1. Introduction

Optical fibers and waveguides are gradually substituting the metal wire connections [1]. They provide larger bandwidth at high interference immunity and lack of emission. As the data transmission rate is increasing the optical connection moves from long range to enterprise network [2] and it is even on the way to enter the domain of chip-to-chip and on-chip communication [3]. This trends strengthen the demand for miniaturization and integration of optical signal transmission components, which include waveguides, modulators, photodetectors, switches and Wavelength-Division-Multiplexing (WDM) elements. Many of these components are based on the phase properties of optical signals. Tunable phase shift is the basis for Mach-Zehnder interferometers, which constitute optical switches and modulators [4]. Tunable time delay is necessary for the optical buffering in routers and synchronization components [5], where an optical signal should be stored and released after a certain period of time. And the dispersion accumulated in the optical fiber should be compensated in dispersive elements with opposite sign of dispersion [1].

As will be shown in this thesis the small group velocity of light in certain structures can be used to dramatically decrease the size of phase shift, time delay, and dispersion compensation components. These structures, also called as slow light structures, have received a lot of attention in recent years [6][7][8][9][10][11]. Going in parallel with the development of Electromagnetically Induced Transperency (EIT) [12][13][14], the slow light structures demonstrate larger bandwidth [15] and proven microscale implementation [7][16][17]. The functional length of the optical components can be decreased proportional to the group velocity reduction. Thus, where conventional units require several centimeters long structures, the tenfold group velocity reduction decreases their lengths to millimeter length.

1.1 Photonic crystal line defect waveguides in SOI

Different slow light structures were presented recently including Bragg stack at the band edge [10], coupled cavity waveguides [18] and photonic crystal line-defect waveguides [6][7]. Every of the named structures has its advantages and disadvantages.

We discuss in this thesis the photonic crystal line-defect waveguides which demonstrate some superior properties. Photonic Crystals (PCs) are periodically structured dielectric materials with period in the range of the photon wavelength [19][20][21][22]. Line-defects in photonic crystals can guide light due to the photonic band gap effect [6][23][24], different to the conventional total internal reflection. The recent advantages in manufacturing techniques lead to substantial loss reduction in such waveguides to approximately 1dB/mm [16][25][26]. Since the slow light effect was first time demonstrated in line-defect waveguides by Notomi *et al*. [6] many publications appeared concerning different possible applications. They correspond to the areas named above: increased phase shift [17][27], large tunable time delays [7][8][15][28], large dispersion [29].

On the other hand, PC line-defect waveguides can be implemented in the Silicon-on-Insulator (SOI) system, which has many advantages. First of all, the index contrast of silicon to air is sufficient for a pronounced Photonic Band Gap (PBG) effect. In this PBG frequency range there is sufficient place for the line-defect modes with engineered dispersion relation. And the same index contrast in the vertical direction opens enough space below the light cone [30]. Secondly, the SOI system is compatible with conventional silicon chip manufacturing technology and allows simple integration of optical and electronic components on the same chip [31][32]. There are already successful examples of optical modulators [17][33], Raman lasers [34] and Wavelength Division Multiplexing (WDM) components [35] integrated in SOI. Slow light in SOI structure would be an important accomplishment of this technology [7].

1.2 Goals and outline of this thesis

1.2.1 Goals

The goal of this work is to investigate different aspects of small group velocity in PC line-defect waveguides. Based on various simulation approaches and theoretical approximations four major issues of slow light are considered:

- small group velocity with vanishing dispersion
- large second order dispersion
- coupling to small group velocity modes
- disorder induced losses

More specifically, the first goal was to understand the mechanism responsible for small group velocity in line-defect waveguides and the ways to control it. This understanding opens possibilities for the tunable phase shift and time delay. At the same time it is important to keep the second order dispersion low at small group velocity bandwidth. Otherwise the impulse distortion will deteriorate the small group velocity device performance. The aim for time delay was approximately 1 ns in a 1 mm long structure on a 100 GHz bandwidth. This requires the propagation velocity equal to 0.003 speed of light in vacuum.

The second goal was to investigate the possibilities for dispersion compensation in line-defect waveguides of millimeter length. The typical length between reproducers in the optical long distance network is 100 km. The dispersion accumulated in a 100 km fiber equals approximately to 2000 ps/nm. To compensate the effect of the fiber dispersion a compensator is required with -2000 ps/nm/mm dispersion. The same as for time delay device the higher order dispersion should be avoided. Two approaches are discussed in this thesis. The dispersion is caused by the different time delay of the adjacent wavelengths. This time delay difference can be achieved by different propagation velocity or different propagation length, which require modified dispersion relation or chirped structure correspondingly.

The third goal was to find an efficient coupling approach from strip dielectric waveguide into a slow light line-defect waveguide. The direct butt-coupling of such waveguides leads to extensive losses and reflections. Thus, a special mode converter should be designed, where the strip waveguide mode would be adjusted to the slow light mode.

The last goal of this thesis was aimed at the imperfection tolerance of the slow light structures. Inaccuracies, defects and boundary roughness in the PC structures due to imperfect manufacturing can lead to scattering losses of the propagating optical mode. The effect of this scattering on the transmission and time delay properties of the slow light waveguides was investigated.

All the above named goals should be fulfilled on the bandwidth of a single WDM channel of approximately 100 GHz (0.75 nm).

1.2.2 Outline

The slow light issues discussed in the previous paragraph will be presented in the following chapters:

In chapter 2, the background information about PC line-defect waveguides and their simulations is discussed. Line-defect waveguide parameters and dispersion relations are presented. Three simulation approaches are described: Transfer Matrix Method (TMM), Eigenmode Expansion Method (EEM), and Finite Integration Technique (FIT). This methods are presented with a self-written code for TMM, freeware CAvity Modeling FRamework (CAMFR) for EEM, and commercial software Microwave Studio (MWS) of CST for FIT method.

In chapter 3, the slow light line-defect waveguide is presented. An approach is discussed to achieve small group velocity with vanishing second and third order dispersion. An example of the waveguide is given with group velocity 0.02 speed of light on the bandwidth of approximately 1 THz. The group velocity reduction is explained through power flow redistribution.

In chapter 4, large second order dispersion is demonstrated near the anticrossing point in single and coupled line-defect waveguides. Theoretical estimations are given for maximal achievable dispersion. Quasi constant positive and negative dispersion is predicted in the order of 100ps/nm/mm on the bandwidth of 100GHz.

In chapter 5, an approach is developed to estimate the time delay of Bloch mode propagation in chirped periodical structures. The approach is demonstrated on high index contrast chirped Bragg mirrors and complex photonic crystal waveguide structures, including coupled waveguides and a slow light waveguide. It allows simple design of time delay and dispersion compensation waveguides in chirped PC structures.

In chapter 6, an approach is presented to couple light into a slow light mode of a PC line-defect waveguide. Two stage coupling is proposed, where strip waveguide mode is coupled to the "index guided" mode of the PC waveguide and the "index guided" mode is butt-coupled or adiabatically changed into a slow light mode. A comparison with one dimensional structure at the band edge is provided which demonstrates the advantage of the line-defect waveguides.

In chapter 7, characteristics of disordered Bragg stacks and line-defect waveguides are simulated. The backscattering effect on transmission and time delay is estimated. First, the reflection at a single defect is calculated and then the results are used to estimate reflection intensity in the disordered structure with statistical distribution of defects. The dependency of the backscattering intensity on the group velocity and disorder amplitude are investigated.

In chapter 8, the results of the previous chapters are summarized and the outlook for further investigations is given.

2. Background

The background information about PC line-defect waveguides and their simulations is presented. Three simulation approaches are described: Transfer Matrix Method (TMM), Eigenmode Expansion Method (EEM), and Finite Integration Technique (FIT). This methods are presented with a self-written code for TMM, freeware CAvity Modeling FRamework (CAMFR) for EEM, and commercial software Microwave Studio (MWS) of CST for FIT method.

2.1 Photonic crystal line-defect waveguides

Photonic crystal is a dielectric material or a set of different dielectric materials with periodical distribution of refractive index. An introduction to photonic crystal theory can be found in the book of Joannopoulos, Meade and Winn [36]. We will concentrate on the two dimensional triangular lattice photonic crystals with cylindrical air holes in silicon. The line-defect is obtained by leaving out a row of holes along the $\Gamma\mathrm{K}$ direction, which corresponds to the direction to the first nearest neighbor holes.

2.1.1 2D structure

The essential properties of the line-defect waveguide can be investigated on the 2D structure. In this case the third dimension is disregarded as if the photonic crystal is infinite in this direction. In Fig. 2.1 a schematic picture of a line defect is shown with one row of holes missing in the $\Gamma\mathrm{K}$ direction. Several parameters define the waveguide structure. Lattice constant a is equal to the distance between closest holes. W is the waveguide width, it is measured relative to a single row missing waveguide $W = a\sqrt{3}$. Radius of the holes is r. All the dimension parameters are usually normalized to the lattice constant. The structure can be scaled to operate at any required frequency by the adjustment of the lattice constant, as can be derived from scaling properties of Maxwell equations [36]. The refractive index of the silicon matrix is taken as 3.5.

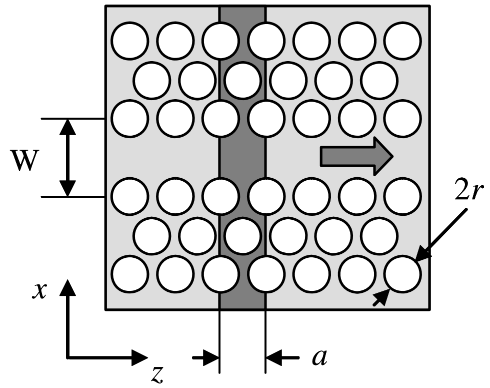

Fig. 2.1: Schematic picture of the W1 line-defect waveguide. A periodical unit is highlighted with dark grey color. The direction of mode propagation is shown with a grey arrow.

A triangular lattice of holes can have a complete band gap for light polarized in the plane of periodicity, which is usually defined as TE polarization. At this frequency range, called also as Photonic Band Gap (PBG), light is completely reflected and the photonic crystal behaves as an omnidirectional mirror. Thus line-defect waveguide effectively consist of two photonic crystal mirrors. If some modes can fit between these two mirrors then these modes propagate along the line-defect. The wider is the waveguide the larger is the number of guided modes. The dispersion relation of these modes can be found from an eigenmode problem, which can be defined for the periodical unit of the line-defect waveguide highlighted in the Fig. 2.1. Due to the Bloch theorem the electric field on the left and right side of this unit are related by the following equation:

$$\mathbf{E}(x, z + a) = \mathbf{E}(x, z)\,\mathbf{e}^{ika} \tag{2.1}$$

where k is the wavenumber. Applying different simulation approaches the eigenmodes can be found that fulfill the Maxwell equations and the Bloch boundary conditions. The eigenvalue of this problem is the frequency of the mode. Thus the dispersion relation can be obtained by scanning the eigenmode frequencies for different wave numbers. Such dispersion diagram, also called “band diagram”, is presented in Fig. 2.2a. The frequencies and wavenumbers are presented in normalized units. Thus the band diagram is in this case lattice constant independent.

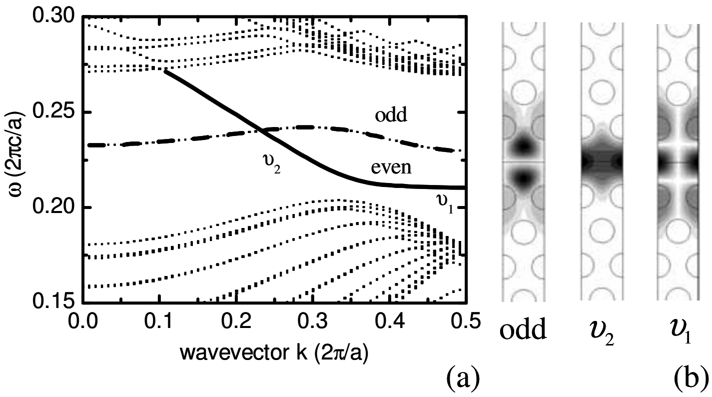

Fig. 2.2: (a) The band diagram of a 2D PC line-defect waveguide with one row of holes missing ($r = 0.3a$, W1, $n = 3.5$, TE polarization). (b) The amplitude of the magnetic field of mode υ_2, mode υ_1 and the odd mode (mode with a node on the line defining the lateral symmetry) are presented.

In Fig. 2.2 the modes of W1 waveguide are presented by thick lines. The radius of the holes is $r = 0.3a$, which is a typical value. Much larger holes are not possible due to the fact that the silicon walls between adjacent holes become to thin for lithography manufacturing. Thin dotted lines in Fig. 2.2a correspond to the modes outside PBG region, they are guided in the bulk PC and hence are not confined to the line defect. There are two continuous dispersion curves in the PBG region with different lateral symmetry of eigenmodes. The symmetry of eigenmodes is defined by its magnetic field in respect to the lateral plane in the waveguide center along z direction and normal to x direction (see Fig. 2.1). The amplitude of magnetic field is presented in Fig.2b. The odd mode has mode profile with a node in the middle of the line defect. The even mode has two different field distributions at the regions signed by υ_1 and υ_2. Though the line-defect modes are complicated they still remind the modes of a conventional dielectric waveguide, where υ_2 looks like a fundamental mode, odd mode looks like a first mode and υ_1 like a second mode. But due to the periodicity the modes are mixed and do not follow in the typical order.

The group velocity of the modes can be calculated as a dispersion relation derivative:

$$\upsilon_g = \frac{d\omega}{dk} \tag{2.2}$$

Thus the flatter the curve the smaller the group velocity. In the Fig. 2a the υ_1 region corresponds to a very flat dispersion curve with very small group velocity. The investigation of this mode will be done in chapter 3.