Ultrafast all-optical modulator with femtojoule absorbed switching energy in silicon-on-insulator

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Abstract: We demonstrate an all-optical switch based on a waveguide-embedded 1D photonic crystal cavity fabricated in silicon-on-insulator technology. Light at the telecom wavelength is modulated at high-speed by control pulses in the near infrared, harnessing the plasma dispersion effect. The actual absorbed switching power required for a 3 dB modulation depth is measured to be as low as 6 fJ. While the switch-on time is on the order of a few picoseconds, the relaxation time is almost 500 ps and limited by the lifetime of the charge carriers.

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The demand for larger bandwidth and higher data rates on shorter and shorter distances raises challenges in recent photonic research [1]. Micro- and nano-structures for fast future chip-to-chip or on-chip optical interconnects in the telecom wavelength window are being studied and developed intensively. Pivotal figures of merit of such integrated optical components are the power consumption and the size of their footprints. Furthermore, the devices should preferably be compatible with the complementary metal-oxide semiconductor (CMOS) fabrication technology. Silicon-on-insulator (SOI) is the ideal platform because the high refractive index contrast between Si and SiO₂ enables strong light confinement [2].

1. Introduction

The demand for larger bandwidth and higher data rates on shorter and shorter distances raises challenges in recent photonic research [1]. Micro- and nano-structures for fast future chip-to-chip or on-chip optical interconnects in the telecom wavelength window are being studied and developed intensively. Pivotal figures of merit of such integrated optical components are the power consumption and the size of their footprints. Furthermore, the devices should preferably be compatible with the complementary metal-oxide semiconductor (CMOS) fabrication technology. Silicon-on-insulator (SOI) is the ideal platform because the high refractive index contrast between Si and SiO₂ enables strong light confinement [2].


An essential functionality is the optical modulator which transfers an optical or electrical data stream into an optical signal. For this task, thermo-optical and electro-optical switches are intrinsically limited in terms of speed and power consumption. In contrast, all-optical switches are ideally not affected by electrical resistances and capacitances that are imposing performance boundaries. Devices with sub-femtojoule switching energies have been demonstrated very recently [3] using direct-bandgap semiconductors. For refractive modulators from monolithic silicon, the plasma dispersion effect of free charge carriers [4] is the most widely adopted modulation mechanism because of the very small nonlinear coefficients.

In order not to induce strong absorption by free charge carriers the magnitude of the refractive index change should be less than $10^{-3}$. Given this small index change, Mach-Zehnder-based modulators are inevitably quite large (> 100 μm length) and power-hungry (750 pJ per bit) [5], which is a major drawback for integration [1]. Resonant or slow light structures can improve this significantly, however, at the cost of a reduced spectral bandwidth. Micro-cavities confine the light in a very small region, and the optical field is resonantly enhanced. This increases the interaction of the light with the charge carriers while the size of the device can be reduced at the same time. The resonant optical field intensity inside a cavity scales as $Q/V_m$, where $Q$ is the quality factor and $V_m$ is the modal volume. Therefore, cavities with large quality factor and small modal volume are much preferred [6, 7]. For very high quality factors, however, the photon lifetime inside a cavity becomes an issue for fast modulation [8]. To realize switching times in the picosecond range, the quality factor should be on the order of 10000 or less.

All-optical modulation has been shown in waveguide-coupled micro-ring cavities using two approaches. In the first approach the control beam has surface-normal incidence and a photon energy above the silicon bandgap [9]. In the second approach the resonant enhancement of two-photon absorption is utilized by coupling the control light through a waveguide into the cavity [10]. Bistable all-optical switches where the control pulse is guided through waveguides [11, 12] and is in the same wavelength range (i.e. infrared) as the switched light [13] are arguably of interest for many applications in intra-chip optical communication. However, for inter-chip communication based on polymer waveguides which operate in the near infrared at 850 nm [14], an efficient and fast all-optical transducer such as the one presented here would be beneficial at the interface between the off- and on-chip optics.

Apart from the cavity photon lifetime, the speed of an all-optical switch based on the plasma dispersion effect can be limited by the lifetime of the free charge carriers. Several strategies have been implemented to remove the free charge carriers. Either the carriers are sweep-out by electric contacts [15], captured by ion implants [16, 17] or captured by grain boundaries when using polysilicon [18]. Because the modal volume of the micro-rings is still rather large, alternative cavity designs have attracted much attention recently. Photonic crystal cavities [13, 19] and circular grating resonators [20] have been used to realize all-optical modulators. The 2D photonic crystal cavities demonstrated experimentally very low injected switching energies of less than 100 fJ and recovery times of 300 ps [13]. However, they require a relatively large area and the coupling to photonic crystal waveguides. In contrast, waveguide-embedded 1D photonic crystal defect cavities [21–24] are of particular interest since their space requirement in the transversal direction is small, and they are coupled directly to ridge waveguides.

Recently all-optical switching experiments have been described [24] which use a 1D photonic crystal waveguide structure and nanosecond pump pulses at 532 nm with energies of 2 pJ. A high quality factor of approximately $1.2 \times 10^5$, however, prevents a high-speed response and thereby dispenses one of the main advantages of using an all-optical switch.

In the present work we demonstrate an ultrafast all-optical switch which only absorbs a few femtojoules for the switching process using a similar 1D photonic crystal cavity. We characterize the structures by means of linear optical transmission and thermo-optic measurements. Fem-
to second pump and probe experiments are performed with a normal-incidence control beam and a waveguide-coupled signal beam to investigate the fast switching process.

The paper is structured as follows: In Sec. 2 the design and fabrication of the device is presented. In Sec. 3 the linear and thermo-optic properties of the device are measured. Employing pump and probe measurements the spectral and temporal evolution of the device transmission are determined in Sec. 4. Finally, the conclusion is given in Sec. 5.

2. Device Design and Fabrication

The fundamental building block of the studied optical switch is a 1D photonic crystal defect cavity directly embedded into a Si ridge waveguide, as shown in Fig. 1(a). The cavity consists of a number of holes $N$ forming the Bragg mirrors around a central defect region. To achieve a high quality factor, taper sections [22, 23] are added between the respective mirror sections and the central defect, realized by four additional holes which decrease in size towards the cavity center and slightly changed distances between the holes. We optimize the geometry for high quality factor and low modal volume using 3D finite-difference time-domain (FDTD) calculations [25], see Fig. 1(b). Table 1 summarizes the geometric parameters for a target resonance wavelength $\lambda$ near 1550 nm.

The number of holes of the mirror determines the quality factor. For small $N$, $Q$ rises exponentially because the losses through the mirrors dominate and their reflectivity rises exponentially with $N$. At about $N = 14$ the quality factor saturates and is limited by the scattering losses from the cavity. The photon lifetime inside the cavity is given by

$$\tau = \frac{Q\lambda}{2\pi c}$$

where $c$ is the speed of light. In order to achieve a photonic response time $\tau < 10$ ps for ultrafast optical switching, the targeted quality factor must be less than 10000. Therefore, we set $N =$
Table 1. Geometric parameters of the 1D photonic crystal micro-cavity obtained through optimization using FDTD

<table>
<thead>
<tr>
<th>( r_0 ) (nm)</th>
<th>110</th>
<th>86</th>
<th>83</th>
<th>71</th>
<th>54</th>
<th>350</th>
<th>372</th>
<th>320</th>
<th>321</th>
<th>324</th>
<th>559</th>
<th>530</th>
<th>220</th>
</tr>
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6 – 7 (excluding the taper) for the investigated devices. The calculated modal volume is \( V_m = \int \varepsilon |E|^2 dV / \max(\varepsilon |E|^2) \approx 5 \lambda / (2n)^3 \) where \( E \) is the local electric field, \( \varepsilon \) the dielectric constant and \( n \) the refractive index of Si.

The device is fabricated using SOI wafers with a 220 nm-thick Si layer supported by a 2 \( \mu \)m-thick SiO\(_2\) layer. The structure is defined by electron-beam lithography using hydrogen silsesquioxane (HSQ) as negative tone resist. The pattern transfer is achieved in a two-step HBr-chemistry-based inductively coupled reactive-ion etch process which is described elsewhere in detail [26]. The entire process flow, including lithography and etching, has been optimized to minimize the side-wall roughness of the waveguide while maintaining the dimensional accuracy of the holes. Figure 1(c) shows a scanning electron microscope (SEM) image of the fabricated micro-cavity. Finally, the structure is cladded with poly(methyl methacrylate) (PMMA). Coupling to the device is achieved through inverted tapers with cleaved facets at the ends of the ridge waveguides. The whole structure has a total device footprint of about 8 \( \mu \)m \( \times \) 0.5 \( \mu \)m = 4\( \mu \)m\(^2\).

3. Linear Optical Characterization

In this section we present the linear optical characterization of the micro-cavity. First, the transmission spectrum of the device is measured by using the following setup. Light from a tunable single-mode continuous-wave laser source is transmitted through a linear polarizer and then coupled into the device using polarization maintaining lensed fibers. The light transmitted through the device is collected with a lensed fiber and detected by a power meter.

In Fig. 2 the transmission spectrum of a device for wavelengths between 1510 nm and 1610 nm is shown. For wavelengths smaller than 1570 nm a clear photonic bandgap with a resonance at a wavelength of \( \lambda = 1514.76 \) nm is visible. In the inset of Fig. 2 a high-resolution measurement of the resonance is plotted. By fitting the data to a Lorentzian the full-width at half maximum (FWHM) of 0.35 nm results in a quality factor of 4300. The fringes which appear in the bandgap are artifacts from multimode interference in the broad tapers at the in- and out-coupling facets of the waveguides. Outside the bandgap the fringes with high frequency originate from Fabry-Pérot effects between the cleaved facets which are also observed in straight waveguides.

The resonance frequency of the cavity can be tuned by harnessing the thermo-optic effect because the refractive index of silicon is temperature dependent. In Fig. 3 the resonance wavelength is plotted as a function of the temperature \( T \). When increasing the temperature \( T \) the resonance wavelength shifts to longer wavelengths. From a linear fit we find the slope \( d\lambda / dT = 0.052 \) nm/K which corresponds to a relative shift of \( 3.4 \times 10^{-5} \) K\(^{-1}\) of the resonance wavelength.

From the measured thermo-optic shift we calculate the confinement factor \( \sigma \). The confinement factor corresponds to the amount of light in the silicon of the cavity and therefore relates the relative resonance wavelength shift \( \Delta \lambda / \lambda \) to the relative change of refractive index \( \Delta n / n \):

\[
\frac{\Delta \lambda}{\lambda} = \sigma \frac{\Delta n}{n}.
\]

By utilizing the known thermo-optic coefficients \( dn/dT \), we can infer \( \sigma \) from the observed
Fig. 2. Linear optical transmission spectrum through the device with \( N = 6 \). The inset shows a high-resolution measurement of the resonance and the Lorentzian fit which is used to obtain the quality factor and the center wavelength of the resonance.

Fig. 3. Thermo-optic red-shift of the resonance wavelength from which the optical confinement within the silicon can be deduced.

Temperature-dependent shift. Silicon has a thermo-optic coefficient of \( 1.86 \times 10^{-4} \text{ K}^{-1} \), PMMA of \( -1.3 \times 10^{-4} \text{ K}^{-1} \), and SiO\(_2\) \( 1.0 \times 10^{-4} \text{ K}^{-1} \). We approximate that the light radiates equally into the PMMA cladding and SiO\(_2\) substrate because of their similar refractive indexes. The thermal expansion coefficient of Si is neglected because it is relatively small (\( 2.5 \times 10^{-6} \text{K}^{-1} \)). Furthermore, stress-induced effects are negligible because of the SOI substrate and PMMA cladding. For the experimental data a confinement factor \( \sigma = 0.76 \) is obtained which is in good agreement with \( \sigma \approx 0.7 \) we calculated with FDTD simulations.
4. All-Optical Switching

In this section we determine the performance of the 1D photonic crystal cavity as ultrafast all-optical modulator. We perform a detailed analysis of the spectral and temporal evolution of the transmission through the resonant micro-cavities. The employed femtosecond pump and probe setup is schematically shown in Fig. 4.

The pump pulses are derived from a mode-locked Titanium Sapphire (Ti:Sa) oscillator, which is pumped by a frequency-doubled diode-pumped solid state laser. The pump pulse has a repetition rate of 80 MHz at a center wavelength of 830 nm with a pulse duration of about 80 fs. The probe pulse at a central wavelength of 1530 nm with a FWHM spectral width of about 20 nm and duration on the order of 150 fs is created by an optical parametric oscillator (OPO) pumped by the same Ti:Sa. This probe pulse is coupled into a polarization maintaining fiber and then through an inline polarizer into the in-coupling waveguide via a polarization maintaining single mode lensed fiber. The transmitted pulse with a spectral energy density on the order of a few femt Joule per nanometer bandwidth is collected by another lensed fiber and fed into an optical spectrum analyzer (OSA) with the resolution bandwidth set to 0.06 nm. The pump pulse has an adjustable delay relative to the probe pulse, realized by a corner mirror on a linear positioner stage with 50 mm travel and 100 nm resolution. The pump spot is focused onto the sample with an apochromatic 100X microscope objective which has a numerical aperture of 0.5 and an effective focal length of 2 mm. This results in an approximately Gaussian spot of about 2 μm 1/e²-beam diameter. The same objective lens is also used to visualize the device on a charge-coupled device (CCD) camera and to position the pump beam at the center of the cavity. Because of dispersion in the fiber and the objective, the probe and the pump pulse are both prolonged to a few hundred femtoseconds.

For the pump-probe experiment, we use a device with N = 7 and a two-step MMA/PMMA cladding which fills the holes better. This results in an increase of the resonance wavelength of this cavity to λ₀ = 1528.61 nm with a quality factor of 5500. In Fig. 5(a) the transmission spectra of the micro-cavity before and after optical pumping with 2.8 pJ pulse energy are shown. Directly after the pump pulse the resonance wavelength is shifted to λ₁ = 1528.10 nm with the quality factor lowered to 2700. The extinction ratio at the initial resonance wavelength before pumping is measured to be 7.5 dB. The blue-shift and therefore the negative refractive index change is a clear indication of the plasma dispersion effect [4]. In contrast, a red-shift would
be expected from the thermo-optic effect by heating the device with the absorbed pulse energy. The free charge carriers also lead to an additional small absorption of the probe pulse which is reflected by the reduced transmission amplitude and the lowered quality factor.

![Graph](image)

Fig. 5. (a) Transmission spectra before (black) and after (red) optical pumping with a 2.8 pJ-pulse. The smooth solid lines are Lorentzian fits to the resonance peak from which the center wavelength and the quality factor are extracted. (b) Shift of the resonance wavelength $\Delta \lambda$ as a function of pump pulse energy $E$. The solid lines are linear (red) and quadratic (green) fits to the data.

The dependence of the wavelength shift as function of the pump pulse energy is shown in Fig. 5(b). We conclude that 1.2 pJ are required to shift the resonance wavelength by half FWHM of the initial resonance before pumping. This shift corresponds to a 3 dB modulation depth. Applying a linear fit to the data results in a slope $d(\Delta \lambda)/dE = -0.15 \text{ nm/pJ}$. However, a quadratic fit seems to match better the actual observed behavior. Two-photon absorption as a source for the nonlinearity is unlikely because in this range of pump intensities the two-photon absorption coefficient $\alpha_2 < 1 \text{ cm}^{-1}$ [27] is negligible compared to the linear absorption $\alpha = 740 \text{ cm}^{-1}$ [28]. Furthermore, the optical Kerr effect is small, $\Delta n < 10^{-8}$, leaving the origin of the observed apparent nonlinearity open.
In the next step we study the dynamics of the switching process and therefore we vary the time delay between the probe and the pump pulse. Figure 6(a) shows the transmission spectrum as a function of the time delay. An almost instantaneous switching of the resonance followed by a slow relaxation to the initial resonance wavelength is observed. The time-dependent resonance wavelength shown in Fig. 6(b) is obtained from the raw data of Fig. 6(a) is post-processed by low-pass filtering and power-normalization using the transmission far off resonance, which reduces the sensitivity to spectral artifacts and power fluctuations of the OPO. A maximum wavelength shift of -0.51 nm is observed which corresponds to a relative wavelength shift $\Delta \lambda / \lambda = -3.3 \times 10^{-4}$. The time evolution of the wavelength shift is a direct measure of the transient charge carrier density in the cavity. Applying an exponential fit yields an exponential recovery time of 445 ps, limited by carrier diffusion and recombination [29]. This is in good agreement with the values for other nanophotonic structures in the literature [9, 17, 20]. However, for high-speed applications this lifetime can be significantly reduced for example by electrical carrier sweep-out [15] or ion implantation [16, 17].
By varying the time delay around zero between the femtosecond pump and probe pulses in steps of 2 ps we are able to investigate the switching process in more detail. Figure 7(a) shows the data which has been Fourier-filtered and power-normalized in order to reduce the artifacts introduced by the OPO.

Figure 7(b) shows the temporal behavior of the transmission at the unswitched resonance wavelength $\lambda_0$ and the switched resonance $\lambda_1$, as indicated by the dotted lines in Fig. 7(a). The fall time to change the transmission from 90% down to 10% is 12 ps, and the rise time is 3 ps. Assuming that the only limitation is the photon lifetime $\tau$ in the cavity, this corresponds to quality factors of 6700 and 1700, respectively, which is in reasonable agreement with the observed spectral line widths of the initial and shifted resonances.

In the following, we calculate the necessary energy to obtain optical switching. As the charge carrier density generated by the pump pulse is not directly accessible we estimate the optical energy which is actually absorbed in the 1D photonic crystal cavity and account for the overlap of the resonant mode with the pumped volume. From the image through the confocal setup, we obtain a 1/e$^2$-diameter of 2 $\mu$m for the almost Gaussian shaped pump spot. Due to the geometrical overlap with the waveguide cavity, about only 20% of the pump beam energy actually reaches the cavity region. The extinction coefficient in silicon at a wavelength of 830 nm
is \( k = 0.004895 \) [28], such that only a small fraction is absorbed in the thin top silicon layer. Furthermore, there are reflections at the various material interfaces due to the refractive index differences. From calculations we find that only 2.4% of the above mentioned 20% are actually absorbed. This constitutes a value which is averaged between the two extremes of 1.1% and 3.7%. This uncertainty arises because the oxide thickness of the SOI wafer is not precisely known and therefore the reflection at the SiO\(_2\)/Si-substrate interface can lead to either constructive or destructive interference. Hence, an incident energy of 2.8 pJ corresponds to 13 fJ of actual absorbed optical energy, i.e., 54000 photons, to shift the resonance by -0.5 nm or 7.5 dB modulation depth. For 3 dB modulation depth, only about 6 fJ would need to be absorbed.

Next, we evaluate if these energies are in accordance with the expected values for the plasma dispersion effect. Assuming a photon-to-charge conversion efficiency of unity for all absorbed photons, a pulse with 2.8 pJ from which actually 13 fJ are absorbed creates in the cavity center an average excitation density of free electrons and holes of about \( n_{e,h} = 2.3 \times 10^{17} \text{ cm}^{-3} \). The refractive index change can be calculated using the following equation [2]:

\[
\Delta n = -8.8 \times 10^{-22} n_e - 8.5 \times 10^{-18} n_h^{0.8}. 
\] (3)

The calculated refractive index change of \( \Delta n = -8.6 \times 10^{-4} \) results in a relative refractive index change in the silicon of \( \Delta n/n_{Si} = -2.5 \times 10^{-4} \). Using the confinement factor \( \sigma = 0.76 \) obtained from the thermo-optic measurements and Eq. (2), we calculate the relative wavelength shift to be \(-1.9 \times 10^{-4}\) and absolute wavelength shift to be -0.3 nm. This agrees reasonably well with the directly measured shift of -0.5 nm corroborating the absorbed switching energy to be 13 fJ for a 7.5 dB modulation depth. Differences are expected because of made assumptions of a spatially constant intensity of the resonant cavity mode as well as of the pump spot and the uncertainties in the absorbed power and the actually generated carrier densities. The additional carrier-induced absorption is calculated to be [2] \( \Delta \alpha = 8.5 \times 10^{-18} n_e + 6.0 \times 10^{-18} n_h = 3.3 \text{ cm}^{-1} \). This, however, cannot fully explain the observed reduction of the \( Q\)-factor.

We compare our results to recent all-optical switching experiments from Belotti et al. [24]. They used a similar 1D photonic crystal waveguide structure and nanosecond pump pulses at 532 nm and obtained similar pump energies. The about 30 times higher quality factor compensates for the reduced efficiency from the larger pump spot of 10 \( \mu \text{m} \) diameter and the pump duration of 2.5 ns which is longer than the carrier recombination time. However, as stated above, the high quality factor prevents a high-speed response.

5. Conclusion

Ultrafast all-optical switching with very low optical power has been demonstrated using a waveguide-embedded 1D photonic crystal micro-cavity. The control pulse at a wavelength of 830 nm switches the resonance in the telecom wavelength range within a few picoseconds. While the energy in the pump spot is on the order of 1 to 3 pJ per pulse, the actually absorbed optical power and therefore the absorbed switching energy is as low as 13 fJ to obtain a modulation depth of 7.5 dB. We achieve this with a cavity quality factor of less than 10000 which enables a high-speed response on the order of a few picoseconds. The observed lifetime of the generated free charge carriers on the order of a few hundred picoseconds could be reduced using well-known techniques [15–17] down to 10–20 ps [30] which would then be on the order of the photon lifetime. In order to significantly enhance the absorption efficiency and therefore reduce the required injected switching energy, resonant second order gratings transversal to the waveguide cavity could be used [31]. The device footprint of 4 \( \mu \text{m}^2 \) and the use of the SOI platform are ideal for the integration within the CMOS process. This shows that compact, very efficient and yet fast all-optical refractive switches can be realized in monolithic silicon.
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