losses at the tapers and at the bend. One way to reduce the bandwidth of the filter without increasing the length of the device would be to take advantage of slow propagating modes in PhC waveguides.

Contribution of the author: fabrication, data analysis, end-fire measurements. Participation in writing.

PAPER I: Fabry-Pérot cavities based on 2D Photonic crystals fabricated in InP membranes

In this paper, we measure the transmission and analyze the out-of-plane losses in FP filters based on PhCs etched in a suspended InP membrane. We measure a cavity quality factor of 3200 for a resonant wavelength in the $1.5\ \mu\text{m}$ wavelength range. The low transmission at resonance is attributed to out-of-plane scattering at the cavity mirrors. The out-of-plane radiation is observed by imaging the sample from a top using an infrared camera equipped with a microscope objective. This confirms that even if PhC waveguides etched in high index contrast system can support lossless modes, suppression of the translational symmetry in the waveguide generates strong out-of-plane scattering.

Contribution of the author: fabrication, data analysis, end-fire measurements, writing.

Chapter 10

Conclusion

Achievements

In summary, this thesis has addressed the following issues:

- Fabrication of 2D PhCs in InP-based materials.
- Experimental determination of optical losses in basic PhCs structures.
- Utilization of PhCs for optical filtering applications.

Concerning the fabrication of PhCs, Ar/Cl₂ CAIBE was identified as a suitable process for deep etching in InP-based materials (Paper A). The process temperature is a critical parameter of the process (Paper B). The achieved results can be considered as the state of the art in PhC etching in InP: after optimization of the etching conditions, an etch depth in the range 2.5-4.5 μm could be achieved for holes with diameters in the range 250-350 nm (Paper D). The sidewalls of the etched holes are smooth, while the hole shape is cylindrical in the upper section and conical towards the bottom. A decrease of the hole depth is observed for a decreasing hole diameter. This CAIBE lag was utilized for the realization of a tapered waveguide section performing mode conversion between a W3 and a W1 waveguide (Paper E and F). A coupling of 70% was obtained between a standard ridge waveguide and a W1 waveguide.

The optical properties of basic PhC structures etched with Ar/Cl₂ CAIBE, such as waveguides, mirrors and 1D cavities were investigated. In Paper B, we reported a transmission loss of 10 dB/mm in a W3 waveguide in the 1.5 μm wavelength range. The PhC was etched 2.5 μm into the planar waveguide. For 10-row mirrors with an air-filling factor of 0.25-0.30, maximal transmission values around 80% and 60% were measured in the dielectric and the air band respectively (Paper C). A transmission of 3 to 5% is measured in the photonic bandgap, probably due to light transmission below the mirror. After an improvement of the hole shape and depth, this bandgap transmission could, however, be reduced

from 14% to 3% for 4-row PhC mirrors (Paper D). Another consequence of this improvement is an increase of the quality factor of the 1D cavities from 28 (Paper C) to 310 (Paper D).

Since PhCs etched in InP/GaInAsP/InP are intrinsically liable to loss, they are not suitable for the realization of single-defect cavities for filtering applications. As a step towards loss-tolerant filter designs, we manufactured and characterized two PhC-based filters:

- a Fabry-Pérot filter inserted in a PhC waveguide (Paper G). A W3 waveguide is used instead of the standard monomode W1 waveguide, that suffers from low transmission. A maximal quality factor of 460 was measured for this structure.
- a contra-directional coupler (Paper H). This filter is based on the contra-directional coupling between two PhC waveguides. This is the first demonstration of a drop function using PhCs in this configuration. A bandwidth of 10 nm and a drop efficiency of 18% were measured.

At the cost of extra design constraints, the InP membrane platform can be used as a low-loss alternative to InP/GaInAsP/InP. To investigate the potential of PhCs etched into an InP membrane, we manufactured a $26\text{ }\mu\text{m}$ long Fabry-Pérot cavity inserted in a W1 waveguide and characterized by means of the end-fire method (Paper I). A quality factor of 3200 was demonstrated. This work was also intended to establish the membrane technology for potential future applications.

Future work

Dry etching: The out-of-plane losses due to the finite depth or the conical shape of the dry-etched holes are still above the intrinsic limit. We believe that, by further process optimization and provision of a resistant etch mask, one can obtain lower losses. Besides that, dry-etch induced damage needs to be well characterized optically. In particular, methods to reduce damage need to be developed for the fabrication of high quality PhCs into active sections. Last but not least, the mechanisms behind the CAIBE lag need to be characterized and understood.

Bandgap transmission: The relatively high bandgap transmission in InP based PhC is still not fully explained. Its suppression should improve the performances of PhC cavities. Experiments are currently underway.

PhC filters: The filter designs proposed in this work need to be improved for the realization of a compact and low-loss optical filter. In particular, for Fabry-Pérot filters, losses and mode conversion at the cavity mirrors must be reduced. Tunability of such devices needs to be investigated. First results on

the thermal tunability of PhC cavities were reported.

PhCs on InP membranes: The membrane technology developed in this work could be very useful for ultrasmall optical sources provided that schemes for current injection and thermal dissipation can be implemented. Optimization of mirror geometry in Fabry-Pérot cavities, for both low and high index contrast structures.

PhC lasers: Active devices such as InP-based lasers using PhC concepts are attractive and could benefit from the fabrication techniques developed in this work. Some recent work has already shown encouraging results.

Other properties of PhCs, or relevant applications, that we did not investigate in this thesis, could be subjects of exciting research. The peculiar dispersion of PhCs outside the photonic bandgap, for instance, can be utilized to design superprisms for signal filtering or novel lenses for imaging optics.

Transmission through three coupled Fabry-Pérot cavities

In Ref. [117], the transfer matrix method is applied to calculate an exact expression of the transmission t through three coupled Fabry-Pérot cavities:

$$t = T_1 T_2 T_3 T_4 \left/ \left| e^{i(-\phi_1 - \phi_2 - \phi_3)} + \sqrt{R_1 R_2} e^{i(\phi_1 - \phi_2 - \phi_3)} \right. \right. \quad (1)$$

$$+ \sqrt{R_2 R_3} e^{i(-\phi_1 + \phi_2 - \phi_3)} \quad (2)$$

$$+ \sqrt{R_1 R_3} e^{i(\phi_1 + \phi_2 - \phi_3)} \quad (3)$$

$$+ \sqrt{R_3 R_4} e^{i(-\phi_1 - \phi_2 - \phi_3)} \quad (4)$$

$$+ \sqrt{R_1 R_2 R_3 R_4} e^{i(\phi_1 - \phi_2 + \phi_3)} \quad (5)$$

$$+ \sqrt{R_2 R_4} e^{i(-\phi_1 + \phi_2 + \phi_3)} \quad (6)$$

$$+ \left. \sqrt{R_1 R_4} e^{i(\phi_1 + \phi_2 + \phi_3)} \right|^2 \quad (7)$$

The notation used thereby is the same as in Fig. 6.7. The optical loss in the cavity are not taken into account in this equation, but it can be introduced easily by replacing the ϕ_j 's by $\phi_j + i\alpha_j$. The mirror losses are also neglected, so that $R_j + T_j = 1$. t can be also written as follows:

$$t = T_1 T_2 T_3 T_4 / D \quad (8)$$

with

$$D = 1 + R_1 R_2 + R_2 R_3 + R_1 R_3 + R_3 R_4 \quad (9)$$

$$+ R_1 R_2 R_3 R_4 + R_2 R_4 + R_1 R_4 \quad (10)$$

$$+ 2 \cos(2\phi_1) \sqrt{R_1 R_2} (1 + R_3 + R_3 R_4 + R_4) \quad (11)$$

$$+ 2 \cos(2\phi_2) \sqrt{R_1 R_2} (1 + R_1 + R_1 R_4 + R_4) \quad (12)$$

$$+ 2 \cos(2\phi_3) \sqrt{R_1 R_2} (1 + R_1 + R_1 R_4 + R_2) \quad (13)$$

$$+ 2 \cos(2\phi_1 + 2\phi_2) \sqrt{R_1 R_3} (1 + R_4) \quad (14)$$

$$+ 4 \cos(2\phi_1 + 2\phi_3) \sqrt{R_1 R_2 R_3 R_4} \quad (15)$$

$$+ 2 \cos(2\phi_2 + 2\phi_3) \sqrt{R_2 R_4} (1 + R_1) \quad (16)$$

$$+ 2 \cos(2\phi_1 - 2\phi_2) \sqrt{R_1 R_3 R_2} (1 + R_4) \quad (17)$$

$$+ 4 \cos(2\phi_1 - 2\phi_3) \sqrt{R_1 R_2 R_3 R_4} \quad (18)$$

$$+ 2 \cos(2\phi_2 - 2\phi_3) \sqrt{R_1 R_2} (1 + R_1) \quad (19)$$

$$+ 2 \cos(2\phi_2 - 2\phi_3 + 2\phi_3) \sqrt{R_1 R_4 R_2 R_3} \quad (20)$$

$$+ 2 \cos(2\phi_1 - 2\phi_2 - 2\phi_3) \sqrt{R_1 R_4 R_2} \quad (21)$$

$$+ 2 \cos(2\phi_1 + 2\phi_2 - 2\phi_3) \sqrt{R_1 R_4 R_3} \quad (22)$$

$$+ 2 \cos(2\phi_1 + 2\phi_2 + 2\phi_3) \sqrt{R_1 R_4} \quad (23)$$

$$(24)$$

Each term of this sum corresponds to the contribution of an internal cavity to the transmission spectrum. For example, the term 12 corresponds to cavity $\mathcal{C}1$, the term 15 to cavity $\mathcal{C}1 + \mathcal{C}2$ and the term 18 to the fictive cavity $\mathcal{C}1 - \mathcal{C}2$. In the case where the reflections R_j are small, some of these contributions become negligible. The preponderant contributions are those of cavities $\mathcal{C}1$ (12), $\mathcal{C}2$ (13), $\mathcal{C}3$ (14), $\mathcal{C}1 + \mathcal{C}2$ (15), $\mathcal{C}2 + \mathcal{C}3$ (17) and $\mathcal{C}1 + \mathcal{C}2 + \mathcal{C}3$ (24).

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