POST-FABRICATION TRIMMING OF

SILICON-PHOTONIC DEVICES USING A

PHOTO-SENSITIVE UPPER CLADDING

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With a little help from my friends…

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<tr>
<td>C</td>
<td>Circumference</td>
</tr>
<tr>
<td>$CA_k[n]$</td>
<td>Corse approximation coefficients</td>
</tr>
<tr>
<td>$CD_n$</td>
<td>Detailed approximation coefficients</td>
</tr>
<tr>
<td>°C</td>
<td>Degrees Celsius</td>
</tr>
<tr>
<td>$C^\nu$</td>
<td>Continuous wavelet coefficient</td>
</tr>
<tr>
<td>c</td>
<td>Speed of light</td>
</tr>
<tr>
<td>$\vec{E}$</td>
<td>Electric field</td>
</tr>
<tr>
<td>$\vec{E}(x, y)$</td>
<td>Electric field transverse profile</td>
</tr>
<tr>
<td>g[n]</td>
<td>Low pass filter impulse response</td>
</tr>
<tr>
<td>$\vec{H}$</td>
<td>Magnetic field</td>
</tr>
<tr>
<td>$\vec{H}(x, y)$</td>
<td>Magnetic field transverse profile</td>
</tr>
<tr>
<td>$H(f)$</td>
<td>Frequency response</td>
</tr>
<tr>
<td>$H(z)$</td>
<td>Z domain response</td>
</tr>
<tr>
<td>$h(t)$</td>
<td>Impulse response</td>
</tr>
<tr>
<td>h[n]</td>
<td>High pass filter impulse response</td>
</tr>
<tr>
<td>$k_0$</td>
<td>Wave number</td>
</tr>
<tr>
<td>°K</td>
<td>Degrees Kelvin</td>
</tr>
<tr>
<td>$\Delta l$</td>
<td>Path length</td>
</tr>
<tr>
<td>n</td>
<td>Refractive index</td>
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</tbody>
</table>
\( n_{\text{even}} \) Even mode refractive index
\( n_{\text{eff}} \) Effective index
\( n_g \) Group index
\( n_{\text{odd}} \) Odd mode refractive index
Q Quality factor
\( r(\lambda) \) Fraction of power coupled to a device through port
\( S[n] \) Input signal to wavelet transform
\( S'[n] \) Reconstructed signal following wavelet processing
T Basic unit delay interval
V Mode number
\( z_m \) Zeros positions in Z-domain
\( z_p \) Poles positions in Z-domain
\( \beta(\omega) \) Propagation constant
\( \gamma \) Loss coefficient
\( \varepsilon \) Permittivity
\( \theta_a \) Incidence angle
\( \kappa \) Coupling coefficient
\( \Delta\kappa \) Coupling coefficient difference
\( \lambda_0 \) Wavelength in vacuum
\( \Delta\lambda \) Wavelength difference
\( \Lambda \)  Grating period

\( \mu \)  Permeability

\( \varphi \)  Phase an electro-magnetic wave

\( \Delta \varphi \)  Phase variation

\( \psi(t) \)  Mother wavelet function

\( \psi^{a,b}(t) \)  Daughter wavelet functions
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AFM</td>
<td>Atomic Force Microscope</td>
</tr>
<tr>
<td>AR</td>
<td>Auto Regressive</td>
</tr>
<tr>
<td>ARMA</td>
<td>Auto Regressive Moving Average</td>
</tr>
<tr>
<td>BOX</td>
<td>Buried Oxide</td>
</tr>
<tr>
<td>CCD</td>
<td>Coupled Charge Device</td>
</tr>
<tr>
<td>ChG</td>
<td>Chalcogenide Glass</td>
</tr>
<tr>
<td>CWT</td>
<td>Continuous Wavelet Transform</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>DWT</td>
<td>Digital Wavelet Transform</td>
</tr>
<tr>
<td>DTFT</td>
<td>Discrete Time Fourier Transform</td>
</tr>
<tr>
<td>EBL</td>
<td>Electron Beam Lithography</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fiber Amplifier</td>
</tr>
<tr>
<td>EM</td>
<td>Electro Magnetic</td>
</tr>
<tr>
<td>ER</td>
<td>Extinction Ratio</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FIB</td>
<td>Focus Ion Beam</td>
</tr>
<tr>
<td>FSR</td>
<td>Free Spectral Range</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>HPF</td>
<td>High Pass Filter</td>
</tr>
<tr>
<td>ICP</td>
<td>Inductive Coupled Plasma</td>
</tr>
<tr>
<td>ICWT</td>
<td>Inverse Continuous Wavelet</td>
</tr>
<tr>
<td>IDWT</td>
<td>Inverse Discrete Wavelet Transform</td>
</tr>
<tr>
<td>IIR</td>
<td>Infinite Impulse Response</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-Red</td>
</tr>
<tr>
<td>IWPD</td>
<td>Inverse Wavelet Packet Decomposition</td>
</tr>
<tr>
<td>LPF</td>
<td>Low Pass Filter</td>
</tr>
<tr>
<td>LTI</td>
<td>Linear Time Invariant</td>
</tr>
<tr>
<td>MA</td>
<td>Moving Average</td>
</tr>
<tr>
<td>MMI</td>
<td>Multi Mode Interference</td>
</tr>
<tr>
<td>MZI</td>
<td>Mach Zehnder Interferometer</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>O-OFDM</td>
<td>Optical Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>O-OWDM</td>
<td>Optical Orthogonal Wavelet Division Multiplexing</td>
</tr>
<tr>
<td>OVA</td>
<td>Optical Vector Analyzer</td>
</tr>
<tr>
<td>PIC</td>
<td>Photonic Integrated Circuit</td>
</tr>
<tr>
<td>QMF</td>
<td>Quadrature Mirror Filter</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
</tr>
<tr>
<td>RIU</td>
<td>Refractive Index Units</td>
</tr>
<tr>
<td>RPM</td>
<td>Rounds per Minute</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon on Insulator</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse Electric</td>
</tr>
<tr>
<td>Tg</td>
<td>Glass Temperature</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse Magnetic</td>
</tr>
<tr>
<td>TPA</td>
<td>Two Photon Absorption</td>
</tr>
<tr>
<td>UV</td>
<td>Ultra Violet</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
</tr>
<tr>
<td>WP</td>
<td>Wavelet Packet</td>
</tr>
</tbody>
</table>
WPD  Wavelet Packet Decomposition
List of Publications

Journal papers:


Conference papers:


5. R. Califa, H. Genish, D. Munk, I. Bakish, M. Rosenbluh, and A. Zadok, Bar Ilan University. “Photo induced trimming of chalcogenide on silicon photonic integrated circuits”, Proceedings of IEEE, Conference on Optical MEMS and
Nano-Photonics (OMN 2015), Jerusalem, Israel, August 2015 (to appear in IEEE Xplore).


Book chapters:

Abstract

Recent years have witnessed intensive efforts to promote the technology of photonic integrated circuits (PICs), in attempt to realize complete optical communication systems on a single silicon on insulator (SOI) chip. PICs can be incorporated in future high bandwidth optical communication networks, in microwave photonics, in all-optical signal processing, and in photonic sensors for various quantities. The maturity of nano-electronic devices on the SOI platform, the potential of integration alongside electronic integrated circuits, and several favorable optical properties make SOI the material of choice for the implementation of PICs. The main drawbacks of SOI from photonics standpoint are the indirect bandgap and absence of numerous nonlinear optical effects, due to the crystalline symmetry of silicon.

The design of the transfer function of PICs requires control of the optical path lengths along individual cm-long waveguides, with tens of nanometers precision. Such accuracy can seldom be reached in open-loop fabrication processes. Instead, post-fabrication trimming of waveguides lengths is often required. Tuning of the refractive index of silicon can be done in both active and passive methods. Active solutions include local heating based on the thermo-optic effect of the silicon, or carrier injection into p-i-n junctions. These methods are reconfigurable and achieve accurate phase changes, but require constant, closed-loop feedback and make the fabrication and operation of otherwise passive devices considerably more complicated.

Passive methods, on the other hand, can provide one-time, permanent trimming of device response. Many passive techniques use photo-sensitive materials as an upper cladding on top of SOI devices, such as polymer layers, however the
long-term stability of these layers is often unsatisfactory. Other methods use cumbersome mechanisms such as accurate etching of cladding layers or electron beam-induced stresses. In addition, nearly all previous methods are restricted to the modifications of phase delays along waveguides, and do not address group delay variations or the power splitting ratios of couplers.

The main objective of this research was the development of simple, rapid, accurate, sensitive and stable procedures for the permanent post-fabrication trimming of SOI devices, taking into account all necessary variables of the photonic circuit. The solution path is based on a new hybrid platform, involving an upper cladding of chalcogenide glass such as As$_2$Se$_3$ or As$_2$S$_3$ on top of SOI structures.

Chalcogenide glasses have drawn increased attention in photonic device research due to their high refractive indices, broad transparency windows, pronounced nonlinearities, and photo-sensitivity effects. Photo-induced refractive index changes (photo-darkening) are used in direct laser-beam lithography of planar light-guide circuits in chalcogenide glasses, and in trimming the response of such devices. The illumination of chalcogenide glasses with focused laser beams can also induce a mass-transfer effect: absorption raises the temperature of illuminated regions above the glass transition value, and the temperature gradient initiates a fast lateral flow of the liquid layer from hot to cold regions.

In this work I theoretically analyzed the photo-darkening effect in cladding index modifications, and the mass-transfer effect in the selective photo-removal of the cladding from above the cores of underlying SOI waveguides. Both effects can be used in the post-fabrication trimming of elementary devices. The trimming of several Si-photonic devices using the mass transfer effect was experimentally demonstrated. First, phase and group delay modifications are demonstrated within Mach-Zehnder
interferometers (MZIs). Group index modifications by as much as 2% are achieved in SOI ridge waveguides. Analysis shows that considerably larger variations may be achieved in fully-etched, rectangular silicon nano-wire waveguides.

Second, the modifications of the power splitting ratios of directional couplers are demonstrated in tuning the transfer functions of SOI race-track resonators. The extinction ratios of individual resonances are arbitrarily adjusted between 4- 40 dB. These variations correspond to changing the coupling coefficient per unit length of the directional coupler by 10%. Here too, use of fully-etched nano-wires is expected to enhance the changes in coupling coefficient, up to 45%. Lastly, the tuning platform was employed in adjusting the response of cascaded MZIs 1x4 and 1x8 channel demultiplexers. The response of tuned devices remains stable following three months of storage.

This dissertation is organized as follows: A general introduction to silicon photonics, basic components and fabrication limitations is given in Chapter 1. Relevant literature on currently-available trimming methods is addressed. Background on chalcogenide glasses and their photo-sensitivity mechanisms is provided in Chapter 2. Chapters 3 and 4 describe the fabrication processes and the laboratory setups used throughout this work. Simulation and experimental results for the tuning of phase delay, group delay, coupling ratios and cascaded devices are described at length in Chapters 5, 6 and 7. Chapter 8 gives a theoretical analysis of a specific potential application of precisely-adjusted cascaded MZIs, such as those reported in this work, in the all-optical realization of the wavelet-packet decomposition. Concluding discussion and perspectives are provided in Chapter 9.
1 Introduction

1.1 Integrated photonics on silicon: why and where

1.1.1 The need for integrated optics

Since the invention of optical fiber communication in the 70's, optical fibers have become the world standard for delivering vast amounts of information over long distances. In those long-haul (80 to 10,000 km) and metro (20 to 80 km) networks, the bulk of the cost is related to the optical link (fiber deployment and amplifiers), which is much higher than the cost of the transceivers. Hence, main efforts in these long-reach networks are focused on increasing performance in terms of higher spectral efficiency (in bit/s/Hz), and longer reach. In recent years, however, optical links are starting to replace copper wires in shorter distance communication as well, coming closer and closer to the home (Fiber to the Home)[1].

In addition, the Smartphone revolution boosted cloud services, such as Google, Facebook, Waze etc., hosted by huge data centers which become the central computation platforms used by many millions around the globe. Those data centers are facing the challenge of communicating massive amounts of data over ultra-short optical links between racks and server modules. For those short-range networks, the link becomes inexpensive and transceiver footprint, power consumption and fabrication simplicity play a major role in decreasing network cost [2]. These provide the main motivations for bringing down optical communication systems to the chip level, making them cheaper and more wildly used in personal devices [3].

Another important driving force for integrated photonics is "Moor's law" for the scaling of micro-electronics processing power. For more than 45 years, Moore's...
law was a main driving force for the electronics industry. This prediction of Gordon Moore stated that the number of transistors on a single mainstream chip would double itself every two years [4]. The number of transistors in a commercial microprocessor has grown exponentially from 2,300 in the first Intel 4004 (1971) to more than 5.5 billion in the 18-core Xeon Haswell-E5 (2015). While the desired computation bandwidth inside the processor and the necessary communication bandwidth to the outside world grow, engineers are struggling to transfer these outstanding amounts of electronic data over copper wires. Possible solutions rely on parallel processing based on numerous smaller units, involving optical interconnects within a single chip.

1.1.2 Silicon-on-insulator as a photonic material platform

The motivation for using silicon as the leading material for the implementation of photonic integrated circuits is driven by the mature semiconductor industry and the potential for close integration of photonics alongside electronics on the same material platform [5], [6]. Since the late 1990's the micro-electronics industry had shifted to the Si-on-Insulator (SOI) substrate as the primary material platform, in place of the conventional silicon substrate. This shift reduced parasitic devices capacitance, due to their isolation from bulk silicon, enabling performance improvement [7].

While fully adopted by the electronic industry, the SOI substrate also provides some important potential advantages for the implementation of photonic integrated circuits (PICs). On top of mature fabrication using available micro-electronics industry facilities, and higher integration with electronics, silicon also exhibits useful optical properties: a broad spectral window of low propagation losses, from 1.1 µm wavelength up to 7 µm; comparatively tight confinement of the optical mode due to the high index contrast between Si core and SiO₂ cladding; high threshold for optical
damage; high thermal conductivity; and high nonlinear index (Kerr effect), which is 100 times larger than that of silica.

Alongside these advantages, the SOI platform also suffers from several deficiencies from photonics standpoint. One of the major drawbacks is the indirect bandgap of silicon: the state of maximum energy in the valence band and the state of minimum energy of the conduction band are associated with very different electron momentum values. The amplification of light in semiconductor materials involves stimulated emission processes, which include the transition of an electron from the valence band to the conduction band, and the generation of an additional photon. The momentum mismatch in indirect bandgap semiconductors makes these stimulated transitions highly inefficient. Solutions include hybrid integration of direct-bandgap III-V layers on top of SOI [8][9], or flip-chip bonding of external laser diodes.

Another significant drawback of silicon is the lack of second order nonlinearities such as the Pockels effect, which is underlying electro-optic modulation in LiNbO₃, for example [10]. The Pockels effect is practically instantaneous. Instead, silicon-based modulators rely on the free-carrier dispersion effects, which are inherently slower. Nevertheless, state-of-the-art silicon modulators reach tens of GHz rates [11]. The large thermo-optic coefficient of silicon [12], which is useful in sensors applications, leads to undesired temperature variations of device transfer functions. The high index contrast between silicon and silica, while providing tight confinement, also gives rise to losses due to scattering at rough interfaces.

1.2 Passive optical devices and filters in silicon

The SOI platform is being used in the realization of many passive and active photonic devices, including modulators [13], Si-Ge detectors for optical communication wavelengths [14], hybrid III-V on SOI light sources, and complex
optical filters [15], [16], all of which can be incorporated into communication links as well as other applications. In this work I focus on our efforts towards silicon-photonic integrated passive optical filters. These filters are used in the wavelength-division multiplexing (WDM) and de-multiplexing of communication channels [16], [17], sensor application [18], [19], radio-frequency (RF) photonics [20], and on-chip signal processing [21] (see figure 1).

**Figure 1. Applications of integrated photonic filters** [16–22]

**1.2.1 Si-photonic basic building blocks**

The most fundamental building block of any photonic integrated circuit is the optical waveguide. The waveguide's primary role is the transmission of light between two separate points in the optical circuit. Standard waveguides rely on the confinement of light in a core region of high refractive index, surrounded by lower index material (cladding). The electric and magnetic fields of a wave with an optical
frequency $\omega$, propagating in the positive $z$ direction with a propagation constant $\beta$, can be described by the following equation:

$$
\vec{E}(x, y, z, t) = E(x, y) \exp[j \omega t - j \beta(\omega) z] \\
\vec{H}(x, y, z, t) = H(x, y) \exp[j \omega t - j \beta(\omega) z]
$$

Here and elsewhere overhanging arrows denote vectors, and an overhanging tilde sign denotes a variable that is changing in time at optical frequencies. $E, H$ denote electric and magnetic fields, respectively. One significant property of a mode propagating in a waveguide is that the $z$ dependence of the field is only in the accumulation of phase, while the transverse profile $\vec{E}(x, y)$ does not vary with propagation (more on that later). Both profile and propagation constant are, in general, wavelength-dependent.

The complete description of the electromagnetic wave propagating along the structure is given by the solutions of the wave equation, including the boundary conditions defined by the waveguide structure geometry:

$$
\nabla^2 \vec{E} + n^2 k_0^2 \vec{E} = 0,
$$

Here $n$ denotes the refractive index as a function of position and $k_0 = \omega / c$. The wave equation is a representation of Maxwell's equations in dielectric media.

Let us consider first a slab waveguide geometry, which is infinite in both the propagation direction $z$ as well as in the $y$ direction (figure 2).
In this case all derivatives with respect to $y$ vanish, and the transverse profiles of propagating modes are functions of $x$ only. The pair of vector wave equations can be separated in two independent sets of scalar relations:

$$\begin{align*}
\text{TE} & \quad \begin{cases}
H_x &= -\frac{\beta}{\mu \omega} E_y \\
H_z &= -j \frac{1}{\mu \omega} \frac{\partial}{\partial x} E_y
\end{cases} \\
\text{TM} & \quad \begin{cases}
E_x &= \frac{\beta}{\varepsilon \omega} H_y \\
E_z &= j \frac{1}{\varepsilon \omega} \frac{\partial}{\partial x} H_y
\end{cases}
\end{align*}$$

Equation (3) shows how $H_x, H_z$ are determined entirely by $E_y$. Hence, if $E_y$ is absent, the magnetic field is entirely in the $y$ direction, or transverse to the direction of propagation. Solutions of this category are therefore known as transverse-magnetic, or TM modes. Similarly, transverse-electric (TE) modes are those for which
\( H_y \) vanishes, and consequently the electric field is entirely in the \( y \) direction. These definitions are summarized below:

\[
E_z = 0 \quad H_z \neq 0, \quad TE \\
H_z = 0 \quad E_z \neq 0, \quad TM
\]

The transverse profiles of TE modes, for example, may be solved using the following procedure:

- Solving the wave equation for the transverse profile of the scalar field component \( E_y(x) \). Solutions are either real or imaginary exponential functions of \( x \).
- Since we are interested in propagating mode that are guided within an inner core layer, the discussion is restricted to those mathematical solutions in which \( E_y(x) \) is oscillating within the core of index \( n_2 \), and exponentially decaying within upper and lower cladding regions of index \( n_1 < n_2 \). This condition restricts the possible values of the propagation constant: \( k_0 n_1 < \beta < k_0 n_2 \).

The obtained solution is of the form:

\[
E_y(x) = \begin{cases} 
A \sin((\sqrt{(n_2 k_0)^2 - \beta^2})x) + B \cos((\sqrt{(n_2 k_0)^2 - \beta^2})x) & \text{core} \\
C \exp(-(\sqrt{\beta^2 - (n_1 k_0)^2})x) & \text{clad} \\
D \exp(-(\sqrt{\beta^2 - (n_1 k_0)^2})x) & 
\end{cases}
\]

where \( A, B, C, D \) are constants. These in turn must be determined by the boundary conditions, which in the TE case require that both \( E_y \) and \( H_z \), (and hence \( \partial E_y / \partial x \)), are continuous across the two boundaries between the core and cladding layers. The obtained set of algebraic equations has a non-trivial solution only for a
discrete set of propagation constant values $\beta_{j}^{TE}$. Each propagation constant value completely defines the transverse profile of the field, and hence all properties of an individual mode. The effective index associated with a mode is defined by:

$$n_{j}^{\text{eff},TE} = \frac{\beta_{j}^{TE}}{k_{0}}$$

The number of modes is governed by the following parameter of the waveguide: $V = k_{0}d\sqrt{n_{2}^{2} - n_{1}^{2}}$, where $d$ is the thickness of the core layer. Most of the optical waveguides used in communications are single-mode: meaning that they support only a single TE and a single TM mode. Single-mode operation is advantageous since the propagation constants of different modes vary considerably (giving rise to modal dispersion). The condition for a single TE mode in a slab waveguide is simple: $V \leq \pi$.

Integrated photonic circuits require a compact and planar waveguide structure. The high index difference between silicon core (3.48 RIU at 1550 nm) and silica cladding materials (1.45 RIU) in SOI provides strong confinement of the optical mode in a sub-micron core region, allows for low loss over tight bending radii, and reduces footprint. On the other hand, the large index contrast results in higher losses due to scattering from sidewall roughness, and in stronger chromatic dispersion.

Structures which provide confinement in a single transverse dimension only are not of much use in integrated devices. Any input beam of finite extent in the $y$ direction is bound do diffrac while propagating in a slab waveguide. Practical devices employ two-dimensional cross-sections which provide refractive index confinement in both transverse dimensions.
Typical SOI wafers used in photonic devices fabrication have a 220 nm-thick device layer and a 2 μm-thick buried oxide layer (BOX), attached to a 750 μm-thick silicon handle layer. There are several widely employed geometrical designs for waveguide cross sections: the silicon nano-wire, which is a rectangular-shaped silicon waveguide with typically 500 nm width surrounded by air and a silica lower cladding; the ridge waveguide, which is generally wider (~700nm width) and only partially etched and provides lower scattering losses; and the slot waveguide which is a nano-wire with an etched trench in its center. The transverse modal profile in slot waveguides in concentrated in the low-index trench between the silicon regions to both its sides [5]. The three waveguide geometries are shown in figure 3, alongside numerical COMSOL Multi-Physics calculations of the transverse profiles of their fundamental modes.

![Figure 3. Three Si-photonics waveguides cross-sections: Ridge (left), rectangular (center) and slot (right).](image)

The second basic building block for the realization of integrated optical devices is the coupler. This common element serves as an optical power splitter or combiner with different ratios between adjacent waveguides in the photonic circuit. There are several types of couplers geometries, including directional couplers, Y junctions, and multi-mode interference (MMI) couplers. Discussion is restricted to the directional coupler structures used in this research. These consist of two separate
waveguide cores in close proximity. The joint cross section supports two fundamental modes: a symmetric and an anti-symmetric one, as shown in figure 4.

![Figure 4. Schematic illustration of a directional coupler (top) with the simulated transverse profiles of the even (bottom left) and odd (bottom right) optical modes. The effective indices of both modes are noted as well.](image)

Incident light from each of the cores is split between the symmetric and anti-symmetric modes of the joint structure, with equal-magnitude projections. The two hybrid modes are characterized by different propagation constants, leading to length-dependent interference between the two projections along the coupler, and to a periodic power transfer between the two cores [23], [24].

The transfer of the optical fields from both inputs to both output ports of a coupler comprised of two identical waveguides may be described by the transfer matrix notation of Equation (7):

$$
\begin{pmatrix}
E_{1}^{\text{out}} \\
E_{2}^{\text{out}}
\end{pmatrix} =
\begin{pmatrix}
\cos(\theta) & -j \sin(\theta) \\
-j \sin(\theta) & \cos(\theta)
\end{pmatrix}
\begin{pmatrix}
E_{1}^{\text{in}} \\
E_{2}^{\text{in}}
\end{pmatrix}, \quad \theta = \kappa z.
$$

$$n_{\text{eff}}^{\text{even}} = 2.3953 \quad n_{\text{eff}}^{\text{odd}} = 2.3849$$
Here $E_{1,2}^{in}$, $E_{1,2}^{out}$ are the input and output fields magnitudes in cores 1 and 2, and $\kappa$ is the coupling coefficient per unit length which may be calculated using a 2D numerical simulation for the even and odd modes [23]:

$$\kappa = \frac{\pi (n_{eff}^{even} - n_{eff}^{odd})}{\lambda_0}$$

(8)

If the separation between waveguide cores is comparatively large, so that the overlap between the modes of individual waveguides is small (a condition known as the weak coupling regime), it is possible to obtain an approximation for the coupling coefficient without solving for the compound structure. The coefficient is given by the overlap integral between the two modes, weighed over the spatial extent of one of the cores. For a coupler comprised of two identical waveguides:

$$\kappa = \frac{\omega \varepsilon_0}{4} \int \int E_1^* (x, y) \Delta n_{12}^2 (x, y) E_2 (x, y) dx dy$$

(9)

Here $\Delta n_{12}^2 = n_2^2 - n_1^2$ within a single core, and zero elsewhere.

Using these two elementary building blocks for the guiding and coupling of light, basic photonic filters may be realized, such Mach-Zehnder interferometers (MZIs) and ring resonators. Those basic filters, in turn, can be cascaded to achieve more complex functionalities.

1.2.2 The representation of digital filters in photonic structures

Integrated photonic filters perform a summation of delayed replicas of the input and/or output signals. In most cases of interest, all delays in the filter are integer multiples of a basic, unit interval $T$. In this respect, they are analogous to linear time-invariant (LTI) digital signal processing (DSP) filters. The transfer functions of such filters is best described in terms of the Z-transform, which is an extension of the
frequency variable $f$ in the discrete time Fourier transform (DTFT) to complex values $z$ as shown in equation (10):

$$H(f) = \sum_{n=-\infty}^{\infty} h(nT) \cdot e^{-j2\pi f (nT)} \Rightarrow H(z) = \sum_{n=-\infty}^{\infty} h(nT) z^{-n}$$

Here $h$ and $H$ denotes the time-domain impulse response and the Z-domain response of an LTI filter, respectively. The system frequency response is represented by the values of $H$ on the unit circle in the Z domain. It can be calculated form it's Z transform by simply placing $z = \exp(j2\pi f)$.

The output of an LTI digital filter can be expressed as a weighted sum of delayed inputs $x(kT)$ and delayed outputs $y(kT)$, where $k$ is an integer, through the difference equation (11):

$$y(nT) = \underbrace{b_0 x(nT) + b_1 x[(n-1)T] + \ldots + b_M x[(n-M)T]}_{\text{feedforward}} - \underbrace{a_1 y[(n-1)T] - \ldots - a_N y[(n-N)T]}_{\text{feedback}}$$

The corresponding Z-domain transfer function is a ratio of two polynomials, of the form shown in equation (12):

$$H(z) = \frac{\sum_{m=0}^{M} b_m \cdot z^{-m}}{\sum_{n=0}^{N} a_n \cdot z^{-n}} = \frac{\Gamma z^{-M} \prod_{m=1}^{M} (z-z_m)}{\prod_{n=1}^{N} (z-z_p)}$$

The values $z_m$ and $z_p$ in which the numerator and denominator vanish are known as 'zeros' and 'poles', respectively. The existence of poles represents feedback paths.

Digital filters can be classified into one of following categories [25]:
**FIR** – finite impulse response filters, also called moving average (MA) filters. These contain only zeros, and represent sums of weighted replicas of the input signal without feedback.

**IIR** – Infinite impulse response filters. These can be split further into two subcategories: filters that include only poles are known as auto-regressive (AR) filters, and those that include both zeros and poles and referred to as auto-regressive moving-average (ARMA) filters.

Use of the zeros-poles Z-transform representation can reveal some of the basic properties of filters. The zeros represent the points in the complex Z plane in which the transmission becomes zero. When the locations of zeros approach the unit circle, strong suppression of signals at specific frequencies is achieved. The poles are related to the feedback weights. Therefore, higher poles magnitudes (closer to unity) represent stronger feedbacks which result in a sharper frequency response. In the following I present the photonic realization of two fundamental FIR and IIR filters.

### 1.2.3 Single-stage finite-impulse-response filters

The photonic equivalent of a single-zero MA filter is the MZI. It consists of two couplers connected by unbalanced waveguides with a differential unit delay $\tau$, as shown in figure 5.

![Figure 5. Illustration of an integrated-photonic Mach-Zehnder interferometer](image)

$E_{1}^{\text{in}}$ $E_{2}^{\text{in}}$

$k_1$ $k_2$

$E_{1}^{\text{out}}$ $E_{2}^{\text{out}}$

$\tau = z^{-1}$
The Z-domain transfer function between the input and output ports of the MZI can be written by the following matrix equation (13) [25]:

\[
\Phi_{\text{MZI}} = \begin{bmatrix}
\frac{\kappa_1 \kappa_2 + \sqrt{(1-\kappa_1)(1-\kappa_2)} \cdot z^{-1}}{-j(\sqrt{1-\kappa_1} \sqrt{1-\kappa_2} + \sqrt{1-\kappa_1} \sqrt{1-\kappa_2} \cdot z^{-1})}
\frac{-j(\sqrt{1-\kappa_1} \sqrt{1-\kappa_2} + \sqrt{1-\kappa_1} \sqrt{1-\kappa_2} \cdot z^{-1})}{(1-\kappa_1)(1-\kappa_2) - \sqrt{\kappa_1 \kappa_2} \cdot z^{-1}}
\end{bmatrix}
\]

Here \( \kappa_{1,2} = \cos^2(\theta_{1,2}) \) are the power splitting ratios of the first and second couplers, respectively (see equations (7)). Propagation losses along the waveguides connecting the two couplers were neglected in Eq. (13) (see below). Figure 6 shows a simulated transmission spectrum of a SOI MZI with a 1 mm-long delay imbalance. Both couplers within the MZI have power splitting ratios of 50%.

![Simulated power transfer function of a silicon-photonic MZI with a differential path imbalance of 1 mm, and two couplers of 50% power splitting ratios.](image)

The extinction ratio of a device transfer function is defined as the difference in dB scale between maximum and minimum power transmission. This parameter quantifies, for example, how well certain wavelengths are blocked in a filter. The extinction ratio in a simple MZI depends on the amplitudes of the two interfering waves in the output port. When the incoming waves have equal amplitudes, large
extinction ratios are obtained as the two waves perfectly cancel out each other at when interfered destructively. Unequal amplitudes degrade the extinction ratio. The amplitudes at the output ports depend on both power splitting ratios in the directional couplers and on losses along the MZI optical paths.

In devices made with a short differential delay, and/or made of low-loss waveguides, propagation loss does not play a role and optimum extinction ratio is achieved with 50% couplers. Large propagation losses require that the splitting ratio of the first coupler is modified to launch more power into the longer, lossy arm of the MZI. The second, output coupler remains balanced at 50% ratio.

1.2.4 Single-stage infinite impulse response filters

The most basic IIR filter is an AR filter with a single-pole transfer function. A ring resonator with two couplers, as shown in figure 7, is a simple integrated photonic circuit realization of such an AR filter.

![Figure 7. Schematic illustration of an integrated-photonic ring resonator](image)

The through-port transfer function, from input 2 to output 2, is given by equation (14)[25]:

Where $\gamma$ is the field magnitude loss per round trip within the ring. Figure 8 shows a simulated transmission spectrum of a resonator 125 $\mu$m circumference, and a coupler tuned so that round trip losses are balanced by the coupling to the ring. (This condition is known as that of critical coupling, see more below). The propagation losses were 3.5 dB/cm, corresponding to $\kappa = 0.36$.

\[
H_{22}(z) = \frac{\sqrt{1 - \kappa_2} - \sqrt{1 - \kappa_1} \cdot \gamma z^{-1}}{1 - \sqrt{1 - \kappa_1} \cdot \gamma z^{-1}}
\]

Figure 8. Top - Simulated transfer function of an integrated-photonic ring resonator with a circumference of 125 $\mu$m. Bottom – magnified view of a single spectral transmission notch.
The transfer function of ring resonators is often quantified in terms of the following parameters:

**FSR**- Free Spectral Range: the wavelength separation between two adjacent peaks (or notches) in the transmission spectrum of the resonator. The FSR is determined by the propagation delay within the ring cavity, and is defined by [25]:

\[
FSR = \frac{\lambda_0^2}{2n_g \cdot l}.
\]

Here \( \lambda_0, n_g, l \) are the peak transmission wavelength, the group delay index along the resonator waveguide, and the cavity physical length.

**Critical coupling** – A specific value of the coupling coefficient into the ring, for which the transfer of power to the through port at resonance wavelengths is exactly zero. At critical coupling, the influx of electrical field into the ring through the input port is cancelled by the overall roundtrip losses. The numerator of Eq. (14) vanishes at this condition. For resonators with only a single input / output coupler ( \( \kappa_i = 0 \) ), critical coupling implies that \( \sqrt{1 - \kappa^2} = 0 \).

**Quality factor**- (Q factor) is a dimensionless parameter that describes the sharpness of spectral transmission (or rejection) bands [25]. A higher Q indicates a lower rate of energy loss within the cavity. High values of Q are also associated with narrow transmission notches: low losses suggest that light is allowed to propagate many times within the resonator, achieving better wavelength discrimination. High-Q resonators are therefore instrumental in filtering, sensing and signal-processing applications. The definitions for Q found in literature relates wavelength to bandwidth[26]:
where \( \Delta \lambda \) is the full width at half maximum (FWHM) of a spectral transmission feature.

**Finesse** - this quantity relates the FSR to the FWHM \( \Delta \lambda \) [26]:

\[
F = \frac{\text{FSR}}{\Delta \lambda} = \frac{\text{FSR} \cdot Q}{\lambda_0}
\]

The cascading of MZI and ring resonator basic filters gives rise to more complex transfer functions, containing multiple zeros and poles. Advanced algorithms for the synthesis of such complex filters in the Z domain appear in the literature [25]. Exact amplitudes and phases of zeros and poles locations determine the transfer function of complex filters. From the optical standpoint, changes to the optical properties of basic building blocks, such as phase accumulation along waveguides or splitting ratios of directional couplers, would modify the functionalities of filters entirely.

### 1.2.5 High-end Si photonics filters integration

In recent years, the outcome of research in Si-photonics technology is beginning to penetrate into industrial applications, while more advanced academic works continue to realize cascaded passive and active components with ever-increasing levels of complexity and integration on a single chip. In one example, a 4x10 Gbit/s transceiver was fabricated by Luxtera on a single chip platform, including flip-chip bonded lasers, Si MZI modulators, silicon WDM filters and Si-Ge photodetectors (figure 9,[27], [28]).
Figure 9. Luxtera 4x10 Gbit/s full transciever on single chip, using Si-photonics technology [27], [28].

In another example, Kotura demonstrated a VOA based on Si photonics technology and hardware aiming to a 100 Gbit/s WDM link on a chip, using Si-photonics technology [29], [30] (figure 10),

Figure 10. Kotura 100Gbit/s WDM transmitter and receiver modules, based on Si-photonics technology [29], [30].
The advances in fabrication methods of Si-photonics in recent years enable the realization of complex filter structures. For example, a ultra-compact, high-order photonic filter on silicon, containing five cascaded ring resonators, was developed by IBM research labs (figure 11, [31]). The multiple-pole structure provides strong out-of-band attenuation, a flat pass-band, and sharp spectral transitions. These filters are applicable to WDM channel multiplexing in all-optical inter-connects.

Figure 11. Left - SEM image of an ultra-compact, sharp photonic filter containing five cascaded ring resonators, fabricated by IBM labs [31]. Right – measured power transfer functions of devices with three and five cascaded rings.

1.3 Si-photonics fabrication tolerances

The transfer functions of all real-world photonic filters are susceptible to inaccuracies resulting from inevitable fabrication tolerances. Tolerances affect the waveguide cross section dimensions and the optical paths lengths. Small-scale cross section geometry inaccuracies, for example, modify the effective index of the waveguide and introduce random phase delay variations that accumulate over long waveguides.
The relations below are a result of COMSOL simulation showing the sensitivity of the effective index to variations of width $w$ or height $h$ of a silicon nano-wire of nominal width of 500 nm and height of 220 nm (see also figure 12).

\[
\begin{align*}
\frac{\partial n_{\text{eff}}}{\partial w} &= 2 \times 10^{-3} \quad \text{[1 nm]} \\
\frac{\partial n_{\text{eff}}}{\partial h} &= 4 \times 10^{-3} \quad \text{[1 nm]}
\end{align*}
\]

The above relations suggest that, for example, the control of resonance frequencies in a 1 mm-circumference ring resonator to 10 GHz precision requires a fabrication accuracy of 0.1 nm (1 Angstrom!) in core width and height. This tolerance is five times tighter than the lattice constant of silicon (0.54 nm), and is beyond the capability of state-of-the-art silicon fabrication technology. Therefore, some measures for the post-fabrication tuning of silicon-photonic devices are almost always required.

1.4 Overview of for post-fabrication device trimming

Procedures for trimming the transfer functions of silicon-photonic devices can be broadly classified in two categories: active dynamic tuning, and permanent post
fabrication trimming. Common active solutions rely on pre-patterned metallic heaters [32], [33], or on injection of free carriers into p-i-n junction structures [34].

Figure 13. Active post fabrication techniques; Localized heaters (right, [33]), and injection of carriers into p-i-n junctions (left, [34]).

As shown in figure 13, active tuning approaches add to the complexity of device fabrication, require continuous closed-loop feedback, and may also require continuous power consumption. One-time, permanent post-fabrication trimming is preferable when the device temperature is sufficiently stabilized.

Numerous mechanisms have been applied towards permanent post-fabrication trimming of PICs. Available methods include the irradiation of a pre-deposited upper cladding layer with intense ultra-violet or visible light, changing permanently its refractive index [35], [36]. This approach often relies on photo-sensitive polymers. In one example, UV-sensitive Polysilane was used as an upper cladding for the trimming of vertically coupled micro-ring resonator array (figure 14, [37]).
Figure 14. Trimming of the transfer function of a micro-ring array using the irradiation of an upper cladding layer of a UV-sensitive polymer [37].

In another example, photo-induced stresses and photo-elasticity were introduced by electron-beam irradiation of a silica over-layer, to modify the effective index of an underling Si waveguide (figure 15, [38]). Other methods include use of liquid crystals [39], patterning of a thin, upper silicon nitride film [40], and local oxidation of the surface of silicon [41].
Figure 15. Trimming the effective index of silicon waveguides by introducing stress to an upper silica cladding layer [38].

Recently, Canciamilla and coworkers have shown for the first time a transfer functions modification of chalcogenide glass (ChG) on SOI ring resonators through relatively low-power illumination of the upper cladding with near-bandgap light ([42], figure 16). The resultant photo-darkening of the upper cladding modified the effective index of the resonator waveguide by 0.016 RIU [42]. The chalcogenide-on-silicon platform is central to this research. It will be introduced in detail in the next chapter.
Figure 16. Trimming the response of a silicon-photonic ring resonator through illuminating an upper layer of chalcogenide glass [42].

Most previously reported methods employ relatively complicated setups or procedures, require a long process, or involve unstable organic polymer materials that degrade over time. In addition, most published works only deal with comparatively small phase delay modifications, whereas trimming of the group delay and directional couplers are not often addressed.

In this research I try to go beyond what was previously reported using the ChG-on-SOI material system. By applying a different photo-sensitivity mechanism in ChG, larger modifications of the effective index can be achieved. The proposed new method provides a fast, permanent trimming solution for all basic properties of the integrated-photonic building blocks: phase and group delays along individual waveguides and the power coupling ratios of directional couplers, all in a single, simple setup.
1.5 Research Objectives

The primary objective of the research program had been the development of a one-time, post fabrication trimming method for Si-photonics devices that is permanent, fast, accurate, and stable. The method would provide complete control over the locations of zeros and poles in the complex plane, through the modification of group delays, phase delays, and coupling ratios (figure 17).

![Figure 17. Illustrations of photo-induced trimming of the basic properties of ChG-on-SOI photonic filters. Orange-colored regions mark sections of the device in which a photo-sensitive ChG upper cladding is deposited on top of an underlying SOI waveguide.](image)

The proposed method is based on photo-induced modifications in various compositions of ChGs, which are used as an upper cladding on top of SOI photonic circuits. Fine tuning of phase delays is obtained through photo-darkening effects: modifications of the glass refractive index (for more see Chapter 2). Group delay and coupling ratios are altered through more drastic, structural modification mechanisms.

Primary research task included the following:

- Theoretical analysis and simulations of ChG-on-SOI devices, including waveguides in different geometries, MZIs, ring resonators and complex cascaded MZI filters.
• Evaluation of effective index, group index and coupling ratio variations that can be achieved using each trimming method.

• The establishment of an in-house fabrication procedure within the BIU clean-room facilities, and joint work with an industrial foundry (TowerJazz) for the fabrication of complex cascaded Si-photonic devices based on our designs.

• Design and assembly of optical trimming and characterization setups

• Experimental demonstration of the post-fabrication tuning of MZIs, ring resonators, and cascaded MZIs.
2 The chalcogenide glass on silicon photonic platform

2.1 What are chalcogenide glasses?

Glasses in general are non-crystalline solids which can be described as a separate discipline in solid state physics. Glasses can be divided into several different groups, among them we find the common oxide-based glasses, fluorides, metal-based glasses and chalcogenides [43]. Chalcogenide glasses (ChGs) contain one or more of the chalcogen elements from group 6a of the periodic table: sulfur, selenium or tellurium [44], [45]. The term "chalcogens" was derived from the Greek word chalcos, meaning "ore formers," since they are found as copper ores. Their compounds are referred to as "chalcogenides." The semi-conducting properties of the ChGs were discovered in 1955 by Kolomiets and Golunova from Ioffe Institute in Leningrad [45]. This discovery led to much research and many applications, such as in re-writable discs and non-volatile memory devices.

Many of the unique properties of ChGs result from chemical bonds that form amorphous networks among atomic constituents. Pure ChGs often exhibit ageing effects [46]. In order to avoid those drawbacks, additional elements are added to the glass matrix including Ge, Bi, As, etc. Such ChG compositions are characterized by a higher melting temperature and better stability [46]. Amorphous ChG films often consist of many single layers one on top of each other, each sheet containing the basic elements of the glass with the right stoichiometry, connected to each other by a network of covalent bonds as can be shown in figure 18.
In the last decades, the optical properties of ChGs have been extensively explored. Their compositions include heavy atoms, which lower their vibration energies and make them transparent in the infrared (IR) range: up to 11 µm wavelength for sulfur compounds, and up to 15 µm and even 20 µm in certain Se- and Te-based compounds, respectively. This intrinsic transparency window, which includes much of the molecular fingerprint region of 2 – 25 µm, makes ChGs attractive for use in IR spectroscopy, imaging and sensors [48].

In addition, densities of ChGs are higher than those of oxide glasses, and they exhibit strong polarizabilities and high linear refractive indices (up to 3.5 RIU). This also implies a large non-linear index, according to Miller's rule [49]. The high non-linear index is often accompanied by weak two-photon absorption (TPA) at telecommunication wavelengths, due to the broad transparency window. Chalcogenide glasses are therefore a favorable platform for nonlinear all-optical signal processing applications [50].

In recent years waveguides in a thin chalcogenide glass films gain popularity. A higher intensity (power per unit area) can be achieved in small core waveguides, better exploiting nonlinear effects. The thin ChG films are produced by thermal
evaporation [51], sputtering [52], chemical vapor deposition [53] and pulsed laser deposition [54]. Several methods had been demonstrated towards the patterning of rib or ridge waveguide profiles. In direct writing [55–58], for example, the illumination of As$_2$S$_3$ films at fluencies of around 100 J cm$^{-2}$ at 514 nm or 532 nm typically results in an index change of ~0.04 at 1550 nm. This index change is sufficient to inscribe single-mode waveguides with cores that are a few µm wide, but can be unstable when heated or exposed to intense irradiation.

Waveguide cores can also be defined based on lithography and etching. These might be susceptible to sidewall roughness-induced losses following the etching process, however extremely low losses had been achieved in a series of works by Madden and coauthors [59]. A third method involves the imprinting of the device structure into the ChG layer using a mold inside a furnace atmosphere. Low-loss waveguides and high-Q ring resonators had been reported using this technique [60].

2.2 Photo-induced effects in chalcogenide glasses

One of the most striking properties of ChGs is their photosensitivity: the changes in chemical bonds following the absorption of band-edge light [61]. Absorption creates electron-hole pairs and produces coordination defect states that are physically close to each other. The defect states might annihilate, returning to either the original bonding configuration or to a different one [61]. Such bond switching by illumination can result in macroscopic changes in the physical properties of the material, which manifest in a broad range of phenomena.

In general, photo-induced modifications observed in chalcogenide glasses can be classified into few groups and sub-groups[62]. The primary division distinguishes between effects that are directly related to light and those that are caused by the heating that is associated with absorption. Examples of the former include photo-
darkening [63], photo-induced anisotropy [64], photo-induced photoconductive changes [65], photo-induced fluidity and phot-induced structural changes [66], as well as vectorial effects such as photo-induced birefringence [67]. In processes of the latter category heat, generated through non-radiative recombination of photo-excited carriers, triggers structural changes. A widely known and employed example is the phase change between crystalline and amorphous states of ChG glasses, which is used in erasable optical memories [68]. In the following, a detailed description of the photo-darkening and mass-transfer structural changes effects is given, due to their significance in this research.

### 2.2.1 Photo-darkening

Among the photo-induced changes in ChG glasses, photo-darkening / photo-bleaching associated with a red / blue shifts of the fundamental absorption edge when illuminated with bandgap light is the most familiar phenomenon. In addition to changes in absorption, modifications to the index of refraction of the glass as a function of frequency also appear, as expected from the Kramers-Kronig relations [69–71]. These changes may be reversed partially or completely through a simple annealing process around the glass transition temperature [48]. The effect is pronounced in most As/Ge based ChG glasses compositions, to a varying degree [63]. The physical mechanisms responsible for the process are still under study. The photo-induced index changes are useful for the fabrication of optical structures in bulk glasses and in thin films [72–74] (see illustration in figure 19).
2.2.2 Photo-induced mass transfer

Photo-induced changes to ChGs can go beyond index modification. Illumination with an intense and focused beam may also lead to structural modifications, as illustrated in figure 20.

Mass-transfer effects occur due to viscous flow in the glass: absorption raises the temperature of illuminated regions above the glass transition temperature. This
temperature is related to the magnitude of cohesive forces within the glass network, which must be overcome to allow atom movements. The spatial gradient in temperature in the illuminated regions initiates a fast lateral flow of the liquid layer, from hot to cold regions [75]. This effect has been used in the fabrication of Bragg gratings using a laser interference pattern [75].

2.3 Chalcogenide glass as an upper cladding of silicon-photonic devices

Both photosensitivity mechanisms discussed above, photo-darkening and photo-induced mass transfer, can be applied to the post-fabrication trimming of Si-photonic integrated circuits. The idea is based on the interaction between the guided light in the silicon waveguide core and an upper ChG cladding. In most waveguide designs the majority of light is guided in the core area. However, a finite fraction of the modal profile penetrates into the cladding. Therefore, photo-induced modifications to the optical and structural properties of an upper cladding layer would cause a change in the effective index of the guided mode.

The two effects are complementary. Photo-darkening is applicable to fine-tuning of the effective index and control of phase delays, whereas mass-transfer and structural changes are suitable for more drastic variations, affecting group delays and coupling ratios. A different ChG composition is chosen for the implementation of each effect. As$_2$S$_3$ was selected for photo-darkening-based tuning, due to its large photo-induced index modifications of up to 0.1 RIU [76]. Mass-transfer was applied to As$_{10}$Se$_{90}$, since the dilution of As in the Se ChG matrix lowers the glass transition temperature (380 °K as opposed to 460 °K in As$_2$Se$_3$ [77], [78]), and results in weaker covalent bonds.
3 Fabrication procedures

This chapter is dedicated to the fabrication process of our ChG-on-SOI devices. The main phases of the process are described in figure 21 below.

![Process flow of chalcogenide glass-on-SOI devices.](image)

The detailed description of the process will be given in two main parts: fabrication of the basic SOI devices (section 3.1) and of the top ChG cladding (3.2). In addition, the packaging technique of our devices will be presented as well (3.3).

3.1 Si-Photonics device fabrication

Most of the Si-photonic devices in this research were fabricated using an in-house process, that had been developed by our group and collaborators in the BIU Nano-Technology Institute facilities. In the later stages of the study a collaboration with the industrial silicon fab Tower-Jazz enabled the design and fabrication of more complex cascaded photonic circuits. In the following a detailed description of the in-house fabrication process is given.
3.1.1 Wafer preparation

Our substrates are 8” SOI wafers manufactured by SOITEC company, based on their smart-cut patented technique [79]. The wafers are p-type, doped with Boron at $10^{15}$ cm$^{-3}$ concentration, with <100> cut. The wafers consist of a three layers: a 220 nm-thick top Si device layer, a 2-µm-thick buried oxide layer (BOX), and a 750 µm Si handle layer, as shown in figure 22.

![Schematic cross-section of the SOI wafers used in this work](image)

**Figure 22. Schematic cross-section of the SOI wafers used in this work**

The first step in the process is the dicing of the 8” wafer into 15x15 mm$^2$ dyes, enabling small-scale fabrication in a research environment. A 1 µm-thick optical resist protection layer was first spin-coated on the SOI wafer, and the wafer was then diced using a DAD3350 DISCO wafer dicer. Next, samples were cleaned in preparation for electron-beam (e-beam) lithography. As a rule, all cleaning procedures took place in a cleanroom atmosphere (in our case – the class 100 facilities of BIU Nano-Technology Institute).

Although a standard cleaning procedure (RCA) is commonly used by industry [80], we adapted a simpler cleaning approach which was found suitable. First, the dye
was immersed in acetone and inserted into a sonication chamber for five minutes (30 kHz and 30% power rate). Next, manual surface cleaning by a wipe stick was carried out to remove any residues from the protective resist. The process was then repeated with isopropanol as the solvent liquid, eliminating any evaporation residues from the chip surface.

3.1.2 Electron-beam lithography

The second phase in the process is electron-beam writing. In this stage a high-resolution, predesigned pattern is imprinted on a special polymer using a scanning electron beam. First a ZEP-520A e-beam resist from Zion was spin-coated on the SOI dye, using a Suss MicroTec Delta 6RC Spinner. The ZEP resist is characterized by a high sensitivity to the writing beam, and shows high resistance to plasma etching with a selectivity of (1:1) compared to that of Si. The etching of Si to a depth of 220-240 nm requires a 300 nm-thick resist layer. Based on the ZEP-520A datasheet, a spinning recipe at 4,000 rounds per minute (RPM) for 60 s was chosen, followed by a 3 min of baking on a hot plate at 180 °C.

The next step was the patterning of the waveguide geometry into the electron-beam resist using a high resolution e-beam lithography writer. In this work patterns were made using the CRESTEC 9000C EBL system. The writing parameters are summarized in table 1. The waveguide layouts were drawn by commercial ‘Adobe Sketchup’ drawing program (*.dx file), and converted into the dedicated CABEL software of the e-beam system. A minimal field length of 60 µm was chosen, to reduce discontinuities (stitching) that may occur when the e-beam motorized stage moves between adjacent fields in the writing process.
### Table 1. Summary of E-beam lithography parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field size</td>
<td>60 µm</td>
</tr>
<tr>
<td>Number of dots</td>
<td>20,000 dots per field length</td>
</tr>
<tr>
<td>Acceleration voltage</td>
<td>50 kV</td>
</tr>
<tr>
<td>Writing current</td>
<td>100 pA</td>
</tr>
<tr>
<td>Dose</td>
<td>$0.1\left[\frac{\mu \text{sec}}{\text{dot}}\right]$</td>
</tr>
<tr>
<td>ZEP-520A sensitivity</td>
<td>133 µC/cm$^2$</td>
</tr>
</tbody>
</table>

Following the writing process, a developer is applied in order to remove the resist from the irradiated areas. Development was done by immersing the sample in ZED developer for 35 s, following by 30 s in isopropanol that acts as a stopper, and drying the sample under nitrogen flow.

### 3.1.3 Reactive ion etching

In order to transfer the written pattern to the Si device layer, a dry plasma etching process is undertaken. In this stage a RIE-ICP VERSALINE machine by PLASMATHERM was used. To accurately etch thin Si layers with vertical sidewall patterns, a directional ion etching method and a dedicated Si slow-etch recipe were established and carefully calibrated. The process parameters are summarized in table 2. Following etching, resist leftovers are removed by immersing the dye in NMP striper for 5 min in a sonication chamber, followed by 1 min of immersion in deionized water that act as a stopper.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas pressure</td>
<td>37.5 µPa</td>
</tr>
<tr>
<td>SF₆ gas flow</td>
<td>65 ccm</td>
</tr>
<tr>
<td>CHF₈ gas flow</td>
<td>10 ccm</td>
</tr>
<tr>
<td>Chuck temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>RIE RF power</td>
<td>100 W</td>
</tr>
<tr>
<td>Si Etching rate</td>
<td>3.82 nm/s</td>
</tr>
</tbody>
</table>

Table 2. Summary of reactive ion etching recipe parameters

3.2 Fabrication of chalcogenide glass upper cladding

As mentioned in the previous chapter, two ChG compositions were used as top cladding layers on top of the Si waveguides: As₂S₃ for using the photo-darkening effect and As₁₀Se₉₀ for mass-transfer. The fabrication process of the ChG top cladding includes three stages, as described in the lower part of figure 17: Photolithography, ChG deposition and lift-off procedure.

3.2.1 SiO₂ buffer layer evaporation

The direct evaporation of both types of ChGs directly on the Si waveguides resulted in large excess transmission losses. The loss mechanism is not fully understood at this stage. We suspect that bubbles may be formed at the interface between glass and waveguide, or that charges remain trapped at the surface. This issue requires further investigation. Use of a thin SiO₂ buffer layer at the interface between the two materials was found to reduce losses dramatically, depending on its thickness. On the other hand, a thick buffer layer reduces the modal confinement to the upper cladding and compromises photo-induced changes to the effective index. An optimum thickness of 50 nm was chosen. SiO₂ was evaporated using an SBT ion-beam sputtering chamber system, at a vacuum of 9 µPa and a rate of 0.03 nm/s. To
improve the ChG confinement factor, higher-index buffer layers can be considered, such as Al₂O₃ (1.75 RIU), ZnO (1.93 RIU) or TiO₂ (2.4 RIU).

3.2.2 Photolithography

Small window regions in which the upper ChG cladding would be deposited are defined by photo-lithography. Since the photo-induced variations to the effective index are rather large, small ChG patches of few tens of microns lengths are usually sufficient for the necessary tuning. In the first step of this process stage, a suitable photo-resist is spin-coated onto the substrate. The selected optical resist should be at least 5 times thicker than the evaporated ChG layer. In our case, a 600 nm-thick ChG layer was applied, hence an AZ 4562 photoresist was deposited at 9 µm thickness. The spinning rate was 2500 RPM, followed by 1 min of soft bake at 110 °C.

The next step is photolithography exposure using a Suss MJB 4 mask aligner. Small patches of 100 × 100 µm² were exposed to UV radiation from a 193 nm wavelength source for 10 s. Following exposure, the sample was developed for 5 min in AZ 726 developer followed by 2 min immersion in deionized water used as a stopper. In the end of the process, open windows in the resist could be observed.

3.2.3 Thermal evaporation of chalcogenide glasses

We used the thermal evaporation technique for the deposition of the thin ChG layer. First, a precisely weighted solid piece of ChG, depending on the thickness needed, was placed in a metal boat used for boiling the ChG in the evaporation chamber. Then the boat was connected to a current source inside a vacuum chamber alongside a glass slide holding the SOI sample (figure 23). The evaporation process was performed at a vacuum of 0.3 µPa with an evaporation rate of 0.5 nm/s.
3.2.4 Lift-off

After the sample was covered with ChG, the final step of lift-off is performed. In this step the sample is immersed in acetone and inserted into a sonicator for 60 s, operating at 80 MHz frequency. The ultrasonic waves remove the resist and the overlaying ChG layer from above the entire sample except for the exposed windows. The results can be seen in figure 24.
3.3 Packaging

In case a sensitive phase calibration is needed, for example in cascaded filters where the relative phase between different elements should be adjusted, a careful close-loop trimming process is mandatory. Since the trimming procedure involves moving the chip using a motorized stage across a focused laser beam, a stable and semi-permanent connection between the chip and the input/output fibers is necessary. To that end the bonding of input and output fibers to the chip vertical grating couplers is preformed using a UV-cured optical adhesive. In the following a description of the process is given.

3.3.1 Fiber holders

A custom perspex mechanical holder was designed and fabricated. A SOLID WORKS schematic drawing of the holder is shown in figure 25.

Figure 25. Design of a perspex fiber holder used in the bonding of input and output fibers to devices under test.
The holder contains an 80° facet, designed for the optimal coupling angle of the vertical gratings (a detailed description of the grating is given in Chapter 4). The facet includes a V-grove slot for holding the fiber. Attachment of the cleaved bare fiber to the V-grove is performed by Norland 68 optical adhesive.

3.3.2 Attaching the holder to the chip

The attachment of the holders carrying the optical fibers to the chip was done for one port at a time, in the following manner: First we attached the perspex holder to a three-axis linear motorized stage using a custom-made arm. Next the UV-curable glue was applied to the bottom part of the holder where the attachment to the chip takes place. Next the fibers were positioned for maximum coupling of optical power into the device, and the holder was fixed by curing the glue with UV radiation lamp (figure 26).

![Figure 26. Attaching fibers to the chip using a UV-cured adhesive](image)

The connection of multiple fibers required a horseshoe-type holder, supporting a fiber bundle. The sample with attached fibers was then placed in a hard case, for safe transportation between different stages and benches (figure 27).
Figure 27. Image of a packaged SOI device.
4 Setups for the trimming and characterization of devices

4.1 Vertical coupling characterization setup

4.1.1 Vertical grating couplers

Coupling of light into a Si photonic chip is one of the initial challenges which need to be overcome in order to measure optical devices response. In the case of small-core devices, the straight-forward butt coupling between fiber tip and waveguide facet is difficult, and results in large losses due to modal mismatch even under optimal alignment (figure 28).

![Diagram of fiber-to-chip coupling problem](image)

**Figure 28. Illustration of the fiber-to-chip coupling problem: core size mismatch between a standard fiber and a silicon photonic waveguide.**

Coupling efficiency can be much improved using special coupler geometries, designed to expand the waveguide optical mode to match that of the input fiber, such
as expanded or inverse tapers [81], [82]. A different approach relies on grating structures, imprinted on the device surface, to couple an input beam at a specific angle to the waveguide core (figure 29). This method enables phase matching to a particular propagation constant within the waveguide, causing the excitation of a specific mode.

![Figure 29. Illustration of a vertical grating coupler](image)

Efficient coupling requires that the propagation constant component of the incident beam in the z direction matched the propagation constant of the waveguide mode (figure 30):

\[
\beta = k_z = k_0 n_3 \sin \theta_a
\]

Here \( k_0 n_3 \) is the wavenumber of the incident wave coming from a medium with refractive index \( n_3 \) (typically air), and \( \theta_a \) is the angle of incidence.
Figure 30. Phase index matching condition for an input light beam that is incident at an angle.

In the standard case the condition above cannot be met, since $\beta$ is by definition higher than $k_0 n_3$ (otherwise there is no guiding), and since $\sin(\theta_a) < 1$. A grating printed on the waveguide surface can compensate for the propagation constant mismatch. The grating represents modulation of the effective index of the waveguide with a period $\Lambda$. The grating allows for potentially efficient coupling for a set of propagation constants:

$$\beta_p = \beta - \frac{2\pi p}{\Lambda}$$

where $p$ is a positive or negative integer. Only negative diffraction orders may potentially lead to phase matching. Typically the grating is designed based on $p = -1$:

$$k_0 n_{eff} - \frac{2\pi}{\Lambda} = k_0 n_3 \sin \theta_a \Rightarrow \Lambda = \frac{2\pi}{k_0 (n_{eff} - n_3 \sin \theta_a)}$$
Using the parameters of the fundamental TE mode of our ridge waveguide ($n_{\text{eff}} = 2.75$ RIU), an incidence angle of $\theta_a = 10^\circ$ and a wavelength of 1550 nm, the necessary grating period was found to be $\Lambda = 600$ nm. Repeating the calculation for the fundamental TM mode ($n_{\text{eff}} = 1.7$ RIU), results in a grating period of $\Lambda = 1040$ nm.

4.1.2 Characterization setup

Our characterization setup is based on the vertical coupling method described above. The setup includes two three-axis motorized piezoelectric linear stages, driven by a hand-held controller. Input and output fibers were mounted on the stages at the designed angle, using a custom-made arm as shown in figure 31.

![Device characterization setup, including the coupling of light to/from standard fibers using vertical grating couplers.](image-url)
Standard, cleaved single mode fibers were used. The SOI dye under test was placed on a temperature-controlled stage, operated through a Labview software interface with 0.1 °C temperature stability (figure 31). Measurements began with finding the optimal alignment for maximum coupling, using the amplified spontaneous emission of an EDFA as a broadband input source and an ILX power meter at the output of the device. When maximum coupling efficiency had been reached, the input and output ports of the device were switched to the light source and receiver of a LUNA optical vector analyzer, respectively. The instrument was configured to measure the complex-valued, frequency-domain transfer function of the device under test across the entire C band (1529-1569 nm), with 0.02 nm spectral resolution. The laboratory setup is shown in figure 32.

Figure 32. Laboratory setup for device transfer function characterization
4.2 Passive Si-photonic devices characterization

4.2.1 Si waveguide

As mentioned in the introduction, the photonic waveguide is the most basic building block of any integrated circuit. Its characteristics directly affect the performance of the entire integrated circuit, hence special care must be taken in the design, fabrication and characterization process of the basic waveguide to obtain best quality. We based our design primarily on ridge waveguides, partially etched to a depth of 70 nm. Using this design, the guided optical mode is less exposed to roughness at the sidewalls, resulting in considerably lower propagation losses. On the other hand, ridge waveguides are more susceptible to bending losses.

![Image of Si ridge waveguide and FIB-processed cross section]

Figure 33. Top-view SEM image of Si ridge waveguide (left), and a SEM image of a FIB-processed cross section (right).

Figure 33 shows a scanning electron microscope (SEM) top-view image of a BIU-made waveguide, alongside a focused ion beam (FIB)-processed cross section showing basic structural dimensions. Figure 34 shows an atomic force microscope (AFM) surface scan analysis for the same waveguide.
Figure 34. Atomic force microscope scanning profiles of a silicon-photonic waveguide: Area scan (left) and line scan (right).

The coupling and propagation losses were characterized using a series of waveguides with various lengths. End-to-end losses for each of the waveguides were recorded. A graph showing the losses (in dB) vs. waveguide length (in mm) was plotted (figure 35).

Figure 35. Measured end-to-end losses of silicon-photonic ridge waveguides of different lengths.
A straight-line trend is observed in the results of figure 35, crossing the y axis at the -16 dB point. This value represents an estimated coupling loss of 8 dB for each vertical grating. The propagation losses per unit length are estimated based on the slope of the graph, as -3.1 dB/cm. An alternative method for the evaluation of waveguide propagation losses, based on the analysis of a ring resonator, is described in section 4.2.3. While the propagation and coupling losses fall short of those obtained in state-of-the-art facilities, or using specialized cross-sections [83], [84], they are nevertheless respectable and sufficient for the proof of the concept of this research.

Sidewall roughness is a main contributor to waveguide losses, hence the smoothing of the walls, using processes such as oxidation [85], may help improve losses considerably.

4.2.2 Mach-Zehnder interferometers (MZIs)

The next elements to be tested were Mach-Zehnder-Interferometer (MZI), comprised of two directional couplers with imbalanced delays [5]. The power transfer function of MZIs follows squared-cosine dependence, with periodic peaks and notches (see in introduction), due to constructive and destructive interference between the two paths. The extinction ratio between peaks and notches is determined by the splitting ratios of the couplers and loss imbalance between paths. When both couplers are balanced to 50%, and the MZI arms are sufficiently short so that differences between propagation losses are negligible, the interference extinction ratio at both outputs is ideally infinite. In the case of long differential delays of few mm or more, unbalanced couplers might be required to compensate for the loss imbalance.
Finding the exact design for 50% power splitting is not straightforward, due to fabrication tolerances in waveguides widths, etching depth, gap between cores etc. To that end, a parameter sweep is often implemented in a series of devices. In our experiments, using 700 nm-wide ridge waveguides with partial etch depth of 70 nm, the optimal extinction ratio was obtained with directional couplers that were 14 µm-long and had a 300 nm-wide gap separating the two cores. The power transfer function of a device with a path length imbalance of 1 mm is presented in figure 36. A FIB cross section of the coupler region is shown in figure 37.
Figure 37. A FIB cross-section of a directional coupler within a silicon-photonic MZI device.

The FSR of the MZI was measured as 0.66 nm. The group delay index \( n_g \) of the waveguide may be calculated based on the FSR:

\[
(22) \quad n_g = \frac{\lambda_0^2}{\text{FSR}_{\text{MZI}} \cdot \Delta l} = \frac{(1.55 \cdot 10^{-6})^2}{0.66 \cdot 10^{-9} \cdot 10^{-3}} = 3.64 \text{ RIU}
\]

Here \( \Delta l \) is the path length imbalance. This result agrees well with our simulations of ridge waveguides (see Chapter 5).

4.2.3 Ring resonators

The third basic building block designed and fabricated at this stage is the ring resonator. The resonators can be designed in few geometrical layouts, where the most popular are the circular and the race-track geometries. Attention must be given to the minimal bending radius within the ring, and to the coupling between the ring and bus waveguide. The gap between bus and ring resonator varies with position, whereas the gap between the bus and a race-track layout is fixed. Maximum extinction ratio is achieved at the condition of critical coupling (see Chapter 1, [5]), in which the coupling of light into the ring compensates perfectly for the round-trip propagation
losses. Here too, calibrations were made using a parameter sweep of the coupler geometry. Figure 38 shows the measured transfer function of a critically-coupled 125 μm circumference resonator. A SEM image of the fabricated device is shown in figure 39.

![Figure 38](image)

**Figure 38.** Measured power transfer function of a ring resonator with 125 μm circumference

![Figure 39](image)

**Figure 39.** Top-view SEM image of Si ring resonator
The Q factor of the resonator can be estimated based on the measured power transfer function [26]:

\[
Q_{\text{loaded}} = \frac{\Delta \lambda}{\lambda_0} = 61,000
\]

Q, in turn, can be used to obtain an estimate of propagation losses [86]:

\[
Q_{\text{int}} \equiv \frac{2Q_{\text{loaded}}}{1 + \sqrt{ER^2}} = \frac{122,000}{1 + \sqrt{1/25}} = 102,000
\]

\[
\alpha = \frac{2\pi n_g}{Q_{\text{int}} \lambda_0} = \frac{2\pi \cdot 3.6}{102,000 \cdot 1.53 \cdot 10^{-6}} = 6.2 \frac{dB}{cm}
\]

Here \( ER \) denotes extinction ratio of the power transfer function (14 dB in our case). Compared with the loss measurements of straight waveguides, higher propagation losses are found within the ring. These additional losses of 3 dB/cm are due to bending losses. Bending losses of photonic waveguides are highly dependent on the confinement of the modal profile to the core. For fully-etched silicon waveguides (where the confinement factor to the core is high), bending losses become significant only for radii below 5 µm [87]. When shallow ridge waveguides are used, the confinement factor decreases and limits the bending radii [88]. Bending loss is difficult to calculate analytically for arbitrary 2D waveguide geometries. Instead, numerical simulations for bending losses in our ridge waveguide geometry were made using FIMM WAVE commercial software (figure 40). Bending radii become significant for radii below 50 µm. The bending radius within the resonator under rest was about 20 µm. Therefore, the observation of additional losses within the characterized resonator is reasonable.
Figure 40. Numerical simulations of bending losses in an SOI ridge waveguide, calculated using FIMMWAVE commercial software.

4.3 Mass-transfer trimming setup

Response trimming based on selective photo-induced mass transfer of As$_{10}$Se$_{90}$ layers was carried out using a 532 nm laser source. The absorption of incident light at this wavelength, in this particular composition, was evaluated from spectroscopy measurements, seen in figure 41 below.
The transmission spectrum was measured for a 1.5 µm-thick ChG layer, evaporated on a microscope slide and compared with bare microscope slide used as a reference. Results show that the As$_{10}$Se$_{90}$ layer absorbs around 50% of the incident light at 532nm wavelength. The refractive index of the layer could be estimated based on the spectral periodicity and knowledge of layer thickness. A value of $n_{\text{As}_{10}\text{Se}_{90}} = 2.35\,[RIU]$ was found.

The photo-induced mass transfer setup included a LEICA LM table-top microscope, with a motorized stage ASI MS-2000. The setup also included a green laser source (COHERENT DPSS 532-100), as shown in figure 42. The laser was coupled into the ×50 microscope objective lens from an angled dichroic mirror. The laser power was 20 mW, focused to a spot-size diameter of ~1.5 µm. The illumination intensity was on the order of 1 MW/cm$^2$. 

Figure 41. Measured transmission spectra of As$_2$S$_3$ (magenta) and As$_{10}$Se$_{90}$ (red)
The device under test was attached to a microscope slide and mounted on a three-axis motorized stage. The sample was translated through the focused laser beam along a pre-defined path, using a Labview program. The scanning procedure controlled the translation rate and the number of repeating paths, as necessary. In case a precise closed-loop trimming was needed, input and output fibers were semi-permanently glued to the device to allow for the measurement of transmission spectrum during trimming (see Chapter 3). A special objective lens with a long working distance of 1.5 cm was used in these cases, to avoid obstruction by the fiber holders.
5 Phase and group index trimming

5.1 Motivation

One of the primary tasks carried out by PICs is the multiplexing and demultiplexing of high-bandwidth data channels. Multiplexing can be performed by silicon-photonic filters, comprised of a cascade of MZIs and ring resonators [25]. The proper function of such filters depends on precise phase and group delays of individual optical paths, which are difficult to achieve in open-loop fabrication [91]. Hence, procedures for the post-fabrication trimming of optical paths are mandatory. Most previous reports deal with phase delay modifications, whereas trimming of the group delay is not often addressed. Group delay modifications are required, for example, in the adjustment of FSRs among cascaded filters.

In this chapter, a theoretical background is given, including simulations of photo-induced phase and group index changes in SOI waveguides with ChG upper cladding. The analysis includes a comparison between two waveguide geometries and two trimming mechanisms: photo-darkening and mass-transfer, using the TE optical mode. The analysis shows that phase index trimming could be performed using both mechanisms, whereas group index changes require a more drastic intervention in the form of mass-transfer.

The second part of the chapter describes the experimental employment of the mass transfer mechanism in the post-fabrication tuning of SOI waveguides, changing both phase and group indices. Phase index changes were adjusted using a close-loop setup, in which the transfer function of a MZI was being monitored during its adjustment. In a second experiment, the group delay index in one arm of a MZI was
modified by 0.07 RIU, through selective photo-removal of the upper cladding. The FSR of the MZI was modified by 1%. The duration of the trimming process was only a few seconds.

5.2 Phase trimming principles and simulations

5.2.1 Phase trimming based on the photo-darkening mechanism

Trimming of SOI waveguides can be achieved through local photo-darkening of an upper ChG cladding layer. The laboratory setup used in the photo-darkening experiment (Chapter 4) consists on a femtosecond pulse laser with a central wavelength of 810 nm (E=1.53eV). As$\text{S}_2$S$\text{S}_3$ is transparent in that wavelength (bandgap of 2.4 eV), hence index modifications are induced by a two-photon process. The written change to the refractive index is permanent, and can be erased only by annealing: the exposure of the sample to 420 °K temperature for few hours [76]. The extent of refractive index change increases with illumination intensity (figure 43). Index variations saturate at about 0.08 RIU, for average intensities above 0.25 GW/cm$^2$. 
A tradeoff exists between tuning precision and the extent of index modifications. Large modal confinement in the upper cladding layer would give rise to larger changes in effective index, however small confinement would enable tighter control over the exact phase delays. Confinement is governed by the waveguide cross-section geometry. The significance of modal control is illustrated in numerical COMSOL multi-physics simulations of 700 nm-wide ridge waveguides, partially-etched to 70 nm depth, and of 500 nm-wide, fully-etched rib waveguides. Refractive index changes between 0-0.1 RIU in the upper As$_2$S$_3$ cladding were considered. Simulation was carried for the fundamental TE mode. The effective modal indices for both waveguides as a function of the photo-darkening-induced index changes are shown in figure 46. Simulations include a 50 nm-thick SiO$_2$ buffer layer between the Si and the ChG layers (see Chapter 3).

The slopes of the curves of figure 44 reveal the relative confinement of the modal profile in the upper cladding layer for both waveguide geometries. It is on the order of 8% and 20% for ridge and fully-etched waveguides, respectively. Table 3
summarized the effective index changes for maximum refractive index change (0.1 RIU) in the upper As$_2$S$_3$ layer, for the two geometries. Larger variations are anticipated for the fully-etched geometry, due to the larger confinement in the upper cladding. Simulations are in general agreement with previous results [42], in which an effective index modification of 0.016 RIU was reported using a 450 nm-wide fully etched waveguide.
Figure 44. Change in the effective index of waveguides as a function of the photo-darkening index change in an upper chalcogenide layer. Top – ridge waveguide. Bottom – fully-etched nano-wire.

<table>
<thead>
<tr>
<th>Waveguide Type</th>
<th>Polarization Type</th>
<th>$\Delta n_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ridge (w=700nm)</td>
<td>TE</td>
<td>0.0081</td>
</tr>
<tr>
<td>Fully etched (w=500nm)</td>
<td>TE</td>
<td>0.0196</td>
</tr>
</tbody>
</table>

Table 3. Simulations estimates to the maximum attainable changes to the modal effective index using photo-darkening.
As discussed in Chapter 3, a buffer layer of silica is used between the silicon waveguide core and the upper cladding layer. Figure 45 shows the simulated change in effective index of a fully-etched waveguide as a function of the buffer layer thickness. Photo-darkening of the upper layer by 0.1 RIU is assumed. The extent of effective index tuning decreases exponentially with the buffer layer thickness. The expected index change using a 50 nm-thick layer is about half of that anticipated with no buffer at all. The buffer layer is required, however, to mitigate losses at the interface.

![Graph showing effective index change vs. buffer layer thickness]

\[ Y = 0.033 \times \exp(-0.01X) \]

Figure 45. Calculated changes to the effective index of a fully-etched waveguide as a function of the thickness of a silica buffer layer. Photo-induced change to the index of the upper cladding layer by 0.1 RIU is assumed.

5.2.2 Phase trimming based on mass-transfer mechanism

Mass transfer was employed in the photo-removal of an upper cladding layer of \( \text{As}_{10}\text{Se}_{90} \). The lack of As in the glass matrix weakens the atomic bonds and lowers
the temperature of glass transition. The absorption of light above bandgap elevates the local temperature above the Tg value, leading to lateral flow of the glass from hot to cold regions [92]. The effect is used to selectively remove the upper cladding from above sections of the silicon waveguide core. This change in the geometry brings about rather drastic changes to the phase and group indices of the guided mode. Figure 46 shows numerical simulation results of the modal effective index as a function of the upper ChG cladding thickness. The simulation was carried for the TE mode and addresses the two waveguide geometries of the previous section.

![Figure 46. Waveguide effective index change vs. residual thickness of an upper cladding layer: Ridge waveguide (top), and fully etched waveguide (bottom)](image-url)
The changes in effective index following the complete removal of the ChG upper layer from above waveguides of both geometries are summarized in Table 4.

<table>
<thead>
<tr>
<th>Waveguide Type</th>
<th>Polarization Type</th>
<th>$\Delta n_{eff}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ridge (w=700nm)</td>
<td>TE</td>
<td>0.042</td>
</tr>
<tr>
<td>Fully etched (w=500nm)</td>
<td>TE</td>
<td>0.1038</td>
</tr>
</tbody>
</table>

Table 4. Simulations estimates to the changes to the modal effective index following complete photo-removal of the upper ChG cladding layer.

Although the difference in refractive indices between the ChG layer and air is very large (1.35 RIU), the modification to the modal effective index is much smaller. The cladding removal pushes a larger fraction of the modal transverse profile into the high-index silicon core, counter-acting the reduction in cladding index. Yet, photo-removal leads to index changes that are 5 times larger than those induced through photo-darkening.

The maximum expected changes in the effective index of the TE mode in a partially-etched ridge waveguide, following photo-darkening or mass transfer, are 0.008 RIU (0.3%) and 0.042 RIU (1.8%), respectively. The corresponding variations in phase delay are given by:

$$
\Delta \varphi = \frac{2\pi l \cdot \Delta n_{eff}}{\lambda_0}
$$

(26)

Here $\Delta \varphi$ is the accumulated phase shift, and $l, \lambda_0, \Delta n_{eff}$ are the length of the waveguide segment exposed to illumination, incident wavelength and the change in effective index, respectively.
The dependence of the index change on the thickness of the silica buffer layer, following complete removal of the upper cladding, is shown in figure 47. Exponential decrease in index modification is anticipated in this case as well.

\[ Y = 0.035 \exp(-0.01 \times X) \]

Figure 47. Calculated changes to the effective index of a fully-etched waveguide as a function of the thickness of a silica buffer layer, following the complete photoremoval of the upper cladding layer.

5.3 Group index trimming theory and simulations

5.3.1 Theory and simulations

The group delay index of an optical medium is defined by the following expression [5]:

\[ n_g = n_{\text{eff}} - \lambda_0 \frac{\partial n_{\text{eff}}}{\partial \lambda} \]
Here $\lambda_0$ is the central wavelength of interest. The derivative $\frac{\partial n_{\text{eff}}}{\partial \lambda}$ is primarily affected by the geometrical boundary conditions. Therefore, it is expected that mass transfer would induce larger changes in group index, compared with photodarkening. Table 5 summarizes the expected changes in group index at 1550 nm for the two waveguide geometries, as obtained in numerical simulations of photodarkening and mass-transfer.

<table>
<thead>
<tr>
<th>Wg type</th>
<th>$\Delta n_g$ (Photodarkening)</th>
<th>$\Delta n_g$ (Mass-transfer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ridge, TE mode</td>
<td>0.03</td>
<td>0.107</td>
</tr>
<tr>
<td>Fully etched, TE mode</td>
<td>0.11</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 5. Simulations of the group index changes to ridge and fully-etched waveguides, following photodarkening and mass-transfer modifications to an upper layer of chalcogenide glass

As expected, mass transfer of the upper cladding layer gives rise to higher changes in group delay index, due to its strong effect on waveguide dispersion. Figure 48 shows the waveguide group index vs. cladding index change through photodarkening, for both ridge and fully etch waveguides. Figure 49 shows the calculated change in the group index of the TE mode in a partially-etched ridge waveguide and fully etch Si waveguide, as a function of the removal depth of the upper cladding layer.
Figure 48. Group delay index vs. the refractive index of an upper cladding layer, for a fully-etched waveguide (top) and a ridge waveguide (bottom).
Figure 49. Group delay index vs. the residual thickness of an upper cladding layer, for ridge waveguide (top) and fully etched waveguide (bottom)

5.4 Experimental results

5.4.1 Phase trimming

To demonstrate the phase trimming effect, MZIs with a path imbalance of 1 mm were fabricated in SOI according to the process described in Chapter 3. A 100 x
100 µm² ChG patch was deposited above the longer arm of the MZI. The input and output ports of the device were semi-permanently connected to single mode fibers using perspex holders (Chapter 3), allowing for close-loop trimming. Tuning was carried out using photo-induced mass transfer. Phase delay variations were compared with the predictions of simulations.

The upper cladding layer was removed from four 10 x 10 µm² rectangular sections, as shown in figure 50. The measured transfer functions following each step are shown in figure 51. Variations in phase delay by $\frac{\pi}{2}$ radians occur following the removal of the cladding from above a 25 µm-long section. The corresponding change in effective index is 0.031 RIU. Simulations predict a change in effective index by 0.04 RIU following complete removal.

![Figure 50](image_url)

**Figure 50.** Top-view optical microscope image of a SOI MZI following the photo-removal of an upper cladding layer from four patches.
Figure 51. Measured power transfer functions of a SOI MZI following the photo-removal of an upper cladding layer from four patches.
5.4.2 Group index trimming experimental results

An optical microscope image of a device containing six MZIs, each with a path imbalance of 1 mm, is shown in figure 52.

![Optical microscope image of a device containing six MZIs](image)

Figure 52. Top-view optical microscope image of a SOI sample containing six unbalanced MZIs. The outer square region is covered by a silica buffer layer. The inner square region is covered by the chalcogenide glass upper cladding layer.

A buffer silica layer and a 700 nm-thick upper cladding layer of As$_{10}$Se$_{90}$ were deposited according to the procedures described in chapter 3. Waveguides were fabricated in the 70 nm etch depth ridge geometry. Light was coupled in and out of the devices via vertical grating couplers. End-to-end losses of the MZIs were measured following initial fabrication in SOI, after the deposition of silica, and following the deposition of the upper cladding. The end-to-end loss of as-fabricated MZIs was 19 dB, 16 dB of which are attributed to coupling at the gratings. Losses increased by 5 dB following the deposition of the silica and chalcogenide layers. No significant reflections were observed at the transition points between regions covered by the upper cladding and uncovered ones.

Photo-removal was carried out using the setup described in Chapter 4. A 0.5 mm-long section of the long arm of the MZI was scanned through the focused, 532 nm laser beam. The intensity of illumination was on the order of 1 MW/cm$^2$. Figure
53 shows a top-view optical microscope image of the MZI following photo-removal, and an atomic force microscope (AFM) scanning of part of the illuminated region.

![Image of MZI and AFM scan](image)

**Figure 53.** Top – Optical microscope top-view image of a MZI with 1 mm path imbalance, following the photo-removal of the upper cladding layer from above a 0.5 mm-long segment of the silicon core in the longer arm. Center – AFM scan of part of the region in which

Figure 54 shows a scanning electron microscope (SEM) image of a cross-section of the waveguide following photo-removal, formed by a FIB. Only 50 nm of the original 700 nm-thick upper cladding layer remain above the waveguide core.
Figure 54. FIB cross section of a chalcogenide-on-SOI waveguide, following the photo-induced mass transfer of the upper chalcogenide cladding layer from above the silicon core. The silica and chalcogenide layers are indicated in false colors.

The transfer function of the device before and after photo-removal is shown in figure 55. The FSR of the transfer function was modified by 6.8 pm, or 1% of its original value. Since the cladding was removed from only half of the MZI arm, the results represent a 2% change in the group delay index of the illuminated segments. Simulations suggest a FSR modification of 10.5 pm, or group delay variations of 3%. The most likely source of this discrepancy is an angular misalignment between the waveguide core layout and the scanning trajectory of the device through the green light spot. Angular misalignment of 0.5°, for example, would reduce the length of the waveguide within the MZI arm where the group index is effectively modified from 560 μm to 350 μm, and reduce the change in FSR to 6.8 pm. Note that the trimming process had little effect on the losses or extinction ratio of the MZI. The extinction ratios before and after exposure were 14 dB and 16 dB, respectively.
5.5 Discussion and summary

A new mechanism for the post-fabrication trimming of phase and group delay indices of SOI waveguides had been analyzed and demonstrated experimentally. Trimming is based on two photo-sensitivity effects in chalcogenide glasses, which were deposited as upper claddings on top of the waveguides: photo-darkening and photo-induced mass transfer. The former is mainly applicable to fine tuning of phase delay, whereas the latter is suitable for group delay variations as well due to the associated changes in waveguide dispersion. The relative phase delay between the arms of the MZI was tuned over more than half the FSR, using the mass transfer effect. The relative group delay between the arms of a MZI with 1 mm path imbalance was modified as well, leading to FSR variations by 1%. Analysis suggests that larger variations are expected using similar procedures over fully-etched silicon rib waveguides. The next chapters report the application of the trimming procedures to
the alignment of the transfer functions of cascaded MZI stages, and to adjustments of the power splitting ratio in directional couplers.
Directional coupler trimming

6.1 Motivation

Directional couplers are among the most fundamental building blocks of integrated photonics filters. They are used to combine or split incoming light between waveguide paths, cascaded to form MZIs, and linked to provide feedback in ring resonators [25]. The performance metrics of filters depend critically on precise coupling ratios which may vary due to inevitable fabrication tolerances [91]. Tunable couplers can be implemented, for example, by balanced MZIs with adjustable differential phases [25]. A wavelength-independent, arbitrary coupling ratio can be obtained, at the expense of increased footprint and complexity [25]. If possible, the post-fabrication tuning of a single directional coupler, over a broad range of coupling ratios, would represent a useful alternative.

Active tuning of photonic devices relies on localized heating [33], [93], [94], injection of free carriers into p-i-n junction structures [34], [95], or use of liquid crystals [96]. Several of these methods were also employed in the active tuning of couplers [96], [97]. Active tuning approaches, however, increase the complexity of passive devices and require constant feedback. While many approaches had been proposed for the one-time trimming of phase delays [35], [36], [38], [40], [42], [98–100], comparatively few works addressed the one-time adjustment of directional couplers. In one notable example, the splitting ratio of polymer waveguide Y-junctions was modified by photo-bleaching [101].

In this chapter, I show that the coupling ratio of SOI directional couplers may be modified by the selective photo-removal of the upper cladding layer from above
part of their lengths. Numerical analysis suggests that the coupling coefficient per unit length between the TE modes of two parallel, partially-etched ridge waveguides can be modified by over 10%. Changes in the coupling coefficient between TE modes of fully-etched waveguides reach 45%. The power coupling ratio of a 50 μm-long directional coupler comprised of two such waveguides may be tuned continuously between 0 and 1, with comparatively weak wavelength dependence. The response and dimensions of these couplers are compatible with practical device requirements.

The method is demonstrated experimentally in the post-fabrication tuning of SOI racetrack resonators: the extinction ratios of resonances at specific wavelength ranges are continuously adjusted between 4 and 40 dB. The measured transfer functions following several photo-removal steps are in good agreement with the predictions of simulations. The coupling ratios of tuned devices changed little following three months of storage.

6.2 Theory and simulation

We consider first a directional coupler between a pair of 700 nm-wide, partially etched SOI ridge waveguides. The thickness of the silicon device layer is 220 nm, and it is etched to a residual thickness of 150 nm outside core regions. The lateral gap between the cores is 300 nm-wide. The thickness of the buried oxide layer of the SOI substrate is 2 μm. The cores are covered by a 50 nm-thick silica buffer layer, followed by a 700 nm-thick upper cladding layer of As$_{10}$Se$_{90}$. 
Figure 56. Illustration of the cross-section of a directional coupler comprised of two silicon-on-insulator partially-etched ridge waveguides. The upper cladding chalcogenide layer of the left panel is removed from above the two cores in the right panel.

A schematic cross-section of the coupler is shown on the left-hand panel of figure 56. The upper cladding layer may be locally removed by focused illumination of green laser light (figure 56, right-hand panel). The transverse profiles and effective indices of the TE even and odd super-modes of the coupler were calculated using COMSOL multi-physics 2D simulations. The coupling coefficient between the two waveguides, with the upper cladding layer intact, is given by [23]:

\[
\kappa(\lambda) = \pi (n_{even} - n_{odd}) / \lambda,
\]

where \(n_{even}(n_{odd})\) is the effective index of the even (odd) super-mode. The calculated effective indices at 1560 nm wavelength are 2.7909 and 2.7631 RIU, respectively, corresponding to \(\kappa\) of 0.056 \(\mu\)m\(^{-1}\). Sections not covered by the upper cladding are characterized by \(n_{even}(n_{odd})\) of 2.7402 (2.7154) RIU at the same \(\lambda\). The coupling coefficient in these regions is reduced by \(\Delta\kappa\) of 0.006 \(\mu\)m\(^{-1}\), or about 11% of \(\kappa\).

The fraction of the incident optical power that is coupled to the through port of the device is given by:

\[
r(\lambda) = \cos^2 \left[ \int_0^L \kappa'(x) dx \right] = \cos^2 (\kappa L - \Delta \kappa x)
\]
Here $L$ is the overall length of the coupler, and $x$ is the length of the segment that is not covered by the upper cladding. The position-dependent coupling coefficient $\kappa'$ in Eq. (26) equals $\kappa$ for $0 \leq x' \leq (L-x)$, and $\kappa - \Delta \kappa$ for $(L-x) < x' \leq L$. Figure 57 shows the calculated $r(\lambda)$ between ridge waveguides of the geometry described above, over a length of 300 μm and for different values of $x$. The simulations take into consideration the chromatic dispersion of $n_{even}$ and $n_{odd}$.

![Graph showing coupling ratios](image)

**Figure 57.** Calculated power coupling ratios of a 300 μm-long directional coupler, formed between two partially-etched, 700 nm-wide silicon-photonic ridge waveguides. The transverse separation between the waveguides cores is 300 nm. Different curves correspond to $d$.

The simulation results suggest that $r(\lambda)$ may be tuned over a comparatively broad range of values, between 0.4 and 1 at 1560 nm, through changing $x$. The long coupler is, however, strongly wavelength-dependent. Larger relative changes in coupling coefficient can be achieved using fully-etched silicon rib waveguides. We considered typical waveguides of 500 nm width and 220 nm height, separated by a 200 nm-wide transverse gap between their cores and covered by a silica buffer layer and an upper cladding of As$_{10}$Se$_{90}$ as detailed earlier. The calculated value of $\kappa$...
between two such waveguides is 0.060 $\mu m^{-1}$ at 1560 nm. The coupling coefficient is reduced by $\Delta \kappa$ of 0.027 $\mu m^{-1}$, or about 45% of its value, when the upper cladding is removed.

Figure 58 shows the calculated power coupling ratio to the through port of a 50 $\mu m$-long coupler of the above geometry, for several values of $x$. The large ratio $\Delta \kappa / \kappa$ allows for the tuning of $r(\lambda)$ between 0 and 1, with much weaker wavelength dependence than that of figure 60. The results of figure 58 demonstrate the potential of the proposed method in the tuning of practical devices.

![Figure 58. Calculated power coupling ratios of a 50 $\mu m$-long directional coupler formed between two 500-nm wide, fully-etched silicon-photonic rib waveguides. The transverse separation between the waveguides cores is 200 nm. Different curves correspond to different](image)

### 6.3 Experiments results

A proof-of-concept experimental demonstration of the proposed tuning method of directional couplers is provided in the post-fabrication changes of the transfer function of race-track resonators. The characterization of devices was also
used to validate the predictions of simulations for the photo-induced changes in $\kappa$, and to monitor the stability of the modified response over time. Resonators were fabricated using partially-etched ridge waveguides, with a coupler geometry following that of the calculations leading to figure 57. Although fully-etched waveguides would support a larger ratio of $\Delta \kappa / \kappa$, our current process for the fabrication of these waveguides results in losses per unit length that are exceedingly high.

Patterns were defined in the silicon device layer using electron beam lithography and subsequent reactive ion etching. The circumference $C$ of the resonators was 1.55 mm, and the bending radii within the race-track shape were 20 $\mu$m. A 50 nm-thick layer of silica was deposited on the entire sample by ion-beam evaporation, and a 700 nm-thick upper cladding layer of As$_{10}$Se$_{90}$ was locally deposited on top of specific regions. The deposition regions were defined using photo-lithography and subsequent lift-off. The specific chalcogenide composition was chosen for its pronounced mass transfer effect [75], [92]. Details of the fabrication process are provided in Chapter 3. A top-view, optical microscope image of a device is shown in figure 59.

Figure 59. Top-view, optical microscope image of a fabricated race-track resonator in silicon-on-insulator. An upper cladding layer of chalcogenide glass covers the lighter-colored region. This upper layer was subsequently removed from above a small section of the
Light was coupled in and out of the TE mode of the devices, from/to the cleaved facets of standard fibers, using vertical grating couplers that were patterned at both ends of the bus waveguides. Grating coupler losses and propagation losses of straight waveguides were measured separately as 9 dB per facet and 3.5 dB/cm, respectively. The end-to-end insertion loss of the resonators was 22 dB, attributed primarily to input/output coupling losses. The deposition of the silica buffer layer and the chalcogenide upper cladding layer over short sections introduced negligible additive end-to-end loss.

Selective photo-removal of the upper cladding was carried out using green laser light, focused by a desktop microscope with 50× magnification to a spot-size diameter of 1.5 μm. The intensity of the focused beam was on the order of 1 MW/cm². The device was translated through the focused laser beam by a motorized linear stage at 200 μm/s speed. The laser irradiation removed the chalcogenide layer from parts of the directional coupler length, in 20 μm-long increments. In order to examine the device after illumination, a cross section was made by FIB processing. Figure 60 shows a SEM image of this cross-section demonstrating that the chalcogenide layer is entirely removed from irradiated segments.
The power transfer functions of resonators were measured by a LUNA OVAe-8000 optical vector analyzer, with 2.5 pm spectral resolution. Figure 61 (red trace) shows the initial transfer function of the device, in which an $x = 125 \, \mu m$ long section of the coupler was not covered by the upper cladding. The loaded $Q$ value of the resonator is 30,000, suggesting that critical coupling is achieved at a power coupling ratio of [24], [86]:

$$(30) \quad r = \exp\left[-\frac{\pi n_s}{Q}\right] = 0.69$$

The extinction ratios of the transmission resonances (figure 61) vary between 4 to 40 dB, with $r(\lambda)$ passing through the critical value at 1558 nm. The exact wavelength of critical coupling allows for the calibration of the coupling coefficient as $\kappa = 0.055 \, \mu m^{-1}$, or 2% lower than the prediction of simulations. This value was used in the calculations of figure 57 and figure 61.
Figure 61. Measured spectral transfer functions of a silicon-on-insulator race-track resonator. Different curves correspond to different lengths $x$ of sections within the directional coupler that are not covered by chalcogenide upper cladding (see legend).

The gradual decrease in transmission with $\lambda$ is due to the spectral dependence of the vertical grating couplers. Each photo-removal step of the upper cladding shifted the wavelength of critical coupling by about 4 nm, reaching 1569.5 nm for $x = 185 \mu$m. The shift in wavelength is about 10% smaller than the prediction of simulations (see figure 62), suggesting that $\Delta k$ is 10% smaller than expected.
Figure 62. Calculated spectral transfer functions of a silicon-on-insulator racetrack resonator. Different curves correspond to different lengths $x$ of sections within the directional coupler that are not covered by chalcogenide upper cladding (see legend).

Nevertheless, the continuous tuning of $r(\lambda)$ over a broad range of values is demonstrated (figures 61, 62). The extinction ratio of the resonance at 1558 nm was continuously modified between 40 dB and 4 dB. The coupling ratio at 1569 nm was adjusted between 0.4-1, from initial over-coupling for $x = 125$ μm, through critical coupling, to under-coupling for $x = 245$ μm, as anticipated.

The tuning of $r(\lambda)$ is accompanied by offsets in resonant wavelengths $\lambda_r$:

$$\frac{\partial \lambda_r}{\partial x} = \frac{\lambda_r \Delta n}{C n}$$  \hspace{1cm} (31)$$

Here $n \approx 2.775 [RIU]$ is the effective index of the waveguide mode with the upper cladding in place, and $\Delta n \approx -0.049 [RIU]$ is the change in $n$ following photoremoval, as obtained in simulations (average between $n_{\text{even}}$ and $n_{\text{odd}}$). Based on these values, a wavelength offset of -0.36 nm per each 20 μm removal step is expected. An average offset of -0.39 nm per step was observed in the measurements (figure 63), in
general agreement with expectations. (Note that the offset in $\lambda_1$ is close to the FSR of the device transfer function). Small-scale variations in the offsets following successive steps could be due to inconsistencies in step size or to angular misalignments [92]. Specific values of $\lambda_1$ can be restored by local illumination of short segments within the resonator loop [42], [92], if necessary (see previous chapter).

![Figure 63. Measured spectral transfer functions of a silicon-on-insulator racetrack resonator, following several steps of photo-removal of the upper cladding layer from above the directional coupler. The lengths of the directional coupler not covered by the upper directional coupler.](image)

The transfer function of a different device was monitored over more than 3 months following the tuning of the directional coupler (figure 64). The coupler was 200 $\mu$m long, with a section of 100 $\mu$m length initially uncovered by chalcogenide cladding (red curve). The cladding was then removed from an additional 35 $\mu$m long section (blue curve). The loaded $Q$ of the device was 18,000. The photo-removal changed the extinction ratios of the resonances near 1565 nm from 10 dB ($r = 0.3$) to...
35 dB ($r = 0.532$), and down-shifted the resonance wavelengths by 0.61 nm (more than an FSR). The tuning of $r$ corresponds to $\Delta\kappa$ of 0.0054 μm$^{-1}$, in agreement with expectations. No significant changes in extinction ratios or resonance wavelengths were found over two weeks of monitoring. Following 95 days of storage, extinction ratios were reduced to 32 dB (corresponding to $r = 0.527$). This variation in extinction ratio corresponds to a reduction of $\Delta\kappa$ by 3% of its initial tuning. The resonant wavelengths were down-shifted after 95 days by 0.04 nm, or 6% of their initial offset. This relative drift in $\lambda_c$ is attributed to structural relaxation of the chalcogenide layer after exposure to light at photon energy above the bandgap [42]. The wavelength drift was three times larger than that observed in [42] using a different chalcogenide composition (As$_2$S$_3$). All measurements were taken at $25 \pm 0.1 ^\circ C$ with the device mounted on a temperature-controlled stage working in closed loop. The residual uncertainty in the measurement temperature corresponds to variations of $\pm 0.01$ nm in the resonance wavelengths. The device was stored in the dark between measurements.

**Figure 64.** Measured spectral transfer functions of a silicon-on-insulator race-track resonator, before (red) and after (blue) the photo-removal of the upper cladding from a 35 m-long section of the directional coupler. Additional measurements were taken over 95
6.4 Discussion and summary

In conclusion of this chapter, the one-time, rapid and stable tuning of silicon-photonic directional couplers over a broad range of coupling ratios, using the selective photo-removal of a chalcogenide glass upper cladding, has been proposed, analyzed and demonstrated. Simulations suggest that the coupling coefficient per unit length between two partially-etched waveguides can be modified by 10%. The calculations are supported by the experimental characterization of racetrack resonators, following several steps of tuning. The extinction ratios of specific resonances were continuously adjusted between 4-40 dB.

While the relatively long couplers used in experiments are strongly wavelength dependent, this restriction is not fundamental. Analysis shows that the photo-removal of the upper cladding may modify the coupling coefficient per unit length between standard, fully etched waveguides by 45%. The power coupling ratio of such devices may be adjusted between 0 and 100%, with residual wavelength dependence that is much weaker. The length of a coupler of this type can be 50 μm only, and may be further reduced if a smaller tuning range is sufficient.

The trimming of smaller, high-Q resonators would require high accuracy in the removal process. The resolution step of the photo-removal setup is about 1.5 μm, determined by the illumination spot size. A coupler such as that of figure 59, for example, may be tuned in about 30 steps of complete removal. Finer tuning resolution can be achieved with partial removal of the upper layer, to nonzero residual thickness. Tuning precision is improved further with closed-loop monitoring of the device
transfer function during photo-removal. Yet, the applicability of the method to the trimming of point or ultra-short couplers requires further experimental investigation.
7 Trimming of cascaded filters

7.1 Motivation

Complex cascaded integrated photonic devices are gaining much interest in recent years due to the ability to realize high-end optical filters on small footprint using scalable, commercial SOI technology [6]. Such filters, comprising for example of several MZIs, find applications in the multiplexing and de-multiplexing of WDM channels [22]. Cascaded lattice structures are also used in RF photonics signal processing [102].

In this chapter, the trimming of phase delays, group delays and coupling ratios, described in the previous chapters, are used in the post-fabrication tuning of the response of cascaded MZI devices. A theoretical background on the filter transfer function is provided first, followed by experimental demonstration of 1x4 and 1x8 channel de-multiplexers.

7.2 Theoretical background

7.2.1 Multiplexers and de-multiplexers based on cascaded MZIs.

The response of a cascaded MZIs filter can be described as the product of the frequency-domain transfer functions of individual MZI stages. The specific cascaded architecture considered in this work consists of MZI stages in a tree topology, with differential path imbalances that are integer multiples of a basic unit length $L$. These multiples are arranged in a geometric series: $L, 2L, 4L, \ldots$ A device with $M$ stages has $2^M$ output ports. The primary application of these devices is in the separation of the incoming spectrum into equal spectral channels, each appearing in a different output port [25]. The same device may be operated in the reverse direction as well:
the multiplexing of multiple frequency channels, each incident at a different input port, to a common output. A three-stage, 1x8 de-multiplexer architecture is shown in figure 65. The spectral channels selected in each output are illustrated as well [25].

![Diagram of 1x8 de-multiplexer](image)

**Figure 65.** The design of a 1x8 de-multiplexer, showing the differential delays and differentail phases in each stage and an illustration of the transmitted spectra following each stage [25].

Each frequency channel is being routed to different output port. The Z-domain transfer function from the common input to the output port 1, for example, is given by [25]:

\[
H_1(z) = H^A_{21}(z)H^B_{21}(z)H^C_{21}(z) = (1 + z^{-4})(1 + z^{-2})(1 + z^{-1}) / 8
\]

where \( A, B, C \) denote the three stages. The response consists of seven zeros, all on the unit circle of the complex Z plain (see figure 66). The zeros are located at angles that are integer multiples \( n \pi / 4 \), \( n = 1, \ldots, 7 \), with no zero on the real axis (\( n = 0 \)). In the frequency domain, therefore, most spectral contents are blocked, with the exception of a narrow bandwidth, corresponding to the region on the unit circle where a zero is 'missing'. The Z response of all other output are similar: they all consist of
seven zeros on the unit circle, however the location of the 'missing' zero is different in each port (see illustration for output port 2 in figure 65). Therefore, each output transmits a different spectral range.

A Z domain plot of the zeros for output port 1 and 2 is given in figure 66 [25].

![Z domain plots](image)

**Figure 66.** Locations of zeros on the complex Z plain, representing the transfer functions of the cascaded MZI channel de-multiplexer of figure 65, from the common input to output port 1 (left) and output port 2 (right) [25].

Figure 67 [25] shows the spectral response of each stage independently, leading to output 1.
7.2.2 Fabrication considerations related to cascaded elements

A cascade of two on more filter stages will give rise to a periodic frequency response only if the differential delays within individual stages are integer multiples of a common, basic delay. This requirement imposes high accuracy requirements on the fabrication of optical differential delays. A second issue has to do with the differential *phase* delays within individual stages. As may be seen in figures 65-67, the location of individual zeros depends critically on the complex weights assigned to each path. Therefore, pass lengths within individual MZIs must be controlled to well within the optical wavelength.
The third issue is related to the power splitting ratios of the directional couplers that make up each MZI. The placement of all zeros on the unit circle, with minimal passband loss, requires that all couplers are exhibit power splitting ratios of 0.5. All parameters above are subject to fabrication tolerances. In the next section we employ our new ChG photo-trimming technique to compensate for fabrication errors in 1x4 and 1x8 cascaded MZI Mux devices. The fabrication of these devices will put into use the entire set of tools developed in the previous chapters.

7.3 Experimental results

7.3.1 Trimming a 1x4 cascaded MZI Mux

A 1x4 cascaded MZI was fabricated in-house on a SOI platform, using the process described in Chapter 3. The cascaded device consisted of three individual MZIs. Path imbalances were 1 mm and 2 mm for the two MZI stages. The MZIs were lithographically defined in a sequential manner, one after the other, to minimize stitching effects in the e-beam writer. Two ChG patches were deposited on the long arms of the second-stage MZIs, in preparation for phase trimming procedure as shown in figure 68.
Differential phases are defined with respect to the first-stage MZI, the one with the largest differential delay. The path imbalance in the first MZI, at some reference frequency $\omega_0$, equals an integer multiple of wavelengths. We refer to this condition as 'zero differential phase'. Simulations of the four output ports (figure 69) show that optimal channel de-multiplexing is achieved when the differential phases within the second-stage MZIs, for the same $\omega_0$, are $\varphi_1 = 0, \varphi_2 = \frac{\pi}{2}$. Figure 70 shows the four measured transfer functions of the device, as-fabricated. Significant deviations from the intended response are evident.
Figure 69. Simulation of the power transfer functions from the common input to the four output ports of in a cascaded 1x4 MZI demultiplexer, with optimized differential phases within individual stages.

Figure 70. Measured power transfer functions from the common input to the four output ports of in a cascaded 1x4 MZI demultiplexer, immediately following fabrication.

The study of figure 70 reveals that the transfer functions remain periodic over a broad wavelength range. This fact suggests that the differential group delays within the MZIs are correct. On the other hand, the peak transmissions and rejection levels of the output ports are uneven, indicating the incorrect placement of zeros. This, in turn, suggests that phase delays and/or coupling ratios are incorrect.
Post-fabrication trimming of phase delays was carried out based on the photo-induced mass transfer process developed previously (Chapter 5). To achieve high resolution in phase delay adjustments, photo-removal scanning lines were drawn perpendicular to the MZI arms, as shown in figure 71. This process assured repeatable phase-delay increments. Altogether seven discrete lines were drawn, followed by spectral analysis.

Figure 71. Top-view optical microscope image of part of one MZI within a 1x4 channel de-multiplexer, following the trimming of phase delay through the photo-induced mass transfer of the upper cladding layer along seven vertical lines.

The output spectrum of the four ports after device calibration is shown in figure 72. Much better compliance with the intended transfer functions of figure 69 is evident.
Figure 72. Measured power transfer functions from the common input to the four output ports of a cascaded 1x4 MZI demultiplexer, following the post-fabrication trimming of differential phase delays.

7.3.2 Trimming a 1x8 cascaded MZI Mux

A 1x8 cascaded MZI channel de-multiplexer was fabricated at TowerJazz industrial facilities, based on our design. The device requires a large footprint that is difficult to cover in point-by-point e-beam lithography. The industrial process is based on stepper photo-lithography with 150 nm resolution. The etching process was developed and calibrated according to the experience gained in our in-house process. The layout, comprised of seven MZIs, is shown in figure 73. The differential path imbalances at the three stages of the device were 0.8 mm, 0.4 mm and 0.2 mm. Target values of the differential phase delays within individual MZIs are noted in the drawing as well.
Figure 73. Schematic layout of a 1x8, cascaded MZI channel de-multiplexer, with ChG pathces deposited for post-fabrication trimming of phase delays. Design values of the differential phases are noted within each MZI.

The simulated transfer function of a single output port is shown in figure 74. It consists of a single transmission band and seven blocked bands, corresponding to seven zeros on the unit circle as discussed earlier.

Figure 74. Simulation of the power transfer function from the common input to a single output port of a cascaded 1x8 MZI demultiplexer, with optimized differential phases within individual stages.
Figure 75 shows the time-domain impulse response measurement between the common input and a single output of an as-fabricated device, taken by an optical vector network analyzer. The analyzer measures the complex-valued frequency response of the device (magnitude and phase), and calculates the impulse response through the inverse-Fourier transform. The observed response suggests that the differential group delays within the three stages are 3 ps, 5.2 ps and 10.3 ps: not integer multiples of a basic unit delay. Errors reach 11%. The group delay mismatch must be corrected before phase delays are addressed. Errors stem from the layout of curved features in the very-short path imbalance of 0.2 mm.

![Time Domain Graph](image)

**Figure 75.** Measured time-domain impulse response between the common input and a single output of an as-fabricated 1x8, cascaded MZI channel de-multiplexer.

Delay errors were compensated based on the judicious deposition of ChG upper-cladding patches over selected areas. Time-domain impulse response measurements following trimming are shown in figure 76. Differences between designed and measured delays are reduced to below 2%. 

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Figure 76. Measured time-domain impulse response between the common input and a single output of a 1x8, cascaded MZI channel de-multiplexer, following the correction of differential group delay errors within individual MZIs.

The spectral response of a single output is shown in figure 77, before (top) and after (bottom) the trimming of phase delays within individual MZIs. The adjusted response agrees well with the design objective. Note, however, that the frequency response of the tuned device is slowly drifting between adjacent FSRs, due to residual group delay inaccuracies. The responses of the remaining seven output ports were not yet aligned.
In this chapter we applied the previously-developed post-fabrication trimming method of SOI waveguides to the tuning of cascaded filters. These filters find applications in optical communication systems within transmitter and receiver modules, and in microwave photonics. Each of the constituent elements of the cascaded design must be carefully aligned with respect to the others, in terms of group and phase delays. As demonstrated in the devices fabricated in this work, the post-fabrication trimming of these attributes is mandatory. Herein we successfully demonstrated the calibration of two devices: 1x4 and 1x8 cascaded MZI filters. The process successfully aligned the measured response of the tested port with the design
objective. The complete adjustment of all output ports of the 1x8 device is still under work.
Optical orthogonal wavelet domain multiplexing using photonic devices

8.1 Motivation

8.1.1 Multiplexing schemes in advanced optical networks

Modern optical communication networks aggregate lower-rate data streams from multiple users, and multiplex them together into a high bit-rate channel. Traditionally, multiplexing in optical communication networks had been performed in the time domain. Optical time-domain multiplexing, however, is severely restricted by the rate of driving electronics and analog-to-digital converters. An additional dimension is provided by wavelength division multiplexing (WDM), in which numerous independent optical carriers are being modulated in parallel, and combined into a single 'super channel' [103], [104]. The proper multiplexing and de-multiplexing of WDM channels requires the assignment of 'guard bands': spectral regions that are not used in order to eliminate cross-talk among channels. Guard bands degrade the spectral efficiency of the network.

In recent years, more sophisticated multiplexing schemes, which are largely employed in wireless communication, are being adapted into the realm of optical communication. One such example is optical orthogonal frequency domain multiplexing, or O-OFDM [105–108]. In this format, individual data streams modulate sub-carrier tones that are equally separated in frequency. In effect, the resulting time domain stream represents an inverse-Fourier transform of the incoming data symbols, which are treated as though they were the Fourier coefficients of individual frequency
components. Due to the orthogonality of Fourier tones, data streams may overlap in both time and frequency and still be recovered by a receiver performing a Fourier transform. In principle, such channels may be closely spaced and increase the spectral efficiency. In this chapter, we present the possibility of using an alternative orthogonal basis, that of wavelet transform functions, as potential means for the bandwidth-effective multiplexing of optical communication data streams. Analysis in the literature had shown that use of such optical orthogonal wavelet domain multiplexing (O-OWDM) may have significant advantages with respect to O-OFDM [109], [110]

8.1.2 All optical wavelet domain encoders and decoders

Current high-speed fiber optic networks operate at rates that are near the limits of electronic modules in both modulation and detection. In addition, modern optical communication networks employ coherent formats [111], which rely heavily on digital signal processing for the proper demodulation of received data [111]. The processing rate limits of electronics, referred to as the electronic bottleneck, may restrict the throughput and performance of such networks. Therefore, the potential off-loading of certain processing tasks to the optical layer of the communication network is a highly appealing prospect. Optical signal processing is potentially faster and of higher throughput than its electrical counterpart.

The practical implementation of photonic signal processing would require some extent of device integration. Much effort is dedicated over the last two decades to the development of PICs, which bring together multiple discrete devices on a single substrate. Integration helps to minimize the losses associated with the coupling of light in and out of devices, enhance functionality, and reduce cost and footprint. In this chapter we suggest a novel cascaded PIC architecture for the implementation of
wavelet transform-based encoder and decoder functions [112], showing the potential application of PICs in the all-optical realization of mathematical transforms.

8.2 Theoretical background

8.2.1 The wavelet transform

A wavelet is a waveform of effectively limited duration that has an average value of zero. Wavelets used in signal processing tend to be irregular and asymmetric functions. A family of wavelets can be constructed from a single mother wavelet function $\psi(t)$. Daughter wavelets $\psi^{a,b}(t)$ are formed by translation (parameter $b$) and contraction (parameter $a$) of the chosen mother function [113], [114]:

$$\psi^{a,b}(t) = \frac{1}{\sqrt{a}} \cdot \psi\left(\frac{t-b}{a}\right)$$

In a similar manner to Fourier analysis, a family of wavelet functions can be used as a basis for the decomposition of signals. Unlike Fourier analysis, however, wavelet decomposition breaks up the signal in terms of two arguments: delay and scale. The continuous wavelet transform (CWT) is obtained by projecting a signal $f(t)$ on daughter wavelets of continuously varying $a$ and $b$ values [113], [114]:

$$C(a,b; f(t), \psi(t)) = \frac{1}{\sqrt{a}} \cdot \int_{-\infty}^{\infty} f(t) \cdot \psi^{*}\left(\frac{t-b}{a}\right) dt$$

The signal is reconstructed through multiplying each coefficient by the appropriately scaled and shifted daughter wavelet, an operation known as the inverse continuous wavelet transform (ICWT):

$$f(t) = \frac{1}{C_\psi} \cdot \int_{-\infty}^{\infty} \frac{1}{a} C(a,b; f(t), \psi(t)) \cdot \psi^{*}\left(\frac{t-b}{a}\right) \frac{da}{a^2}$$

$$C_\psi = \int_{-\infty}^{\infty} \left|\psi(\omega)\right|^2 d\omega$$
Unlike the Fourier transform, the CWT conveys information on the instance in which specific spectral components occur. Naturally, different choices of wavelet function family would lead to an entirely different CWT. The many admissible wavelets that can be used contribute to the strength of wavelet analysis.

8.2.2 The discrete wavelet transform (DWT)

Many situations, such as the implementation of the wavelet transform over digital signal processing, call for the discrete version of the operation. Like CWT, the digital wavelet transform (DWT) provides a time-scale representation of a digital signal. DWT coefficients are usually sampled from CWT on a dyadic grid (powers of 2). The DWT is realized by a successive application of a digital high-pass filter (HPF) of impulse response \( h[n] \) and a low-pass filter (LPF) of impulse response \( g[n] \), with \( n \) an integer variable, whose shapes are drawn from the specific choice of wavelet family. Following each filtering cycle the signal is down-sampled by a factor of 2, hence the transform analyzes the signal at different frequency bands with different resolutions. The HPF output in each filtering stage is referred to as the detailed information \( CD_k[n] \), with \( k \) the number of stage, and the corresponding LPF output is known as the coarse approximation \( CA_k[n] \). The entire process is illustrated in figure 78(a) below, and the reconstruction of the original signal \( s[n] \) is illustrated in panel (b) of the figure. The relations among the normalized pass-band frequencies of successive detailed information and the coarse approximation are shown in figure 79.
Figure 78. DWT (a) and IDWT tree structure. \( S[n] \) is the discrete input signal; \( g[n] \) and \( h[n] \) are the discrete LPF and HPF used in the DWT; \( \hat{S}[n] \) is the reconstructed signal; \( g'[n] \) and \( h'[n] \) are the discrete LPF and HPF reconstruction filters used in the IDWT.

Figure 79. DWT Spectrum division; \( CD[n] \) and \( CA \) are the \( n \) level detail coefficients and the coarse approximation coefficients, respectively.

The impulse responses of the HPF and LPF in the DWT are strictly related \cite{[113], [114]}:

\[
g[L-1-n] = (-1)^n h[n]
\]
Filters which satisfy this condition are known in signal processing as quadrature mirror filters (QMF), and form an ortho-normal basis. The filters that reconstruct the signal are related to the original decomposition filters by:

\[ h'[n] = h[N - 1 - n] \]
\[ g'[n] = g[N - 1 - n] \]

8.2.3 Wavelet packet decomposition (WPD)

Better control over the partitioning of the time-frequency plane (e.g. smaller bands at the higher frequencies) can be created by a generalization of the DWT. That improvement yields a more flexible decomposition named wavelet packet decomposition (WPD) [114]. WPD is being implemented by expanding the DWT scheme into a full symmetric tree decomposition instead of the previous dyadic one.

A WPD tree structure is shown in figure 80 below.

Figure 80. WPD tree structure. S[n] is the discrete input signal; h[n] and g[n] are the discrete LPF and HPF, respectively; CD[n] and CA[n] are the n-level detail coefficients and the n-level coarse approximation coefficients, respectively.
In the WPD both the detail and approximation outputs are successively decomposed. For \( k \) levels of decomposition, the WPD produces \( 2^k \) different coefficients. Spectrum allocation of the different branches in the tree is shown in figure 81.

![Figure 81. WPD Spectrum division; CD[\( n \)] and CA[\( n \)] are the \( n \) level detail and approximation coefficients, respectively.](image)

DWT is mainly used for data compression (JPEG2000), image processing and computer vision, speech recognition and biomedical applications (recognizing abnormal phenomena) [113], [114]. Over the last few years, WPD had been proposed as a potential underlying principle for spectrally efficient multiplexing of independent data streams in high-end optical communication. Compared with O-OFDM, O-OWDM could allow for a more flexible allocation of resources, due to the inherent delay-scale freedom of the wavelet daughter functions. The same properties may help circumvent impairments that are isolated in either time or spectrum. O-OWDM was found to be more robust against inter-symbol interference (ISI) [109], [110]. In this chapter we focus on a particular choice of wavelet basis, that of the Haar-wavelet transform (see next). The concept of O-OWDM had been proposed a number of years ago [115], and several thorough numerical analyses had been provided [110].
realization of the WPD and its inverse using PICs had been proposed in [116], [117] but thus far not carried out.

### 8.2.4 The Harr wavelet packet transform

The most basic family of wavelet shapes is the Haar transform, proposed initially by Alfred Haar in 1910. Since it is the simplest to implement, we adapt it in the study of the O-OWDM photonic integrated circuit. The Haar basic decomposition can be written as [113], [114]:

\[
\begin{align*}
    c[n] &= \frac{1}{\sqrt{2}} s[2n] + \frac{1}{\sqrt{2}} s[2n+1] \\
    d[n] &= \frac{1}{\sqrt{2}} s[2n] - \frac{1}{\sqrt{2}} s[2n+1]
\end{align*}
\]

An \( n \) -samples long signal is decomposed into two groups of \( n/2 \) samples. The first group \( c[n] \) is the sum of pairs \( c[n] \) of the original signal, and can be described as the output of a discrete LPF followed by a down-sampling operation by a factor of two. The second group \( d[n] \) describes the differences between pairs \( d[n] \), and can be represented as the output of a discrete HPF followed again by a down-sampling operation with a factor of two. The Haar wavelet packet transform can be described by the scheme shown in figure 82, and its inverse by the process shown in figure 83.
Figure 82. Two levels Haar WP decomposition; $s[n]$ is the input signal, $g[n]$ and $h[n]$ denote the discrete HPF and LPF impulse responses.

The inverse operation recovers the original signal from its decomposition coefficients:

\[
\begin{align*}
\tilde{s}[2n] &= \frac{1}{\sqrt{2}} c[n] + \frac{1}{\sqrt{2}} d[n] \\
\tilde{s}[2n+1] &= \frac{1}{\sqrt{2}} c[n] - \frac{1}{\sqrt{2}} d[n]
\end{align*}
\]  
(39)

Figure 83. Inverse WP Haar transform; $s[n]$ is the output signal, $g[n]$ and $h[n]$ denote the discrete HPF and LPF impulse responses.

8.3 Realization in the optical domain
8.3.1 Photonic integrated circuits for the realization of the Haar wavelet packet transform

The realization of Haar WP transform in an optical integrated circuit was theoretically suggested by Gabriella Cincotti and coworkers [116–119]. The method is based on the following Mach-Zehnder interferometer (MZI) delay line architecture, as shown in figure 84. The time-domain relations between the input and output of the MZIs are repeated in equations (40) and (41).

Figure 84. Optical implementation of Haar WPD / IWPD based on a MZI; Left - Haar-IWPD used at the transmitter end. Right - Haar-WPD used for the receiver end.

\[
E_{\text{out}2}(t) = \frac{1}{2}[-jS_1(t) + S_2(t)] + \frac{1}{2}[-jS'_1(t - \tau) - S'_2(t - \tau)]
\]

\[
\begin{bmatrix}
E_{\text{out}1}(t) \\
E_{\text{out}2}(t)
\end{bmatrix} = \frac{1}{2} \begin{bmatrix}
E_{\text{in}}(t) - E_{\text{in}}(t - \tau) \\
-j \cdot [E_{\text{in}}(t) + E_{\text{in}}(t - \tau)]
\end{bmatrix}
\]

The relations above show that a single MZI could provide the sum and the difference of its two input field, in series, in one of its output ports (see equation (40)). The operation is equivalent to the LPF and HPF operations of the inverse Haar WPD. Similarly, the same MZI can generate the sum of successive values appearing in one of its input ports at one output, and the difference of the same values at the other output, in parallel. The latter configuration realizes the Haar WPD. Hence, MZIs can function as the basic building blocks of a discrete Haar WPD and IWPD.
Different wavelet bases can be implemented by using a longer MZI cascaded chain, with unbalanced directional couplers [118], [119].

As can be seen in equations (40) and (41), the MZI realization of the WPD includes an additional relative phase shift of 90 degrees in between the two inputs / outputs, which is not part of the Haar formalism. This additional phase must be compensated for. Furthermore, the optical path lengths connecting between cascaded MZIs cannot be controlled at the fabrication stage to a sub-wavelength precision. The proper representation of the mathematical operations in the optical domain would require post-fabrication trimming procedures, such as those described in the previous chapters.

8.3.2 Architectures for optical encoders and decoders representing the Haar wavelet packet decomposition

Three-stage MZI-based PICs for the realization of Haar O-OWDM encoding and decoding are shown in figures 85-86. The encoder calculates the inverse Haar WPD of eight coefficients, incoming from eight parallel input values. The reconstructed signal appears in series at the output of the circuit. Note that padding by seven zeros is necessary between successive bits at each input, so that the transform coefficients of one input parallel word do not overrun those of the next word at the output [105], [120], [121]. The zero padding is the optical-domain equivalent of the up-sampling that is part of a digital inverse WPD. Similarly, a proper gating is necessary at the each of the eight outputs of the decoder circuit, since the original data is only reconstructed at specific time slots within the symbol duration [120]. The remainder of the symbol duration is occupied by noise-like inter-symbol interference.
Figure 85. Schematic illustration of an all-optical Haar WP encoder used in an optical transmitter; s1-s8 are low rate input data channels, with seven-bits zero padding. The output is the multiplexed Haar transform signal.

Figure 86. All optical Haar WP decoder used in an optical receiver; The incoming signal is constructed from eight data channels, which are recovered individually at the eight outputs. The output channels must be down sampled by factor of 8.
8.3.3 Optical orthogonal wavelet domain multiplexing communication link

An O-OWDM communication channel, employing the encoding and decoding PICs, is shown in figure 87. Light from a continuous-wave laser diode is split in eight paths. Light in each path is individually modulated by a separate stream of data, which are prepared with the necessary zero padding as described above. The eight channels are multiplexed by the O-OWDM PIC. At the other end of the link, each of the eight outputs of the O-OWDM decoder PIC is separately gated by an electro-optic switch and detected.

![Diagram of O-OWDM communication channel](image)

Figure 87. Schematic illustration of an O-OWDM data channel, based on encoding and decoding PICs at the transmitter and receiver.

8.4 Discussion and summary

In this chapter we discussed an optical communication link based on wavelet-domain multiplexing. In particular, we proposed the all-optical realization of wavelet-based encoding and decoding using PICs. We showed analytically that the Haar wavelet packet transform can be implemented by a cascaded MZIs tree, similar to that
of chapter 7, with a specific choice of differential phases. The all-optical approach can potentially off-load certain processing tasks from the electronic layer, partially relieving the electronic computation bottleneck. The proposed device can be fabricated and tuned using the trimming methods developed in this research. The wavelet encoders and decoders represent one example of advance passive PICs, implementing complex mathematical operations, which could be realized based on our techniques as part of future work.
9 Conclusions and perspective

9.1 Summary

In this research, a new method for the one-time, permanent post-fabrication trimming of silicon-photonic devices was proposed and demonstrated experimentally. The method relies on photo-induced modifications to an upper cladding of ChG, using two mechanisms: changes to the layer refractive index, or photo-removal via a mass transfer effect. The proposed method is simple and quick to implement. The upper glass layer is considerably more stable than the photo-sensitive polymer layers proposed elsewhere. The trimming method addresses all fundamental parameters of PIC building blocks: phase delays, group delays and coupling ratios. High-precision control over phase delays was achieved in a closed-loop tuning setup, with the device connected to semi-permanent fiber holders. The response of the device could be monitored continuously while it was being modified.

The fabrication of devices can be divided into two main parts: the silicon-photonics platform, and the ChG upper cladding. SOI devices were fabricated in Bar-Ilan University by e-beam lithography followed by plasma etching, or using stepper photo-lithography and etching at an industrial facility. Next, a thin silica buffer layer was deposited, and patch regions of ChG were defined in a photo-lithography and lift-off process.

The method was experimentally demonstrated in the tuning of five different components, made of partially-etched ridge SOI waveguides. Differential phase delays within MZIs were modified using the photo-induced mass transfer. The sensitivity of the process was 50 µrad per 1 µm of photo-removal length. Simulations
suggest that 2.5 times larger phase delay variations may be obtained using fully-etched rectangular silicon waveguides instead of ridge structures.

Group index trimming was demonstrated using the photo-removal of the upper cladding from above a 500 µm-long section of the longer arm of a MZI, with a path imbalance of 1 mm. The FSR of the device was modified by 1%, signifying a 2% change in the group delay index of irradiated segments. Here too, 2.5 times larger modifications are expected using rectangular, fully-etched waveguides.

Changes to the coupling ratios of directional couplers, using cladding photo-removal, were theoretically and numerically analyzed. Results suggest that the coupling coefficient per unit length of couplers made of ridge waveguides and fully-etched waveguides may be modified by as much as 10% and 45%, respectively. Tuning was experimentally demonstrated in the trimming of 300 µm-long directional couplers leading into race-track resonators, comprised of ridge waveguides. Photo-removal enabled the continuous adjustment of the coupling ratio at specific wavelengths, from over-coupling through critical coupling to negligible coupling. The extinction ratios of individual resonances were varied between 4 – 40 dB. The transfer function modifications remained stable following three months of storage. The analysis shows that use of fully-etched waveguides would support the tuning of much shorter couplers between 0-100% power transfer, with wavelength dependence that is much reduced.

Lastly, photo-induced mass transfer was used to adjust differential phase and group delays within individual MZIs in 1x4 and 1x8 cascaded channel de-multiplexer filters. The post-fabrication tuning correctly aligned the transfer functions of the devices with their intended designs. These last examples demonstrate the applicability of the proposed technique to the fabrication of practical devices.
9.2 Loss mechanisms in the chalcogenide-on-SOI platform

9.2.1 Excess loss following the deposition of chalcogenide glass

The deposition of ChG upper cladding directly on top of silicon waveguide cores resulted in large excess losses. The exact loss mechanism is not yet understood. Possible explanations include the trapping of air bubbles in the ChG layer (although none could be observed), or dangling bonds at the interface between ChG and Si that form surface absorption traps at sub-bandgap energies. This problem was partially circumvented with the deposition of a 50 nm-thick silica buffer layer, however the buffer layer reduces the modal confinement in the upper cladding. Better understanding of loss mechanisms would be pursued as part of future research.

9.2.2 Loss at the boundaries between covered and uncovered segments

The selective deposition of a ChG upper cladding on top of parts of the SOI waveguide might lead to additional losses due to mode mismatch between covered and exposed segments, as illustrated in figure 88.
Transmission losses due to modal mismatch may be estimated using the overlap integral between the transverse profiles of the modes in the two regions [25]:

\[
(42) \quad Loss[dB] = -10 \log_{10} \left[ \frac{\int_{area} E_1 E_2^* dA}{\int_{area} |E_1|^2 dA \int_{area} |E_2|^2 dA} \right]
\]

Here \( E_{1,2} \) are the modal profiles in the two regions, and integration is performed over the transverse cross-section. The field profiles for waveguides with and without upper cladding were numerically calculated using COMSOL 2D finite element simulation, for both ridge and full-etch geometries. Modal mismatch losses were found to be 1% for the ridge waveguide, and 4% for the fully etched waveguide. These losses are negligible within MZI devices, but might limit the Q-factor of high-quality resonators.
9.2.3 Bending losses

Bending losses are strongly affected by the modal confinement to the core. High-confinement structures, such as fully-etched silicon waveguides, exhibit low losses down to very small curvature radii of few microns. Bending losses in shallow ridge waveguides are more significant. The deposition of an upper ChG cladding, with a refractive index of 2.35-2.5 RIU, pushes a larger fraction of the modal profile out of the core and makes the structure more vulnerable to bending losses.

Figure 89 shows FIMMWWAVE simulations results of bending losses vs. curvature radius for ridge waveguides with and without the upper cladding. While uncovered ridge waveguides may support radii of 30 μm, the smallest allowed curvature in covered waveguides is increased to the order of 50 μm. Bending losses restrict the application of ChG-on-SOI ridge waveguides in small resonators.

![Figure 89. Numerically calculated bending losses of SOI ridge waveguides as a function of curvature radius, with and without the deposition of an upper ChG cladding layer.](image)

124
9.3 Temperature sensitivity

The thermo-optic coefficient of chalcogenide glasses is

\[
\left( \frac{dn}{dT} \right)_{\text{ChG}} = 5 \cdot 10^{-5} \left[ \frac{\text{RIU}}{\circ C} \right] \] [122], 6 times larger than that of a standard silica cladding:

\[
\left( \frac{dn}{dT} \right)_{\text{SiO}_2} = 8 \cdot 10^{-6} \left[ \frac{\text{RIU}}{\circ C} \right] \] [12]. Therefore, one might expect that a ChG-on-SOI waveguide would be more sensitive to temperature than a standard device with silica cladding. Temperature sensitivity was analyzed in COMSOL numerical simulations of the effective indices of the two waveguides, taking into consideration the thermo-optic coefficients of all layers. The results are summarized in the following table:

<table>
<thead>
<tr>
<th>Cladding material</th>
<th>( n_{\text{eff}} (0 , ^\circ \text{C}) )</th>
<th>( n_{\text{eff}} (70 , ^\circ \text{C}) )</th>
<th>( \frac{dn_{\text{eff}}}{dT} \left[ \frac{\text{RIU}}{\circ C} \right] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO(_2)</td>
<td>2.7421</td>
<td>2.7551</td>
<td>0.0001857</td>
</tr>
<tr>
<td>ChG (As(_2)S(_3))</td>
<td>2.7756</td>
<td>2.7881</td>
<td>0.0001785</td>
</tr>
</tbody>
</table>

Table 6. Calculated temperature sensitivity of an SOI waveguide with an upper cladding layer of ChG or silica.

The results show that although the upper ChG cladding is more sensitive to temperature than SiO\(_2\), the thermal sensitivities of the structures as a hole are practically identical. This observation may be understood given that the thermo-optic coefficient of the silicon core is much larger than those of both glasses:

\[
\left( \frac{dn}{dT} \right)_{\text{Si}} = 1.86 \cdot 10^{-4} \left[ \frac{\text{RIU}}{\circ C} \right].
\] Compared with silica, the high-index ChG layer pushes a larger fraction of the modal profile out of the core, thereby reducing thermal
sensitivity. This effect counter-acts the larger thermal sensitivity of the ChG layer itself.

We therefore find that thermal drifts in ChG-on-SOI devices would be no worse than those of standard SOI devices. Nevertheless, these thermal drifts must be addressed. One possible solution is the stabilization of the device substrate temperature using thermo-electric cooling (TEC). However, power consumption of TEC is large, and cannot be tolerated in many energy-conscious applications. In fact, the power consumption of many active-tuning methods, which do not require TEC, is much smaller. A combination of both approaches, in which a rough calibration is performed first using ChG layers and residual errors are corrected using active heaters, could help reduce the power consumption of active turning even further.

In case an entirely passive solution is required, athermal designs might be used instead. Athermal implementations combine between layers with positive and negative thermo-optic coefficients, which largely cancel out [123], [124]. Post-fabrication trimming using ChG upper cladding would be applicable to such designs as well.

9.4 Stability and degradation over time

9.4.1 Sensitivity to light

The photo-sensitivity of ChG layers is employed in this work in the form of deliberate exposure. However, the intended exposure of the same layers to ambient light could lead to unintended drifting in the layer index and in the device transfer function, based on the very same mechanisms. Unintended exposure may accumulate over time. Possible solutions include the storage of devices in opaque packaging, or the deposition of a protective layer which absorbs visible light and allows for infrared
transmission only. The protective layer would support the tuning of devices through two-photon processes.

9.4.2 Chalcogenide glasses deterioration

As-deposited thin films of ChGs are different from bulk glasses in that they contain a large fraction of homo-polar bonds (S-S or Se-Se in As$_2$S$_3$ and As$_2$Se$_3$, respectively), and even solvents residues in case of spin coating deposition [125]. These homo-polar bonds modify the refractive index of the layer and make it unstable, and also increase surface roughness [125].

Annealing processes following layer deposition lead to the removal of solvent molecules, and to structural transformations towards the “bulk state” [46]. Annealing processes produce films with very low surface roughness, and raise the refractive index towards that of the bulk ChG. For example, the annealing of As$_2$Se$_3$ at 170 °C for 16 hours elevated its refractive index from an initial value of 2.45 RIU to 2.75 RIU at 1550 nm. The corresponding value in bulk glass is 2.83 RIU [125].

Photo-oxidation over time observed in as-deposited As$_2$S$_3$ layers, as a result of exposure to short-wavelength radiation (below 248 nm), plus humidity [126]. The As-As bonds in the as-deposited layer react with water vapors which accumulate on the surface. Subject to the activation energy of photons a corrosion to the upper ChG layer takes place, resulting in As$_2$O$_3$ arsenolite crystal. Exposure to longer-wavelength radiation induces annealing, but not corrosion [126]. Oxidation can be avoided by protecting the thin ChG film by an upper capping layer, such as SiO$_2$, and avoiding humidity and exposure to UV radiation.


[112] Y. Ben-Ezra, D. Brodeski, A. Zadok, R. Califa, and B. Lembrikov, “1 Tb/s transmission system based on hierarchical approach to Wavelet Packet


תקציר

בעשור:last_name, קיימת מגמה רחבת בתחום התקשורת האופטית, של תקנות וخفضים מתמשכים בממדים של מערכות בודדות וגדלות, באמצעות טכנולוגיות שונות. תקנות אלו מתאימות למערכות משולבות ומוזרות ברמה הסילוני. מעגלים פוטונים ממוזרים שכאלו יכולות להיות משובצות, לדוגמה, במערכות ה bucידה, שבהם מתקנים רכיבים אופטיקיים יוכלו להיתכוכו ברחק, ב examples, במערכות עתידיות לתקשורת אופטית רחבת הруд הקשורים במשתנים מסוימים, בтокסיקום מבית (SOI), מספר מבית של התוכניים, במקסם ובמקסם מבית הבוחנות הצבאיות. מенко, ממקסם מבית הבוחנות האופטיות

השימוש בסיליקון מתאימים כיCastle, בטקסטורה המפורחת ואופטיקה של מוחות, כאשר מוחות קרובים לא להשויך, אשר יвязו אופטיקאים למקסם מבית הבוחנות האופטיות

섭קטיות של מוחות קרובים לא להשויך, אשר יвязו אופטיקאים למקסם מבית הבוחנות האופטיות

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 -. שיטת ניסיון להצלחת לוחות פוטונים אופטיקאים של מוחות, כך שיתכן לשימור צמצום האפשריים של הרקע

スピיטן, אוشر עשויה להתא לא רכיבי אופטיקאים של מוחות, כך שיתכן לשימור צמצום האפשריים של הרקע

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פיטות

-לפי פעמים מ-
 Währende der seit Jahren laufenden Entwicklungsarbeiten am IPB wurden die spezifischen Eigenschaften der verwendeten infraroten Materialien in enger Abstimmung mit der erwarteten optischen Leistungsfähigkeit der thermischen Systeme optimiert. 

Die verwendeten Materialien sind eine Kombination von Halbleitern und Polymergeleisen, die speziell für den infraroten Bereich optimiert wurden. Die zwei wichtigsten Auswirkungen auf die Leistungsfähigkeit der thermischen Systeme sind die Absorption der infraroten Strahlung und die thermische Leistungsfähigkeit des Materials. 

Die Absorption der infraroten Strahlung hat einen direkten Einfluss auf die Leistungsfähigkeit der thermischen Systeme. Die verwendeten Materialien sind hochabsorbierend und können somit die infrarote Strahlung effektiv aufnehmen und umwandeln. 

Die thermische Leistungsfähigkeit der verwendeten Materialien ist ebenfalls von entscheidender Bedeutung. Die verwendeten Materialien sind hochleistungsfähig und können somit die infrarote Strahlung effektiv aufnehmen und umwandeln. 

Die Auswirkungen der Absorption und der thermischen Leistungsfähigkeit auf die Leistungsfähigkeit der thermischen Systeme sind interdependent und sollten bei der Planung und Entwicklung der thermischen Systeme berücksichtigt werden. 

Zusammenfassend kann festgestellt werden, dass die verwendeten Materialien für die thermischen Systeme optimiert wurden und somit eine hervorragende Leistungsfähigkeit aufweisen. Die interdependente Auswirkung der Absorption und der thermischen Leistungsfähigkeit auf die Leistungsfähigkeit der thermischen Systeme sollte bei der Planung und Entwicklung der thermischen Systeme berücksichtigt werden.
Throughout the research, the halachah was conducted in practice. The number of components of optical bases was reduced through the use of Mach-Zehnder interferometer (Mach-Zehnder interferometer - MZI).

The waveguide bimorphic and microlithic halachot

changes in the phase and the group are shown through the interferometer (MACH-ZEHNDER INTERFEROMETER - MZI).

In the experiment, changes of 2% in the index of the group in a completely filled ridge waveguide, and

Changes in the index of reflection were examined theoretically and through simulation, depending on the geometry of the optical wave.
The results indicate possible changes in the index of reflection in a length of 54% in completely filled waveguides, and -01% in waveguides filled partially.
The effect is demonstrated halachot, in the halachot of the ring resonator, when changes in the reflection allow entry and exit from the critical point of reflection and blocking of the interferometer in specific lengths. For the MZI, up to 7 components, the interferometer is completely filled, and the interference of the components on the Mach-Zehnder interferometer is the purpose of the components of optical bases.

In summary, the method of halachot is used in integrated circuits and microcircuits, and can be used, for example, in the duplication and separation of channels in optical communication systems.

In the halachot, the halachot of the ring resonator, when changes in the reflection allow entry and exit from the critical point of reflection and blocking of the interferometer in specific lengths.

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עבודת המחברת נעשתה בהדרכת של פרופ' אבי צדוק מפקולטה להנדסה באוניברסיטת בר-אילן.
כיול לאחר ייצור של רכיבים פוטוניים
בSİליוקן באומות העולם שכבת זכוכית עליה
רגישה לאור

היהוך לשם הבודת החזון "דוקטור לפילוסופיה"

מאח: ד.ר טלי פה
הפקולטה להנדסה

הוגש לפניהם של אוניברסיטת בר-אילן;

שם: גן

רמט ג'