Chapter 1

Introduction

Optical interconnects and silicon photonics

Optical technologies constitute the core of long-haul communication. The large bandwidth and low propagation losses provided by fiber based optical communication systems make it possible to transport large amounts of information over long distances, for instance, between continents [1–3]. Beyond that, their superior performance is increasingly pushing the introduction of optical interconnects for communication over shorter ranges. In enterprise networks, for example, comprising distances up to a few kilometers, optical interconnects are deployed for applications requiring large bandwidth and propagation lenghts [3]. Furthermore, as bandwidth requirements increase and the miniaturization of integrated electronics advances, the performance of electrical interconnects decreases even at the very short ranges ($\lesssim 10\,\mathrm{m}$) of board-to-board, chip-to-chip and on-chip communication [3–11]. At these integration levels, too, optical interconnects have been proposed to overcome the expected limitations [3–11].

Within this context, silicon has attracted great attention as a promising platform for the implementation of the required photonic components, both, because of the maturity of the material processing already available from the electronics industry [12], and since it would allow a close integration of photonic and electronic functionalities, improving the overall system performance [3, 5, 13, 14].

The most fundamental components of an optical interconnect are a *light source*, which generates an optical signal onto which the information is coded by an *optical modulator*, furthermore, the *optical transmission system*, which transports the information from one location to the next, where the light finally hits an *optical detector,* which generates an electric signal and passes it on to further electronic components.

However, as the development of photonic technologies advances in the future, it is conceivable to achieve a higher system peformance through an increased level of complexity in the photonic functionality [14]. For instance, a higher integration density could be achieved through the deployment of wavelength division multiplexing (WDM) [10, 11], in the same way that the utilization of wavelength converters would potentially lead to an improved network performance [15, 16]. Furthermore, tunable optical delays are necessary for applications such as optical time division multiplexing (OTDM), and are indispensable as buffers in optical routers [17, 18].

A tunable control of the properties of light, for instance wavelength, wave vector and group velocity, can be realized by performing a time dependent modulation of the structure within which the light is confined, a process which is referred to as a dynamic modulation in the recent literature. The work presented in this thesis is aimed at the implementation of such dynamic effects, at the same time that it pursues the goal of developing an all-optical dynamic switching scheme that can be fully integrated on-chip. Because of their unique properties, photonic crystal devices, fabricated on silicon, provide the platform onto which these effects are realized. In the following, short introductions to dynamic effects and photonic crystals are given, as well as a description of the goals and of the outline of this thesis.

Dynamic photonic devices

There is a very simple and well-known example that allows an intuitive introduction to dynamic effects, namely a guitar [19]. When a guitar string is plucked, it oscillates and emits a tone at a given frequency spectrum; however, if a mechanical property of the string, say, the tension applied on it, is changed while it is still vibrating, the acoustic frequency it generates changes as well.

Similarly, in optics, the recent literature refers to a dynamically modulated photonic structure if its optical properties are changed *while* an optical signal is confined within it [16, 19–30]. Generally, the properties of the light that is enclosed in the dynamically controlled structure change, analogously to the change of acoustic frequency in the case of the guitar. Dynamic photonic devices have been deployed to demonstrate interesting effects such as optical wavelength conversion and tunable optical delays [16, 31], both in structures of dimensions as small as 6 µm and 40 µm, respectively.

The key requirement for the implementation of dynamic effects is an appropriate temporal modulation of the optical properties of the photonic structure. First, it has to be ensured that the modulation only starts once the optical signal has already entered the device, or, in other words, it must be turned on relatively delayed with respect to the arrival time of the optical signal. Second, after being switched on, it must have a rise time which is shorter than the lifetime of the optical signal, otherwise the signal will exit the device before the modulation has taken place. Both requirements can be fulfilled by an optically induced refractive index change, triggered by the linear absorption of a short optical switching pulse that is incident on the device from a direction perpendicular to the plane on which the structure resides. This method has been widely employed in the literature [16, 26, 27, 31–34].

One of the goals of this thesis is to integrate the optical switching pulse on the device plane, such that it copropagates in the same structure as the optical signal which is to be manipulated. This requires, first, a different mechanism of optically inducing a refractive index change, and, second, different propagation velocities for the switching and the signal pulses, such that the requirements on the temporal profile of the modulation can still be fulfilled, as will be explained in more detail in chapters 2 and 4.

A key feature of photonic crystal devices consists in that they provide the possibility of achieving different group velocities for the copropagating switching and signal pulses, which is the reason why they will be deployed in the frame of this thesis.

Photonic crystals

Photonic crystals are dielectric materials exhibiting a periodic dielectric function [35]. The solutions of Maxwell's equations in a photonic crystal are plane waves modulated by an amplitude that possesses the same periodicity as the dielectric function. These so-called Bloch modes can be classified according to their frequency ω and their wave vector k in a dispersion plot $\omega(k)$, which is also known as the band diagram. Photonic crystals and light constitute the optical analogue to atomic lattices and electron wave functions known from solid-state physics [35].

Depending on their periodicity, photonic crystals might exhibit frequency regions within which no optical modes are allowed, so-called band gap regions. Therefore, they open up the possibility of implementing reflecting components for frequencies lying within the band gap, in turn enabling the design of photonic crystal resonators and waveguides [35, 36].

Concerning the work presented here, two key characteristics of photonic crystal devices, especially of resonators and waveguides, are of uttermost importance. In the first place, they provide the possibility of controlling the frequency dependent propagation velocity of light by a careful design of geometry [36–38]. Consequently, it is possible to achieve different propagation velocities for the switching and signal pulses, paving the way for the on-chip integration of all-optical dynamic switching, as presented in chapters 4-5. Second, it is possible to tailor the frequency dependent modal distribution in photonic crystal waveguides, which permits the development of waveguide based tunable optical delays, as will be discussed in chapter 3.

Goals and outline of this thesis

The goals addressed in this thesis are:

- The development of a concept for performing dynamic switching. It is intended to trigger the switching by an optical control pulse, called the switching pulse, which is guided in the same device as the light signal which is to be dynamically manipulated. This mechanism will be referred to as all-optical on-chip dynamic switching, and will be deployed in order to realize different dynamic operations on an optical signal.

- The development of a theoretical concept for dynamically tunable optical time delays and dynamic light stopping in photonic crystal waveguides.

- The experimental demonstration of all-optical on-chip dynamic switching for frequency conversion of optical signals in photonic crystal cavities.

- The experimental demonstration of all-optical on-chip dynamic switching for frequency and wave vector conversion in photonic crystal waveguides.

- The development of a better understanding of the physical processes underlying dynamic effects, therefore providing powerful design rules for the dedicated engineering of photonic functionalities.

Chapter 2 introduces the basic concepts that are necessary for understanding the remaining chapters of this thesis. Here, a short introduction to the fundamentals of photonic crystals is given, as well as a description of the numerical simulation techniques that have been used in the course of this thesis in order to design photonic crystal devices. Finally, dynamic effects and their underlying physical mechanism are introduced, as well as the basic notions of the mathematical description widely employed in the literature. Special attention is paid to the fundamental aspects which are relevant for the concrete realization of the intended all-optical on-chip dynamic switching in silicon. The chapter finishes with a discussion about the limits of the conversion efficiency during dynamic processes, where a differentiation between resonator and waveguide based devices is made.

Chapter 3 presents a theoretical study on the possibility of performing dynamic light storage and tunable optical delays in a slow light photonic crystal waveguide. Compared to resonator based concepts, the presented approach features advantages concerning the conversion efficiency, and potentially offers practical advantages as compared to other waveguide based concepts previously discussed in the literature. Especially, the results of this chapter provide the more general insight that a spatially inhomogenous modulation constitutes a flexible tool for the dedicated engineering of optical funcionality.

Chapter 4 presents the first experimental demonstration of all-optical on-chip dynamic frequency conversion. First, a general switching concept is presented, which is subsequently implemented by employing a photonic crystal cavity. Experimental results are presented, and a detailed discussion on the measured conversion efficiency takes place.

Chapter 5 deals with the realization of all-optical on-chip dynamic switching in a slow light waveguide, following, too, the general switching concept developed in chapter 4. Here, it will be demonstrated that a simulaneous frequency and wave vector conversion is achieved, a process which is referred to as an indirect photonic transition. Remarkably, the results presented in this chapter provide new insights into the physical mechanism underlying dynamic effects.

Finally, chapter 6 summarizes the main results of this thesis, and, especially, highlights three versatile design rules, by means of which a variety of applications are rendered possible. This chapter discusses, too, the main challenges that have to be overcome.

Chapter 2

Background

Electromagnetic phenomena are described by Maxwell's equations, either in their differential or integral form [39]:

$$\nabla\mathbf{D} = \rho \qquad \int_S \mathbf{D}\, d\mathbf{S} = \int_V \rho\, dV \tag{2.1}$$

$$\nabla\mathbf{B} = 0 \qquad \int_S \mathbf{B}\, d\mathbf{S} = 0 \tag{2.2}$$

$$\nabla\times\mathbf{H} = \mathbf{J} + \frac{\partial\mathbf{D}}{\partial t} \qquad \int_C \mathbf{H}\, d\mathbf{l} = \int_A \left(\mathbf{J} + \frac{\partial\mathbf{D}}{\partial t}\right) d\mathbf{A} \tag{2.3}$$

$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t} \qquad \int_C \mathbf{E}\, d\mathbf{l} = -\int_A \frac{\partial\mathbf{B}}{\partial t}\, d\mathbf{A} \tag{2.4}$$

Here, V represents the volume enclosed by the surface S, and A is the open area enclosed by the path C. The relations between the fields $\mathbf{E}$ and $\mathbf{H}$ and their respective fluxes $\mathbf{D}$ and $\mathbf{B}$ are given by:

$$\mathbf{D} = \epsilon_0\epsilon\mathbf{E} \tag{2.5}$$

$$\mathbf{B} = \mu_0\mu\mathbf{H}, \tag{2.6}$$

where ϵ and μ are tensors, in the most general case.

The present chapter starts by introducing photonic crystals and by discussing their general properties, assuming, first, that the materials under consideration are linear and isotropic, such that the dielectric function $\epsilon(\mathbf{r})$ is scalar; further, it will be assumed that the relative magnetic permeability has the value $\mu = 1$. The material nonlinearity, which is of fundamental significance for the all-optical dynamic switching, will be taken into account later. Two photonic crystal components, which are of uttermost importance for the work presented in this thesis, are subsequently described, namely waveguides and resonators. The description of photonic crystals given in section 2.1 is based on reference [35], where a very detailed account can be found.

Given that photonic crystals are complex dielectric materials, numerical methods are necessary in order to find the solutions of Eq. 2.1-2.6. Therefore, a section of this chapter is dedicated to the introduction of numerical simulation tools that render it possible to precisely engineer the optical properties of photonic crystals. The final section deals with dynamic effects, presents an overview of the advances reported in the literature, and discusses specific aspects that are relevant for the achievement of the goals of this thesis.

2.1 Photonic crystals

2.1.1 Infinite photonic crystals

Photonic crystals are dielectric materials with a spatially periodic dielectric function $\epsilon(\mathbf{r})$, where the periodicity might exist along one, two or three dimensions [35]. In the absence of electric charges $\rho = 0$ and electric current densities $\mathbf{J} = 0$, together with the assumptions made above, Eqs. 2.1-2.6 can be rearranged to assume the form of an eigenvalue problem for the spatial distribution of the fields. In order to do so, time-harmonic solutions $\mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r})\, exp(-i\omega t)$ and $\mathbf{H}(\mathbf{r}, t) = \mathbf{H}(\mathbf{r})\, exp(-i\omega t)$ are inserted into Maxwell's equations, and the combined curl expressions result in the so-called master equation [35]:

$$\begin{aligned} \nabla \times \left(\frac{1}{\epsilon(\mathbf{r})} \nabla \times \mathbf{H}(\mathbf{r}) \right) &= \left(\frac{\omega}{c}\right)^2 \mathbf{H}(\mathbf{r}) \\ \hat{\Theta}\mathbf{H}(\mathbf{r}) &= \left(\frac{\omega}{c}\right)^2 \mathbf{H}(\mathbf{r}) \end{aligned} \tag{2.7}$$

Here, $c = 1/\sqrt{\epsilon_0 \mu_0}$ is the speed of light in vacuum. The solutions $\mathbf{H}(\mathbf{r})$ of the master equation 2.7 are therefore eigenvectors of the operator:

$$\hat{\Theta} = \nabla \times \left(\frac{1}{\epsilon(\mathbf{r})} \nabla \times \right), \tag{2.8}$$

with eigenvalues $(\omega/c)^2$. Additionally, a solution $\mathbf{H}(\mathbf{r})$ must obey the requirement that $\nabla\mathbf{H}(\mathbf{r}) = 0$, which results from Eq. 2.2.

By taking the symmetries of the system under consideration into account, it is possible to determine the form of the eigenvectors $\mathbf{H}(\mathbf{r})$ of $\hat{\Theta}$. If the system is invariant under a symmetry operation represented by the operator $\hat{T}$, then $\hat{T}$ and $\hat{\Theta}$ commute, and have the same eigenfunctions.

For instance, a photonic crystal possesses discrete translational symmetry, meaning that $\epsilon(\mathbf{r}) = \epsilon(\mathbf{r}+\mathbf{R})$. Here, $\mathbf{R} = \alpha\mathbf{a_1} + \beta\mathbf{a_2} + \gamma\mathbf{a_3}$ represents any lattice vector, $\mathbf{a_1}$, $\mathbf{a_2}$, $\mathbf{a_3}$ are the primitive lattice vectors and α, β, γ are integers. The eigenfunctions $\mathbf{H_k}$ of the operator $\hat{T}_{\mathbf{R}}$, which peforms the operation $\mathbf{r} \rightarrow \mathbf{r}+\mathbf{R}$, are planes waves modulated by a spatially periodic function $\mathbf{u_k}(\mathbf{r})$, which fulfills the condition that $\mathbf{u_k}(\mathbf{r}) = \mathbf{u_k}(\mathbf{r}+\mathbf{R})$ for any lattice vector $\mathbf{R}$. These solutions are called Bloch states [35]:

$$\mathbf{H_k}(\mathbf{r}) = \mathbf{u_k}(\mathbf{r})\, e^{i\mathbf{kr}} \tag{2.9}$$

As explained above, the solutions $\mathbf{H_k}$ are simultaneously eigenfunctions of the operator $\hat{\Theta}$, and can be classified according to their wave vector $\mathbf{k}$ and their frequency eigenvalue ω in a band diagram representation. Finally, two solutions $\mathbf{H_k}$ and $\mathbf{H_{k+G}}$ are the same if $\mathbf{G} = \alpha'\mathbf{b}_1 + \beta'\mathbf{b}_2 + \gamma'\mathbf{b}_3$ is a reciprocal lattice vector, where $\mathbf{b}_1$, $\mathbf{b}_2$, $\mathbf{b}_3$ are the primitive reciprocal lattice vectors, and α', β' and γ' are integers. This can be seen by noting that $\mathbf{H_k}$ and $\mathbf{H_{k+G}}$ are eigenfunctions of $\hat{T}_{\mathbf{R}}$ to the same eigenvalue, since:

$$\hat{T}_{\mathbf{R}}\mathbf{H_k}(\mathbf{r}) = \mathbf{u_k}(\mathbf{r}+\mathbf{R})\, e^{i\mathbf{kr}+i\mathbf{kR}} = e^{i\mathbf{kR}}\mathbf{H_k}(\mathbf{r})$$

and

$$\hat{T}_{\mathbf{R}}\mathbf{H_{k+G}}(\mathbf{r}) = \mathbf{u_{k+G}}(\mathbf{r}+\mathbf{R})\, e^{i(\mathbf{k+G})\mathbf{r}+i(\mathbf{k+G})\mathbf{R}} = e^{i\mathbf{kR}}\mathbf{H_{k+G}}(\mathbf{r})$$

Therefore, in order to obtain a complete band diagram representation, it is enough to find the frequency eigenvalues for all wave vectors $\mathbf{k}$ lying inside the first Brillouin zone, the latter being defined such that any wave vector $\mathbf{k}'$ lying outside it can be expressed as a sum $\mathbf{k}' = \mathbf{k}+\mathbf{G}$ of a wave vector $\mathbf{k}$ lying inside the first Brillouin zone and a reciprocal lattice vector $\mathbf{G}$.

An important property of the master equation 2.7 is its scale invariance [35]. For instance, if the spatial coordinate is scaled by a constant factor $\mathbf{r} = \mathbf{r}'/s$, the $x-$derivative scales as $\partial/\partial x = \partial/\partial x' \cdot \partial x'/\partial x = s\partial/\partial x'$, and analogously for y and

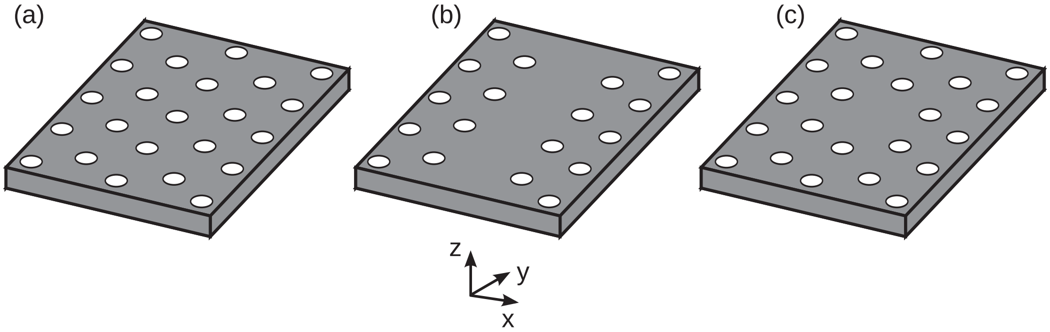

Figure 2.1: (a) A photonic crystal slab, consisting of a triangular lattice of air holes in silicon. The slab is periodic in the xy-plane, and possesses a finite extension in the z-direction. (b) Line defect and (c) point defect in a photonic crystal slab.

z. The master equation assumes the form:

$$\nabla' \times \left(\frac{1}{\epsilon\left(\mathbf{r}'/s\right)} \nabla' \times \mathbf{H}\left(\mathbf{r}'/s\right) \right) = \left(\frac{\omega/s}{c} \right)^2 \mathbf{H}\left(\mathbf{r}'/s\right) \tag{2.10}$$

This expression has the same form as Eq. 2.7, however contains a rescaled dielectric function, as well as rescaled field profiles and eigenfrequencies. In a similar way, two dielectric functions $\epsilon(\mathbf{r})$ and $\epsilon'(\mathbf{r}) = \epsilon(\mathbf{r})/s^2$, which differ only by an overall multiplier, lead to the same eigenfunctions, however, to a scaling of the eigenfrequencies as $\omega' = s\omega$.

2.1.2 Photonic crystal slabs

Photonic crystal slabs are periodic in two dimensions and have a finite spatial extent in the third direction, in contrast to two dimensional photonic crystals, which are infinitely extended in the direction of missing periodicity. The material surrounding the photonic crystal slab is called the cladding material, and has a refractive index of n_{clad}. A photonic crystal slab consisting of a triangular lattice of air holes in a dielectric slab is schematically shown in Fig. 2.1a.

The system under consideration, consisting of the photonic crystal slab and the cladding, possesses translational symmetry in the plane of periodicity of the photonic crystal. In the same way as for the case of three dimensional translational symmetry that was discussed in the previous section, the solutions of the master equation are now found to be plane waves with an in-plane wave vector $\mathbf{k}_{||}$, which are modulated by a function that is spatially periodic in the plane of periodicity of the photonic