Self Phase Modulation and Stimulated Raman Scattering due to High Power Femtosecond Pulse Propagation in Silicon-on-Insulator Waveguides.

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Self Phase Modulation (SPM) and Stimulated Raman Scattering (SRS) in silicon waveguides have been observed and will be discussed theoretically using a modified Nonlinear Schrödinger Equation. The high optical peak powers needed for the experiments were obtained by coupling sub-picosecond (200fs) transform limited pulses with a spectral width of 12nm into a single mode silicon waveguide. Spectral broadening up to 50nm has been observed due to Self Phase Modulation. An intensity increase of the idler spectrum around 1650nm at the expense of the 1550nm pump signal has been observed as function of pump power, indicating the presence of Stimulated Raman Scattering.

Introduction

Over the past few years Silicon-on-insulator (SOI) waveguides gained much interest, because they offer the possibility to monolithically integrate optical devices with CMOS electronics. Furthermore, because of the high refractive index contrast (Δn~2), the waveguide structures can be extremely compact, which is attractive for VLSI photonics. Because of the strong field confinement and the strong Kerr and Raman effects in silicon, the nonlinear effects should be taken into account.

The Nonlinear Schrödinger Equation

The propagation of short electromagnetic pulses inside a channel waveguide with Kerr nonlinearity can be described by a modified generalized nonlinear Schrödinger equation (NLSE)[1-3]:

$$\begin{aligned}\frac{\partial\psi(\tau,z)}{\partial z} &= -\frac{\alpha}{2}\psi(\tau,z)+i\sum_{n=2}^{\infty}\frac{i^n\beta_n}{n!}\frac{\partial^n\psi(\tau,z)}{\partial\tau^n}-\frac{\alpha_0}{2}\psi(\tau,z)-\frac{\alpha_2}{A_{eff}}|\psi(\tau,z)|^2\psi(\tau,z)\\ &+ i\gamma\left(1+\frac{i}{w_0}\frac{\partial}{\partial\tau}\right)\left(\psi(\tau,z)\int_0^{\infty}R(t)|\psi(\tau-t,z)|^2dt\right)\end{aligned} \tag{1}$$

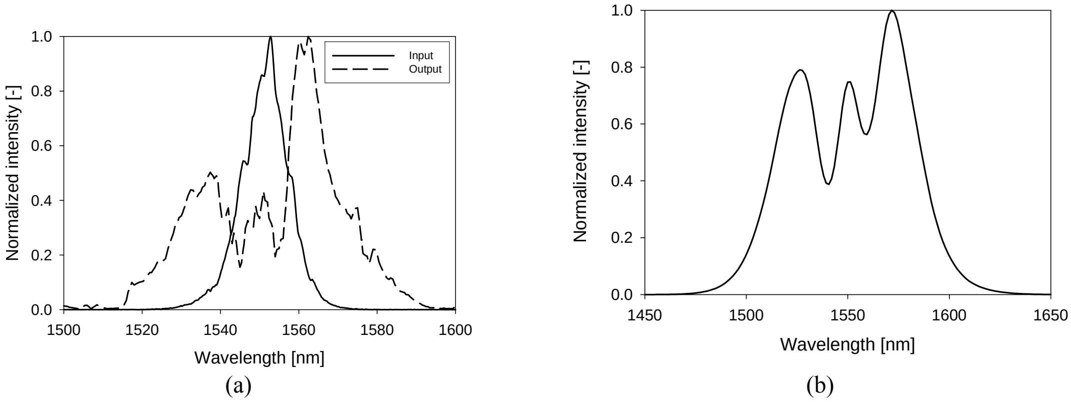
where $\psi(z,\tau)$ is the slowly varying complex envelope of the pulse. In this equation γ is the nonlinear parameter, which can be expressed as $\gamma = 2\pi n_2 / \lambda A_{eff}$, where λ is the wavelength, A_{eff} is the effective area of the propagating mode, and n_2 is the nonlinear refractive index. Additionally, α_0 is the propagation loss, α_2 the two-photon absorption coefficient and the β_j's represent the higher order dispersion terms. The nonlinear response of the waveguide is incorporated in Equation 1 in a general fashion by using the response function $R(t)$ of silicon.

Measurement setup

An 80MHz pulse train (P_{avg}=75mW) of high power pulses derived from an Optical Parametric Oscillator was used as the optical source. The transform limited pulses with a Full Width at Half Maximum (FWHM) of 200fs and a spectral FWHM of ~12nm were coupled into 400nm×400nm silicon-on-insulator waveguides with a length of 7mm using a microscope objective. The coupling losses were estimated to be about 20dB, taking into account modal overlap losses and Fresnel reflections. Reduction of the coupling losses can be obtained by applying nanotapers as described by Almeida et al.[4] The resulting pulse peak power and peak intensity were estimated to be 44W and 275GW/m^2, respectively. The output spectra were recorded with a spectrum analyzer using a polarization maintaining monomode fiber as the transport medium from the device to the spectrum analyzer.

Experimental results vs. simulations.

Figure 1(a) shows the typical normalized input and output spectrum as measured in our experiments. A clear spectral broadening from 12nm FWHM to 50nm is observed due to SPM. Despite the fact that the length of the waveguide is very short, it is believed that the asymmetry in the peak heights is caused by second and third order dispersion (SOD and TOD). It is unlikely that this asymmetry is caused by a phenomenon called intrapulse stimulated Raman scattering (ISRS), which is a process where high-frequency components pump the low-frequency components of the same pulse[5], causing a redshift. This intrapulse Raman scattering depends on the slope of the Raman gain in the wavelength region of interest, which is zero at this spectral range. The properties of the Raman gain in silicon will be further discussed in the next paragraph.
A NLSE simulation result is shown in Figure 1b, where only the SPM, SOD and TOD effects have been taken into account ($R(t) = \delta(t)$ and $\omega_0 = \infty$ in Equation 1). For the Kerr nonlinearity, a value of $n_2 = 4.10^{-18}$ m^2/W has been used.[6]



(a) (b)

Figure 1: (a) Experimental input and output spectra. (b) Simulations using the NLSE..

The computer simulations only weakly mimic the experimental values, this is most likely due to a slight pulse asymmetry which can be seen in the input spectrum in Figure 1(a) and was not included in our model.

Raman amplification

The Raman effect in silicon is ~10^4 times stronger than in conventional silica fibers[7]. Furthermore, the fact that the optical field in silicon-on-insulator structures is much more tightly confined allows the Raman effect to be observed in very short silicon-on-insulator waveguides. This makes this type of waveguide an excellent platform for optical signal amplification on chip. The optical phonon in silicon has a frequency of 15.6THz[8] causing a Raman shift of 520cm^{-1}.[9] Because of the crystalline structure of the silicon, the bandwidth of the Raman phonon spans only 105GHz. This is small compared to the relatively large Raman bandwidth of ~6THz that is present in silica fibers. The result of this small bandwidth is that the Raman gain spectrum is only 0.9nm in width[8] and has a relatively long lifetime of 3ps compared to ~6fs for silica. However, when the silicon lattice is pumped with a high power broadband signal as shown in the previous paragraph, this small gain bandwidth limitation can be overcome.

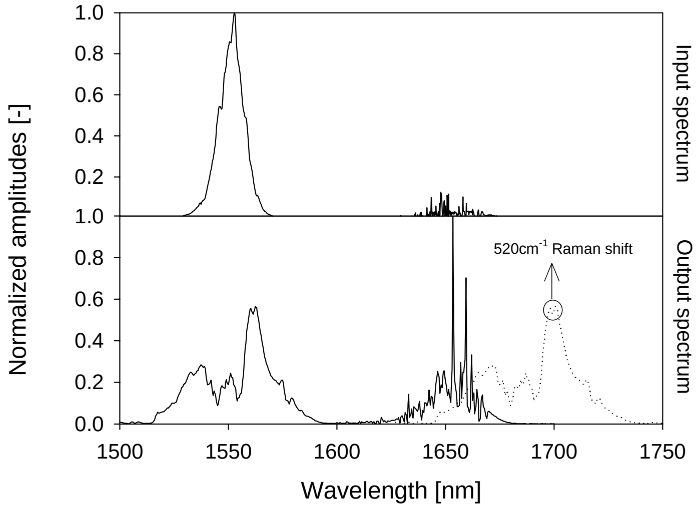


Figure 2: (top) Input spectrum from the OPO with a center pump wavelength at 1550nm and a weak idler signal at 1650nm. (bottom) Broadened output spectrum with an amplified idler signal due to Raman amplification (dotted: 520cm^{-1} shifted pump spectrum).

The input spectrum of the 1550nm pump beam together with a weak idler signal from the OPO at 1650nm is shown in the top of Figure 2. The bottom graph of Figure 2 shows the normalized output spectrum after propagation through the silicon waveguide, which is broadened due to SPM. Furthermore, a strong enhancement of the idler signal due to Raman amplification can be observed. The induced Raman shift of 520cm^{-1} on the pump spectrum is plotted as well and indicates the wavelength region where the Raman amplification takes place and its relative magnitude. The long wavelength part of the idler signal is being pumped by the short wavelength lobe of the SPM broadened pump spectrum.

The normalized power fractions of the pump (1500nm-1600nm) and idler (1600nm-1700nm) wavelengths have been determined for both the input and output spectrum and are listed in Table 1. The contribution of the idler has been increased from 7.2% to 29.5%, indicating that energy is transferred from the pump to the idler wavelengths (assuming that the optical losses are flat in the range 1500nm-1700nm).

Table 1: Power fractions of pump and idler signal for input and output signal, respectively.

Spectral range	Input signal	Output signal
1500nm-1600nm	92.8 %	70.5 %
1600nm-1700nm	7.2 %	29.5 %

Conclusions

Spectral broadening from 12nm to 50nm of 1550nm pump pulses caused by SPM has been observed in silicon-on-insulator waveguides. The intrapulse redshift of the pump pulse is believed to be caused by strong dispersion in the waveguide. ISRS can be excluded to be the cause of the resulting asymmetry of the broadened pump spectrum, since the gain spectrum is extremely narrow and the slope of the gain curve is zero in the wavelength range of the pump. Furthermore, an enhancement of the broad idler wavelengths due to the Raman gain is presented. This broad gain spectrum is pumped by the SPM broadened pump pulse.

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