# Ultrafast all-optical wavelength conversion in Silicon-on-Insulator waveguides by means of Cross Phase Modulation using 300 femtosecond pulses.

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*In this paper we report the ultrafast all-optical wavelength conversion in Silicon-on-Insulator (SOI) waveguides. We used a pump-probe setup with 300 femtosecond pulses to demonstrate large temporal phase-shifts, caused by the Kerr effect and free carrier generation. Large wavelength shifts of a 1683nm probe signal have been observed. The wavelength conversion, ranging from 10nm redshifts to 15nm blueshifts, depending on the time delay between the pump and probe pulses, is caused by the pump induced Cross Phase Modulation. Furthermore, an all-optical switching scheme using SOI microring resonators is discussed. These results enable ultrafast all-optical switching using SOI microring resonators.*

## Introduction

Silicon integrated photonics has received a lot of attention in the last couple of years, because of its compatibility with CMOS electronics [1]. In recent years, many new types of nonlinear active silicon-based photonic devices have been developed. Substantial progress has been achieved in the field of Raman amplification, in both continuous-wave [2] and pulsed pump-probe [3,4] experiments. Other nonlinear effects like two-photon absorption (TPA) [5], self-phase modulation (SPM) [6-8], cross-phase modulation (XPM) and continuum generation [9], four-wave mixing (FWM) [10] and the Kerr coefficient [11] have been successfully demonstrated and thoroughly investigated.

In this paper, we present experimental results of femtosecond pump-probe experiments in Silicon-on-Insulator (SOI) waveguides by means of XPM. Large Kerr-induced wavelength shifts of the probe signal have been observed, whereas the free carrier contribution did not substantially contribute. Since the ultra-fast Kerr effect is the dominating mechanism, this method of wavelength conversion is suitable for ultra-fast all-optical switching.

## Theory

The refractive index of SOI waveguides is changed mainly by two nonlinear effects when strong pump pulses with a FWHM pulse duration of 300fs propagate through the silicon wire. The first one is the instantaneous Kerr effect, inducing a refractive index increase of $\Delta n_{Kerr} = n_2 \cdot I$ [11]. Secondly, free carriers (FCs) are generated by TPA causing a refractive index decrease that can be empirically described by

$\Delta n_{FC} = -(8.8 \cdot 10^{-22} N + 8.5 \cdot 10^{-18} N^{0.8})$ [12], with $N$ the free carrier density. In Figure 1 the contribution to the total induced refractive index change of both the Kerr nonlinearity and the free carrier dispersion is shown for a Gaussian pulse with a maximum intensity of $I_{max}$~150TW/m$^2$. It can be seen that the Kerr contribution is dominant, while the effect of the free carrier accumulation is limited because the pulses are short.

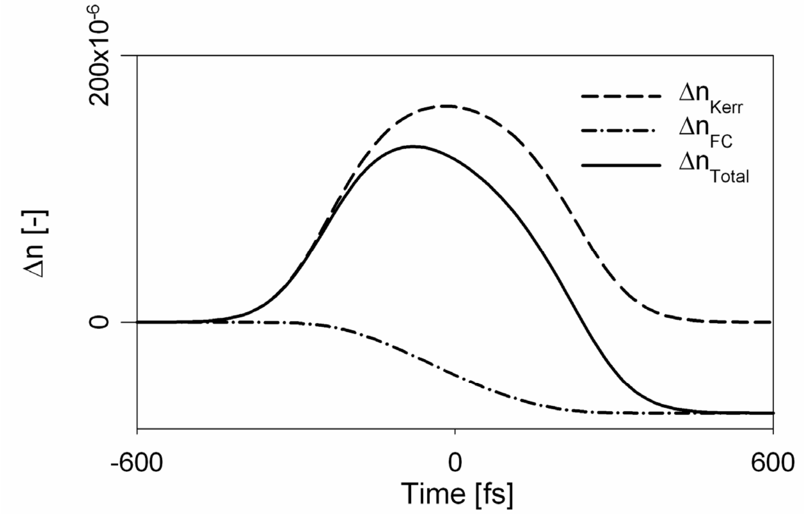

*Figure 1: Modelled Kerr and free carrier induced refractive index change for 300fs pulses with an average power of 500µW in 300×450nm SOI waveguides.*

The temporal shape of the pump pulse is influenced by several mechanisms like TPA, Free Carrier Absorption and the dispersion [13]. Since both the Kerr and free carrier induced refractive index changes are intensity dependent, they both change with the envelope of the pump pulse, resulting in a temporal phase shift $\Delta\phi(t)=2\pi L_{int}\Delta n(t)/\lambda$. Here, $L_{int}$ is the interaction length of pump and probe pulses. Consequently, this temporal phase shift causes a frequency shift $\Delta\omega(t)=d\Delta\phi(t)/dt$, which is the basis for SPM and XPM. In this paper we will only focus on the XPM induced frequency shift causing a wavelength shift of the probe pulses, which is defined as [13]:

$$\lambda_s = \frac{\lambda_0}{1 - \frac{L_{\text{int}}}{c} \cdot \frac{\Delta n(t,z)}{dt}} \tag{1}$$

## Experimental results

Both the pump (1554nm) and probe (1683nm) pulses with a FWHM pulse duration of 300fs are delivered by an optical parametric oscillator (OPO) with a repetition rate of 80MHz. The time delay between pump and probe pulses is controlled with a free-space optical delay line with 6.6 femtosecond accuracy. Both beams are combined using a beam splitter and coupled into a 10cm piece of polarization maintaining fiber (PMF) using a microscope objective. The output of the PMF (30mW average power for the pump and 3mW for the probe) is used to facilitate the simultaneous coupling of the TM polarized pulses into our SOI waveguides having a 450nm×300nm (w×h) cross section (by design) and a length $L$ of 7mm. No spectral broadening due to the fiber nonlinearities has been observed at the output of the fiber, prior to entering the SOI waveguide. After propagation through the SOI waveguide the transmitted pulses are coupled out using a single mode fiber, which is attached to an optical spectrum analyzer. By this means, both intensity and spectral characteristics of the transmitted pump and probe pulses can be detected simultaneously.

In Figure 2 the experimentally observed center wavelength of the probe pulses are plotted as function of delay time. Here a negative delay time means that the probe pulses are running ahead of the pump pulses, *i.e.* are overlapping with the leading edge of the pump pulse. The discrepancy between the experimental results and the simulations is caused by the fact that dispersion effects are not included in the model [13]. We observed a 10nm redshift at negative delay times, indicating that the nonlinearities are dominated by the Kerr effect in case of femtosecond pulses. This is in contrast to the blueshift that is normally observed in pump-probe experiments with longer ps pulses [4], where the free carrier dispersion effect is dominant due to the fact that ps pulses are long enough to build up a sufficient amount of free carriers.

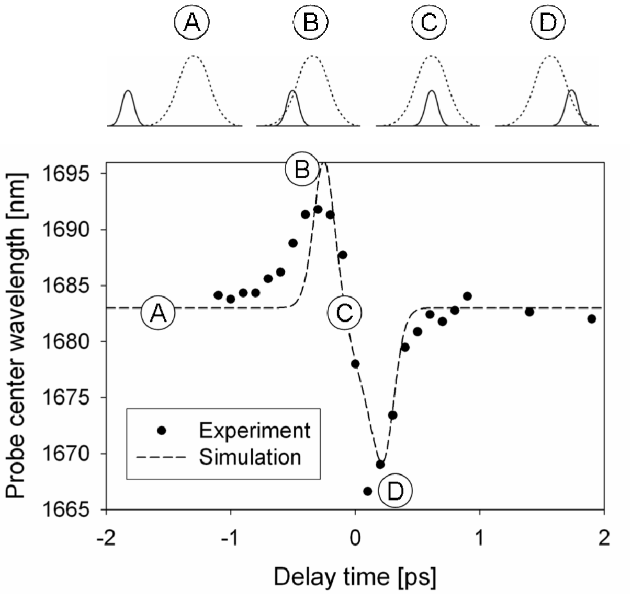

*Figure 2: Center wavelength vs. delay time.*

Ultrafast all-optical switching can be achieved in case that the frequency shifted probe pulse is redirected by a wavelength selective device. In our case we propose a SOI waveguide combined with a SOI microring resonator filter. The wavelength conversion of 10nm taking place in the active port waveguide is in the order of the free spectral range (FSR) of a passive ring resonator with a radius of 10µm. This means that the probe signal can be tuned over the full FSR of the ring by adjusting the time delay. Low Q resonators having short loading and unloading times can be used as passive space switches, because of the large XPM induced wavelength shift. Since the wavelength conversion is determined by the time derivative of the Kerr induced refractive index change, the switching time of such a switch is related to the width of the pump pulse [4], which is in the order of 300fs. This is in contrast to the all-optical switching mechanisms that rely on the FC dispersion, where the switching speed is limited by the FC lifetime in the order of ns.

## Conclusions

We have shown that both 10nm blue and red shifts in SOI waveguides using a pump-probe setup with 300fs pulses are feasible. The XPM is dominated by the Kerr effect, since the pulses in the femtosecond regime are too short to accumulate a sufficient amount of free carriers to have considerable free carrier dispersion. This means that the temporal refractive index changes are mainly caused by the instantaneous Kerr effect and thus both the wavelength up and down-conversion takes place in a sub-picosecond timeframe. The ultrafast wavelength conversion can be exploited for all-optical switching when combined with microring resonator filters.

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