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Light generation, amplification, wavelength conversion, and 3-D photonic integration in silicon

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For some time now, Raman Effect in optical fibers has been exploited in fiber amplifiers and lasers. However, several kilometers of fiber are typically required to create a useful device. Often neglected, is the fact that the gain coefficient for Stimulated Raman Scattering (SRS) is approximately 10^4 times higher in silicon than in the silica fiber. Additionally, Silicon-On-Insulator (SOI) waveguides can confine the optical field to an area that is more than 100 times smaller than the modal area in a standard single-mode optical fiber, resulting in extremely high optical intensities. When combined, these features allow us to observe SRS over the millimeter-scale interaction lengths on a silicon chip. A desirable feature of Raman scattering is that light generation and amplification can be achieved at any wavelength (as long as the corresponding pump laser wavelength is available). Further, it does not require special impurities; therefore, the resulting devices can be integrated with electronic ICs and manufactured in any silicon foundry.

Figure 2 shows the measured stimulated amplification on waveguides with different dimensions. It should be noted that due to large waveguide losses (propagation and coupling) the net gain is negative. The gain spectrum is centered at 1542nm is red-shifted from the pump (@ 1428nm) by 114nm, in excellent agreement with the optical phonon frequency in silicon [1]. The waveguides have the rib geometry and are fabricated along the $[1\bar{1}0]$ direction on a silicon $[001]$. The measured gain bandwidth is 300 GHz, which is broader that the intrinsic Raman linewidth of 100 GHz due to the finite pump linewidth [1]. Typically, waveguide propagation and coupling losses prevent realization of photonic circuits with any significant level of complexity. By compensating for propagation loss and coupling loss, on-chip amplification can enable higher levels of integration in photonic circuits. Achieving high gain requires submicron waveguides as well as means to reduce waveguide losses including the free carrier loss due to two photon absorption

The Raman contribution to the 3^{rd} order nonlinear susceptibility can be used to perform wavelength conversion [2, 3]. Wavelength conversion is of paramount importance in optical networks because it enables optical packet switching, a milestone in the realization of all-optical networks. 1. Figure 2a shows the measured spectrum of wavelength conversion when a 1542nm signal is converted to 1328nm via interaction with a pump at 1428nm [2, 3]. Figure 2b shows eye diagram of converted data recovered at 1328nm. The conversion efficiency was limited by phase mismatch to 10^{-5}. Phase matching and hence efficient conversion can be achieved when waveguide birefringence is used to cancel material dispersion [4].

The next generation of Raman based devices require the ability to reduce the optical mode area while maintaining low propagation losses. In addition, a micro resonator with high quality factor is needed to realized a laser. Combined with 3-D integration, such a technology will create complex photonic circuits consisting of active and passive devices. Figure 3 shows the cross section of a multi-layer Si/SiO2 structure fabricated with the new SIMOX Sculpting process developed at UCLA [5]. The technology offers precise control of coupling coefficient in vertically coupled devices, and low losses made possible by smooth interfaces produced by ion implantation. The process has already produced extremely low loss buried waveguides and high Q optical resonators [5].

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[1] R. Claps, et al., Opt. Exp. **11**, 1731-1739 (2003).
[2] R. Claps, et al., Opt. Exp. **11**, 2862-2872 (2003).
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[5] P. Koonath, et al., Appl. Phys. Lett., **83**, 4909-4911, (2003).

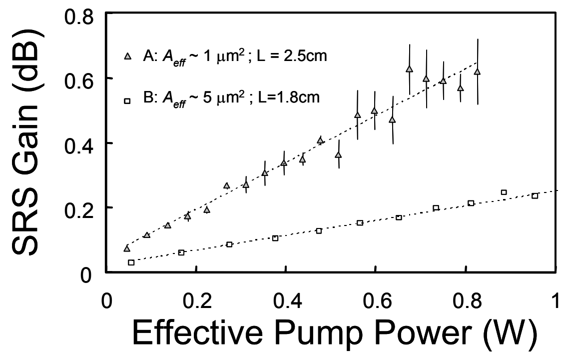

Figure 1 Measured internal Raman gain.

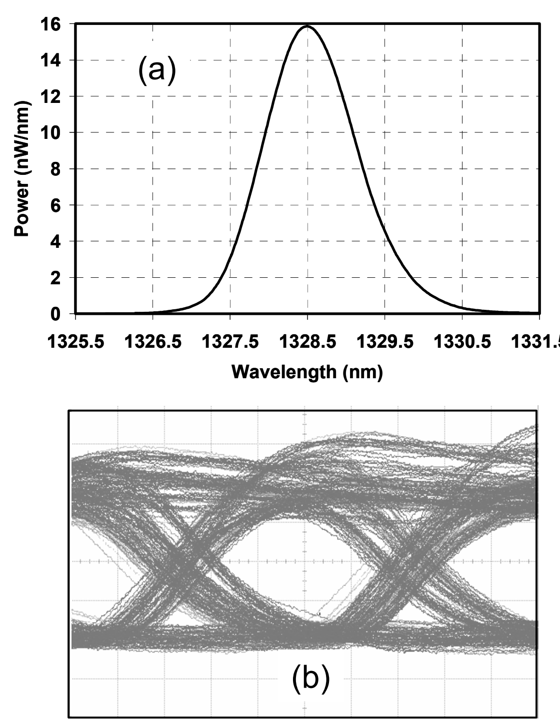

Figure 2 Wavelength conversion from 1542nm to 1328nm. Measure spectrum (a) and eye diagram (b).

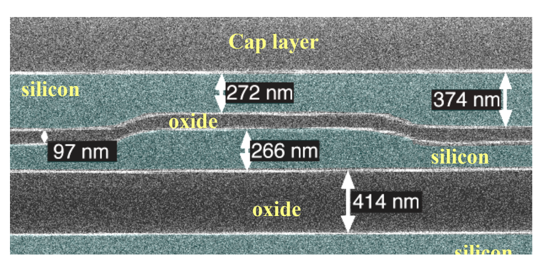

Figure 3 Vertically coupled structures fabricated using the SIMOX 3-D Sculpting