Time-resolved study of Raman gain in highly confined silicon-on-insulator waveguides

Qianfan Xu, Vilson R. Almeida and Michal Lipson

School of Electrical and Computer Engineering
Cornell University, Ithaca, NY 14853
lipson@ece.cornell.edu

http://nanophotonics.ece.cornell.edu

Abstract: We show time-resolved measurement of Raman gain in Silicon submicron-size planar waveguide using picosecond pump and probe pulses. A net nonlinear gain of 6 dB is obtained in a 7-mm long waveguide with 20.7-W peak pump power. We demonstrate an ultrafast all-optical switch based on the free-carrier dispersion effect in the silicon waveguide, whose transmission is enhanced by more than 13 dB due to the Raman effect.

OCIS codes: (230.7380) Waveguides, channeled; (190.4390) Nonlinear optics, integrated optics.

References and links

1. M. Dinu, F. Quochi, and H. Garcia, "Third-order nonlinearities in silicon at telecom wavelengths," Appl. Phys. Lett. **82**, 2954-2956 (2003).
2. G. W. Rieger, K. S. Virk, and J. F. Young, "Nonlinear propagation of ultrafast 1.5 µm pulses in high-index-contrast silicon-on-insulator waveguides," Appl. Phys. Lett. **84**, 900-902 (2004).
3. R. A. Soref and B. R. Bennett, "Electrooptical effects in silicon," IEEE J. Quantum Electron. **23**, 123-129 (1987).
4. R. Clap, D. Dimitropoulos, V. Raghunathan, Y. Han and B. Jalali, "Observation of stimulated Raman amplification in silicon waveguides," Opt. Express **11,** 1731-1739 (2003). http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-15-1731
5. T. K. Liang, H. K. Tsang, "On Raman gain in silicon waveguides: limitations from two-photon-absorption generated carriers", *CLEO/IQEC and PhAST Technical Digest on CDROM* (The Optical Society of America, Washington, DC, 2004), CThT48.
6. A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen, R. Nicolaescu, and M. Paniccia, "A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor," Nature **427**, 615-618 (2004).
7. S. Stepanov and S. Ruschin, "Modulation of light by light in silicon-on-insulator waveguides," Appl. Phys. Lett. **83**, 5151-5153 (2003).
8. V. Raghunathan, D. Dimitropoulos, R. Claps, and B. Jalali, " Wavelength conversion in silicon waveguides using parametric Raman coupling," *CLEO/IQEC and PhAST Technical Digest on CDROM* (The Optical Society of America, Washington, DC 2004), CMP2.
9. S. Nakamura, Y.Ueno, and K. Tajima, "Ultrafast all-optical switching using a frequency shift accompanied by cross-phase modulation in a semiconductor optical amplifier," *Technical Digest. Summaries of papers presented at the Conference on Lasers and Electro-Optics*, 348-349 (2001).
10. Almeida, R. R. Panepucci, and M. Lipson, "Nanotaper for compact mode conversion," Opt. Lett. **28**, 1302-1304 (2003).
11. C. L. Xu, W. P. Huang, M. S. Stern, and S. K. Chaudhuri, "Full-vectorial mode calculations by finite difference method," IEE Proc.-Optoelectron. **141**, 281-286 (1994).
12. R. Claps, V. Raghunathan, D. Dimitropoulos, and B. Jalali, "Influence of nonlinear absorption on Raman amplification in silicon waveguides," Opt. Express **12**, 2774-2780 (2004). http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-12-2774
13. V. R. Almeida, C. A. Barrios, R. R. Panepucci and M. Lipson, "All-optical control of light on a silicon chip," accepted for publication in Nature (2004).
14. P. J. Delfyett, R. Dorsinville, and R. R. Alfana, "Real-time measurements of phonon lifetime using streak-camera-Raman-induced phase-conjugation method," Opt. Lett. **12**, 1002-1004 (1987).
15. T. Tanabe, K. Suto, T. Saito, T. Kimura, Y. Oyama, and J. Nishizawa, "Characteristics of time-gated Raman amplification in GaP-AlGaP semiconductor waveguides," J. App. Phys. **93**, 43-46 (2003).

#5087- $15.00 US
Received 20 August 2004; revised 7 September 2004; accepted 8 September 2004

1. Introduction

Silicon can be an efficient medium to guide light in telecommunication wavelengths. Optical devices and waveguides have been fabricated on silicon-on-insulator (SOI) platform, showing compatibility with existing electronic technologies. As a transmission medium, silicon has much higher nonlinear effects than the commonly used Silicon dioxide. The major nonlinear effects in Silicon are Kerr effect, two-photon absorption effect, free-carrier effect, and Raman effect [1-5]. Various optical devices have been fabricated on the SOI platform based on such nonlinearities, including electrooptic switch [6], all-optical switch [7], wavelength converter [8], and Raman amplifier [4]. Most of these devices are based on micron-size ridged waveguides with relatively large dimensions. Here we present a study of the Raman effect in Silicon waveguides using highly confined strip waveguides. The high confinement in such waveguides induces an enhancement of the nonlinear effects, enabling ultra-compact devices with low operation power.

Stimulated Raman scattering has been explored recently has a possible way to achieve optical gain in Silicon waveguides. 0.25 dB Raman gain has been demonstrated in a 1.8-cm long micron-size ridged waveguides with 1.6-W pump power [4]. In this paper, we use a highly confined strip waveguide, for achieving large Raman gain. We measure a 14-dB Raman gain with 6-dB net nonlinear gain using a pump pulse with 20.7-W peak power. Using a picosecond pulse as the probe, the gain dynamics and the effects of two-photon absorption (TPA) and free-carrier absorption (FCA) on the probe pulse are resolved.

One application of Raman effect in Silicon is to enhance the transmission of nonlinear optical devices based on silicon. Here we demonstrate an ultrafast all-optical switch based on the frequency-shift due to the cross-phase modulation (XPM) caused by free-carrier dispersion effect. We show a 13.2-dB enhancement of the transmission from stimulated Raman scattering when the signal light is at the Stokes wavelength. While an ultrafast switch based on similar principle has been demonstrated using semiconductor optical amplifier as the nonlinear media [9], to the best of our knowledge, this paper is the first demonstration of this type of switch on SOI platform.

2. Time-resolved measurement of Raman gain

A 7-mm strip SOI waveguide is used for measuring the dynamics of the Raman effect. The waveguide was fabricated using a similar process as described in [10]. The core of the waveguide has a height of 250 nm and a width of 450 nm. The modal area of the quasi-TE mode is 0.14 μm^2 at the wavelength of 1590 nm and 0.15 μm^2 at the wavelength of 1730 nm calculated by simulating the mode profile of the waveguide with a full-vectorial finite-difference mode solver [11]. The insertion loss of the waveguide, which include the input coupling loss and the propagation loss of the waveguide, is 3.6 dB for the quasi-TM mode and 5.5 dB for the quasi-TE mode at the wavelength near 1550 nm.

Both the pump pulse at 1589.5 nm and the probe pulse at 1731.5 nm are generated by a tunable optical-parametric oscillator (OPO). Both pump and probe have a Gaussian spectrum with 1.2-nm FWHM. The FWHM widths of the pulses are measured with an autocorrelator to be 3.5 ps for the pump and 3.7 ps for the probe, assuming Gaussian pulse shape. Therefore, the time-bandwidth product of the pump pulse and probe pulse are 0.47 and 0.45 respectively, showing almost transform limited Gaussian pulses. The repetition rate of both pump and probe pulse is 76.8 MHz.

The time delay of probe pulse with respect to the pump pulse is controlled by a translation stage. The pump and probe are coupled into two fibers using fiber collimators and are joined together using a 10:90 coupler. The pump and probe are then in-plane coupled to the waveguide using a nano-taper [10]. The average pump power at the input of the nano-taper is 5.9 mW, corresponding to a peak power of 20.7 W. The power of the probe is kept 20 dB lower than pump in order to avoid the depletion of the pump power due to the Raman effect. Since the probe power is low, the nonlinear effect caused by the probe pulse itself can be neglected. The output of the waveguide is filtered by a grating, and the average probe power is measured. In the experiment, both pump and probe light are in quasi-TE polarization. The walk-off between the pump pulse and the probe pulse due to dispersion in the 7-mm waveguide is measured to be less than 2 ps.

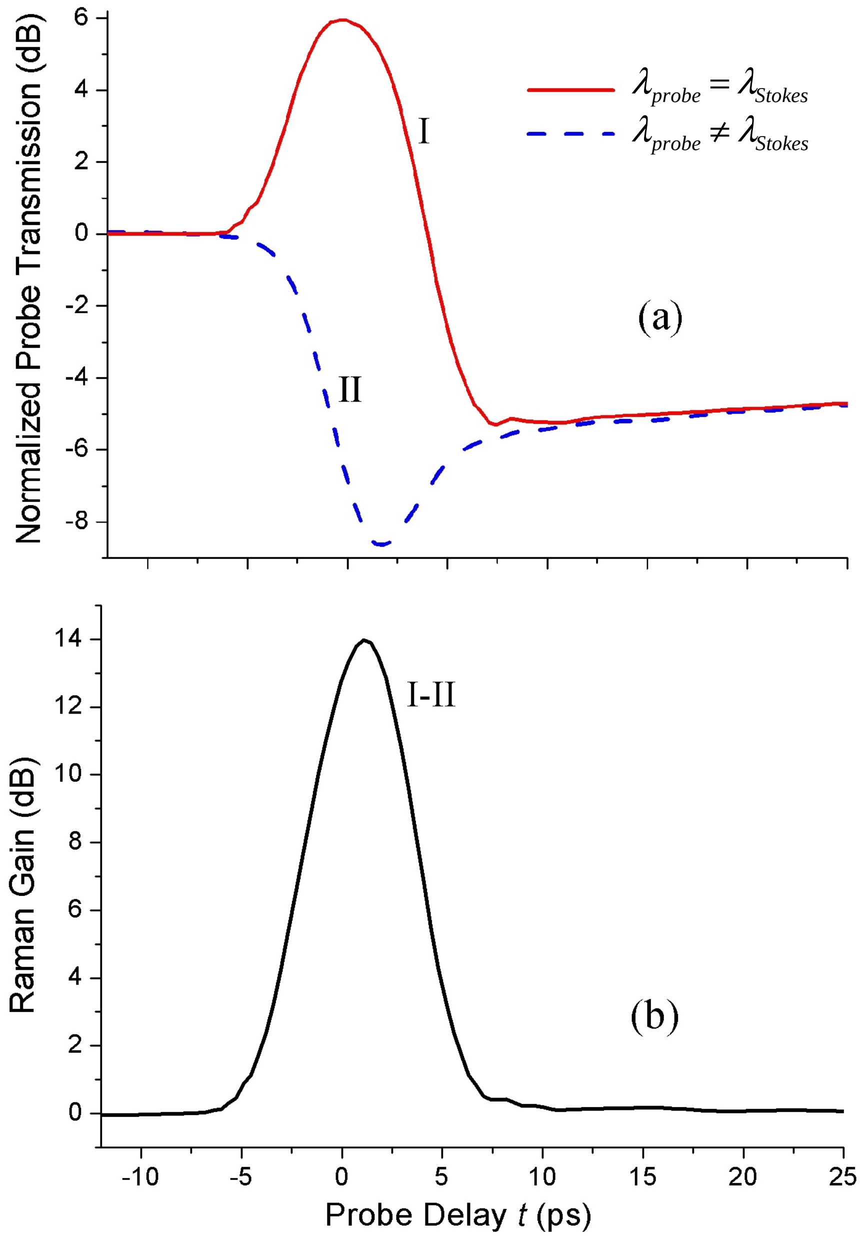

Fig. 1. (a): Normalized probe transmission versus the relative time delay between the probe and the pump when the λ_{pump} = 1589.5 nm, λ_{probe} = 1731.5 nm (red solid line), λ_{pump} = 1580.8 nm, λ_{probe} = 1741.1 nm (blue dashed line), respectively. (b): Raman gain versus the relative delay of the probe, obtained from the difference between the two lines in (a).

Figure 1(a) shows the normalized transmission of the probe pulse through the waveguide versus the relative time delay t of the probe pulse with respect to the pump pulse. The two transmission curves are shown for a probe wavelength corresponding to the Stokes wavelength (solid line) and for a probe wavelength detuned from the Stokes wavelength

#5087- $15.00 US
Received 20 August 2004; revised 7 September 2004; accepted 8 September 2004

(dashed line). When the probe pulse leads the pump pulse (t < -7 ps in Fig. 1(a)), the transmission of the probe is not affected by the pump, since the nonlinear interaction between the pump and the probe is negligible. When the probe pulse overlaps with the pump pulse, the probe pulse experiences Raman gain if it's at the Stokes wavelength, as the red line in Fig. 1(a) shows. At the same time, the probe pulse also experiences Two Photon Absorption (TPA), where one pump photon and one probe photon are absorbed simultaneously, and Free Carrier Absorption (FCA), where the free carriers are generated mainly by TPA of the pump pulse [5,12]. One can see in Fig. 1(a) that the net nonlinear gain, defined by the transmission enhancement of the probe pulse, is as high as 6 dB. In order to separate the Raman effect from the nonlinear absorption effects, we measure the transmission when the probe wavelength is detuned from the Stokes wavelength (blue dashed line in Fig. 1(a)), where Raman gain is expected to be minimal while the nonlinear absorption effects are expected to be dominant. One can see from Fig. 1(a) the combined effect of TPA and FCA. While TPA is only present when the probe pulse overlaps with the pump pulse (-3 ps < t < 6 ps in Fig. 1(a)), FCA is also present when the probe pulse follows the pump pulse (t >6 ps in Fig. 1(a)). This is due to the relatively long free carrier lifetime in the waveguide, on the order of 1 ns [13].

The Raman effect can be isolated from the nonlinear absorption effect by comparing the two curves in Fig. 1(a). The magnitude of Raman gain shown in Fig. 1(b) is obtained by calculating the difference between the red curve and the blue curve. One can see from Fig. 1(b) that the peak Raman gain is 14 dB. The FWHM width of the Raman gain is 6.3 ps, as a result of the dynamic interaction of the pump pulse with a FWHM of 3.5 ps, the probe pulse with a FWHM of 3.7 ps, and the phonon lifetime with a FWHM of 3 ps. The phonon lifetime is estimated [14] from the Raman spectrum FWHM of 105 GHz shown in [4].

3. All-optical switch with Raman gain

Here we use the Raman gain in silicon to enhance the transmission of an ultrafast all-optical switch based on the free-carrier dispersion effect in the waveguide, taking advantage of the high peak gain and fast response of the Raman effect.

The switch is formed by a picosecond pump pulse and a CW probe light injected into the waveguide. When the pump pulse propagates through the waveguide, free carriers are generated due to the TPA effect. The free-carriers effect not only causes excess absorptions, as mentioned before, it also induces a change in the refractive index of the Silicon (Δn) through the free-carrier dispersion effect [3]. The phase of the output probe light is therefore modified ($\Delta\phi$) due to the free carrier dispersion effect as:

$$\Delta\phi(t) = \frac{2\pi L}{\lambda}\Delta n(t) \propto \int_0^t \beta \cdot \left[\frac{P_p(\tau)}{A}\right]^2 d\tau \qquad (1)$$

where L is the length of the waveguide, λ is the wavelength of the light, and β is the TPA coefficient. P_p is the intensity pulse of the probe and A is the area of waveguide. The recombination of the free-carrier is neglected in this equation, since the pulse width is on the order of ps, much smaller than the carrier lifetime of ~ 1 ns. The temporal variation of the phase given in Eq. 1 results in a frequency shift of the probe light:

$$\Delta\omega(t) = \frac{d}{dt}\Delta\phi(t) \propto \beta\left[\frac{P_p(t)}{A}\right]^2. \qquad (2)$$

High modulation of the probe signal is achieved using a narrow filter at the output of the waveguide, which allows only the blue-shifted part of the probe to pass when the pump pulse is present. Here we use a tunable grating filter with 0.25-nm FWHM at the output of the waveguide. The filter is centered at a wavelength 1.6 nm shorter than the wavelength of the CW probe light. When the pump pulse is not present, the transmission of the probe through the filter is less than -40 dB. Only when the pump pulse is present, the probe is blue-shifted and is transmitted through the filter. Since the transmission of the probe is determined by the

#5087- $15.00 US Received 20 August 2004; revised 7 September 2004; accepted 8 September 2004

derivative of the change in index, the switching time of the switch is controlled by the width of the pump pulse, in the order of picosecond. This is in contrast to the previously demonstrated all-optical switch in Silicon [13], where the switching time is limited by the carrier lifetime in the waveguide, in the order of nanosecond.

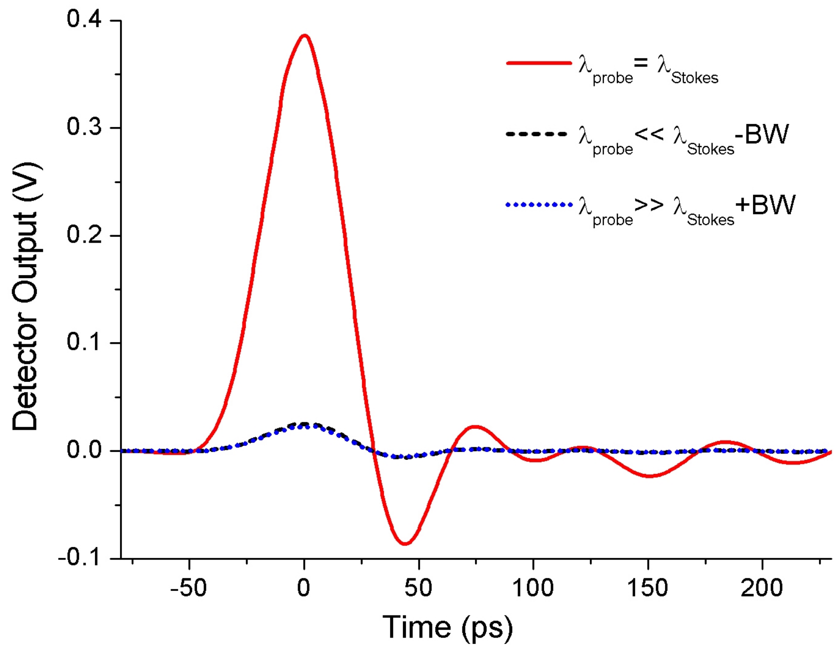

Fig. 2. The output of the ultrafast switch measured by a 12-GHz detector. Solid line: λ_{probe} = 1549.0 nm, λ_{filter} = 1547.4 nm. Dashed line: λ_{probe} = 1539.0 nm, λ_{filter} = 1537.4 nm. Dotted line: λ_{probe} = 1559.0 nm, λ_{filter} = 1557.4 nm. BW = 0.9 nm is the bandwidth of the Raman spectrum.

Here we use the Raman effect to further amplify the probe when the pump is present. In the experiment, the pump is in quasi-TM mode, and the probe is in quasi-TE mode. The central wavelength of the pump is 1433.2 nm. The Stokes wavelength is calculated to be λ_{Stokes} =1548.7 nm [4]. In Fig. 2, we show the output of the filter at the pump peak power of 14.8 W, when the probe is at the Stokes wavelength (solid line), 10-nm lower than the Stokes wavelength (dashed line), and 10-nm higher than the Stokes wavelength (dotted line), respectively. These waveforms show the switching of the probe by the pump pulse. On the time axis, the 0 point correspond to the position of the pump pulse. Since we use a 12-GHz detector with ~ 30 ps rise and fall time to obtain the waveforms, we see much longer pulses than the actual switched probe light. The ripples following the major pulse of each waveform are the result of the detector response. When the probe wavelength does not correspond to the Stokes wavelength, we see only the switching effect (Fig. 2 dashed and dotted lines). The peak transmission of the switch is relatively low, approximately –20 dB, due mainly to the narrow linewidth of the filter we use. When the probe wavelength does correspond to the Stokes wavelength (Fig 2 solid line), the probe is strongly amplified by Raman effect when the pump pulse is present; therefore, the transmission of the switch is greatly enhanced. By comparing the three waveforms in Fig. 2, one can see that the output power when the probe is at Stokes wavelength is 13.2 dB higher than that when the probe is at other wavelengths, showing a 13.2-dB transmission enhancement due to Raman effect.

The solid line with rectangles in Fig. 3 shows the Raman gain obtained in similar experiments performed using different pump powers. At low pump powers, the Raman gain increases linearly with the pump power. At high pump powers (>~ 10 W), the Raman gain saturates and then decreases with the increase of the pump power. Several effects contribute to the saturation of Raman Gain at high power, including the extra loss of the pump due to TPA

Received 20 August 2004; revised 7 September 2004; accepted 8 September 2004

and FCA, and the decrease of 3-dB gain bandwidth at high pump powers [15]. The magnitudes of FCA at different pump powers are measured from the slowly varying component of nonlinear absorption (*t* >6 ps in Fig. 1(a)), and are shown in Fig. 3 (dashed line with triangles).

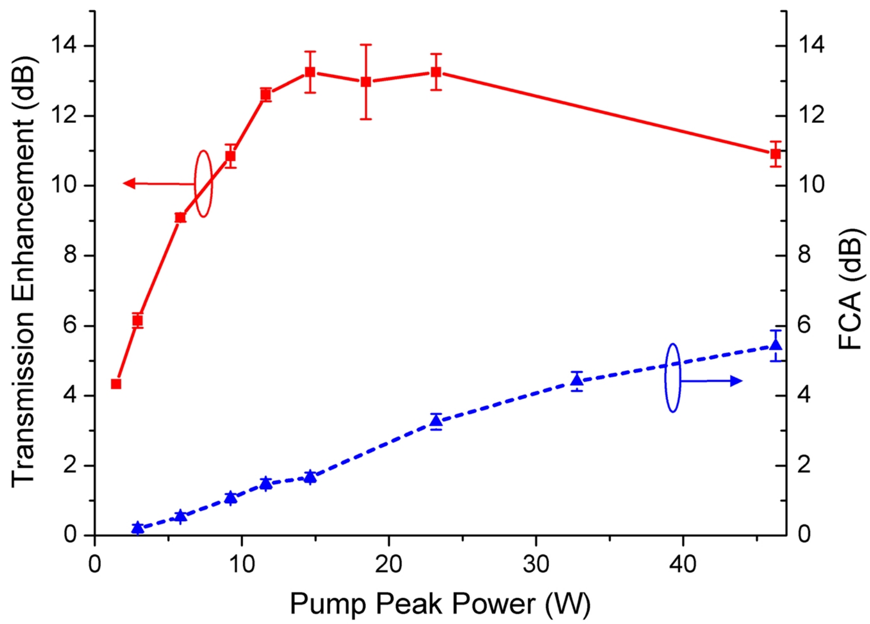

Fig. 3. Solid line with rectangles: the transmission enhancement of the ultrafast switch due to the Raman effect versus the peak power of the pump pulse. Dashed line with triangles: FCA on the probe immediately after the pump pulse passes.

4. Conclusion

We show 14 dB Raman gain and 6 dB net nonlinear gain in a 7-mm long SOI strip waveguide with ultrafast pump-probe measurement. The Raman effect can be applied to enhance the transmission of nonlinear optical devices based on silicon waveguides.

Acknowledgments

This work is supported by the Air Force Office of Scientific Research under grant number AFOSR F49620-03-1-0424. The experiments are performed at the Cornell Center for Nanoscale Systems, supported by the Nanoscale Science and Engineering Initiative of the National Science Foundation under NSF Award # EEC-0117770 and the New York State Office of Science, Technology & Academic Research under NYSTAR Contract # C020071.