Chapter 1

Introduction and motivation

Lightwave technology has been the backbone of long-haul communication and Internet traffic for more than 20 years up to today. It offers enormous transmission capacity, distant repeater spacing, is non-emitting and immune to electromagnetic interference. It is the only technology capable of meeting the vast and exponentially increasing demands of global communication [1, 2]. Owing to the immense bandwidth of optical transmission links and growing data rate demand, which is difficult to meet with electrical links, lightwave systems begin to replace copper in intermediate and short distance communication as well. Fiber to the home [3] and gigabit ethernet local area networks (LAN) [4] based on optical fibers are examples of mature and readily available technologies.

For example, in 2009 Luxtera (www.luxtera.com) introduced a 40 gigabits per second (Gbps) active optical cable transceiver with available cable lengths of 1 to 4000 m for the application in LANs, storage area networks and high performance computing (rack-to-rack and board-to-board interconnects). Apart from the data rate advantage, optical fiber cables facilitate physical installation due to smaller cable diameter, bend radii and immunity to electromagnetic interference compared to copper based interconnects [5]. All these benefits make optical links attractive in a number of application in the near future, where data rates will exceed the 1 Gbps threshold such as:

- Ultra high definition displays and display arrays with e.g. 3072 by 2304 pixels, 60 Hz repetition rate and 24 bit color depth;

- Parallel data access to arrays of multiple solid state disks with more than 0.25 Gbps data rate per disc;

- Data transfer in medical imaging, full body three-dimensional (3D) computed tomography ($\approx$ 20 gigabyte for one process).

At even shorter link distances, namely chip-to-chip and on-chip (die-to-die) communication, optical data links are emerging as a necessary alternative to electrical links [6, 7, 8]. As postulated by Moore's law, the integration density (i.e. transistor density on a chip) has grown exponentially in the last 40 years and simultaneously the data processing capabilities within one chip. However, the electrical data input and output (I/O) does not scale accordingly and requires increased power, reduced range and more sophisticated signal processing to keep up with bandwidth demands [9]. To overcome the limitations of electrical chip I/O, the introduction of optical I/O structures on microchips is necessary. Major microelectronics companies such as Intel, IBM, and Sun Microsystems recognized the advantages of lightwave technology and entered the active research of integrating electronic circuits and components for optical I/O.

Research of integrated lightwave technology encompasses six main areas or building blocks. These include generating the light, selectively guiding and transporting it, encoding light, detecting light, and intelligently controlling all of these photonic functions.

The focus of this thesis is on electro-optic (EO) modulators, which are essential on the transmitter side of optical interconnects to encode the (electrical) information onto a stream of photons. They convert an electric signal to an optical signal by modulating amplitude, frequency or phase of the optical carrier wave. Of special interest for EO-modulation is the Pockels effect, this second order effect, fundamentally a three wave mixing process, connects a change in refractive index with an external electric field and requires a second order nonlinear polarization. The EO-modulators developed in the scope of this project combine the benefits of three kinds of optical media, namely photonic crystals (PhC), silicon and nonlinear optical (NLO) organic materials, all three will be introduced briefly in the following.

Photonic crystals

A photonic crystal is an optical medium with a spatially periodic variation of the dielectric constant. Consequently they are built from at least two different materials, which are structured on the wavelength scale of light. The interaction of an optical wave with a periodic medium leads to the emergence of a spectral band structure, similar to the electronic band structure found in crystalline solids [10, 11]. Choosing an appropriate dielectric lattice geometry creates forbidden frequency regions, called photonic bandgaps (PBG), in which the light wave cannot propagate [12]. This effect originates from destructive interference among the multiply scattered waves at the periodic dielectric boundaries. PhCs are interesting for integrated optical circuits, since the PBG effect allows to manipulate the propagation of light within a few lattice constants. Hence, they offer a high packing density, which is necessary for highly compact optical devices.

Two-dimensional (2D) PhC slabs are slab waveguides periodically structured in both in-plane directions. Consequently, the in-plane light propagation is governed by the band structure of the PhC and out-of-plane confinement is achieved by total internal reflection. These 2D PhC slabs have received considerable attention, because planar structures are relatively easy fabricated using current nano-patterning technology. By introducing point or line defects into the crystal lattice, resonant cavities or waveguides are formed respectively. Variations of the lattice geometry in the vicinity of these defects create virtually infinite degrees of freedom to manipulate the properties of the associated defect modes. For example PhC defect waveguides can be lattice engineered to have small group velocities with almost vanishing dispersion or extremely large (negative) dispersion [13]. Similarly PhC nanocavities have been shown to achieve quality factors exceeding 10^6, while the mode volume is only one cubic wavelength [14]. The resulting enhancement of the light and matter interaction may be exploited to increase the efficiency of NLO-processes. Here, the ability of PhC structures to form highly resonant cavities with a small geometrical footprint is applied to design highly efficient and compact EO-modulator devices.

Silicon photonics

Silicon is the standard material for highly integrated electrical circuits. At the same time it offers very attractive properties for integrated photonic circuits. These include a wide transparency window from near to mid infrared wavelengths. Its high refractive index ($n_{\mathrm{Si}} = 3.5$) at telecommunication wavelengths allows for waveguides with extremely tight bending radii and very compact components, while maintaining a moderate waveguide attenuation of 3 dB/cm [15]. The fabrication of silicon photonic circuits is fully compatible to the Complementary Metal Oxide Semiconductor (CMOS) process of microelectronic fabrication. The sum of these features offers the perspective of highly integrated photonic and electronic circuits on the same silicon chip in the near future [8, 16, 17, 18].

The crystal lattice of silicon is centrosymmetric and hence pristine silicon does not exhibit any $\chi^{(2)}$ nonlinearity, prohibiting EO-modulation. Research was very active in overcoming this limitation. Jacobsen and coworkers broke the centrosymmetry in silicon through strain induced on the atomic lattice and successfully demonstrated EO-activity [19]. However, the achieved Pockels coefficient was one order of magnitude lower than in the standard material used for EO-modulators today, Lithium Niobate (LiNbO_3).

Other approaches for electrically driven modulation of the optical properties of silicon based photonic devices rely on the refractive index change resulting from the modulation of carrier density in silicon either by carrier depletion, injection or accumulation [20, 21, 22]. The achievable modulation speed using these methods is limited by the time constants with which the carriers can be injected into or removed from the area of the optical mode, which is in the order of nanoseconds. However, through the use of reversed biased pn-diodes, modulators with a 3 dB bandwidth of 30 GHz have been demonstrated [20].

The approach to be followed in the present thesis utilizes the excellent linear properties for confining and guiding the optical mode of silicon and its mature fabrication platform. For EO-modulation, the silicon device is to be hybridized with a nonlinear optical organic material to overcome the speed limitations set by the free carrier plasma dispersion in silicon.

Nonlinear optical organic materials

Typical organic NLO-materials with second order hyperpolarizabilities are optical polymers that have been functionalized either by doping of chromophores into the polymer matrix (guest-host system) or covalently binding the chromophore to the polymer chain (side-chain or main-chain systems). These chromophores are molecules, which have a strong dipole moment and high hyperpolarizability, due to the electron donor-π charge transfer bridge acceptor (D-π-A) structure. The nonlinear effect originates solely from the probability density distributions of different interacting electronic states and is hence inherently ultra fast ($<$ ps), enabling modulation bandwidths in the THz range [23]. Through polar alignment of the dipoles in the polymer along a preferential direction, which means breaking the centrosymmetry of the matrix, the bulk material develops a strong second order nonlinear polarization, manifesting in a $\chi^{(2)}$ susceptibility. Due to their dipole character, the chromophores are oriented technically by a strong static electric poling field. This process is referred to as poling.

Molecular engineering has led to a significant increase in the microscopic hyperpolarizability of the chromophores, yielding NLO-organic materials with bulk Pockels coefficients exceeding 300 pm/V at telecommunication wavelengths [24, 25, 26, 27]. This value surpasses $LiNbO_3$ by one full order of magnitude. This is a very important aspect, as the required drive voltage for modulation is inversely proportional to the Pockels coefficient.

Optical organic materials are a well suited material for optical applications because these compounds can show very low optical waveguide losses in the near infrared regime around the telecommunication windows of 1.3 μm and 1.55 μm ($<$ 1.0 dB/cm) due to their amorphous structures and the low absorption of their constituents [28]. The refractive index of polymers is typically quite small ($n \approx 1.6$), which limits its light confinement abilities, mandating large bend radii of waveguides and hence restricts the integration of optical circuits on the chip level. However, in previous projects at this institute, it was demonstrated that polymer waveguide slabs can be a structured on the scale of nanometers to form two-dimensional photonic crystal slabs [29, 30].

NLO-polymers are typically applied on substrates by spin coating or, even simpler, drop casting from solution. The residual solvent is removed by baking the sample at an elevated temperature above the solvents boiling point. Depending on the solvent used, this is done in a range of 80 - 140°C. These features allow polymer materials to be integrated as a back-end process into the CMOS fabrication technology.

Objectives and outline of this thesis

The objective of this work is to develop concepts for EO-modulators, which meet the following requirements:

- operation at modulation frequencies in the microwave regime (> 10 GHz),
- low drive voltages (< 1 V), and
- ultra small geometrical footprint (on the scale of μm).

To fulfill the first two criteria organic NLO-materials are selected as the EO-functional medium, due to their inherently fast nonlinear response ($<$ ps) [23] and their ability to produce very high Pockels coefficients (> 300 pm/V) [26]. To comply with the requirement of a small geometrical footprint, the device design will focus on resonant PhC structures in silicon.

This thesis is structured as follows. In chapter 2, the theoretical background and fundamental concepts required for the results presented in the remainder of this thesis are revised. First, principles of second order NLO in organic materials are discussed and an introduction to the propagation of electromagnetic waves in media with periodically varying refractive index, photonic crystals, is given. Furthermore, physical mechanisms and effects of photonic cavities and resonant structures are reviewed. Finally, the simulation concepts used in this thesis are briefly introduced.

Chapter 3 analyzes possibilities to achieve full three-dimensional light confinement in resonant PhC slab structures (i.e. cavities) fabricated in NLO-polymers. Integrating the resonator structures completely into the NLO-polymer intrinsically leads to maximum field interaction with the NLO-material and hence ensures the largest possible spectral shift of the resonant frequency at a given amplitude of index modulation. Experimental evidence of an omnidirectional photonic band gap in low index contrast PhC is presented. However, the subsequent detailed theoretical study concludes that highly resonant structures with small geometric footprint are not attainable in material configurations with low refractive index contrast.

In the following chapters EO-modulator structures based on Silicon-on-Insulator (SOI) substrates, which have been electro-optically functionalized with second order NLO-organic materials are developed and experimentally validated. Chapter 4 focuses on the design of PhC nanocavities in hybrid silicon-organic materials and the optimization of the spectral properties to enable a maximum modulation sensitivity while minimizing optical losses.

In chapter 5, EO-modulation in hybrid silicon-organic PhC devices with up to 40 GHz modulation bandwidth are experimentally demonstrated. The complete fabrication process with all relevant technological steps is explained. Issues of the high field poling process of second order nonlinear organic materials in narrow slot geometries are addressed. Finally, theoretical limitations of the proposed modulator concept are discussed.

Chapter 6 summarizes the results of the previous chapters and gives an outlook for further research.