Demonstration of a silicon Raman laser

Ozdal Boyraz and Bahram Jalali

Optoelectronic Circuits and Systems Laboratory
University of California, Los Angeles
Los Angeles, CA 90095-1594
jalali@ucla.edu

http://www.ee.ucla.edu/~oecs/

Abstract: We report the demonstration of the first silicon Raman laser. Experimentally, pulsed Raman laser emission at 1675 nm with 25 MHz repetition rate is demonstrated using a silicon waveguide as the gain medium. The laser has a clear threshold at 9 W peak pump pulse power and a slope efficiency of 8.5%.

OCIS codes: (190.4390) Nonlinear optics, integrated optics, (230.4320) Nonlinear optical devices, (230.7370) Waveguides, (250.5300) Photonic integrated circuits, (140.3550) Lasers, Raman, (140.5960) Semiconductor lasers

References and links

1. L. Pavesi and D. J. Lockwood, *Silicon Photonics* (Springer-verlag, New York, 2004).
2. G. T. Reed and A. P. Knights, *Silicon Photonics: An Introduction* (John Wiley, West Sussex, 2004).
3. B. Jalali, S. Yegnanarayanan, T. Yoon, T. Yoshimoto, I. Rendina, F. Coppinger, "Advances in silicon-on-insulator optoelectronics," IEEE Journal of Selected Topics in Quantum Electronics, **4** , 938-947 (1998)
4. R. Claps, D. Dimitropoulos, Y. Han, and B. Jalali, "Observation of Raman emission in silicon waveguides at 1.54 µm," Opt. Express, **10**, 1305-1313 (2002), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-10-22-1305
5. R. Claps, D. Dimitropoulos, V. Raghunathan, Y. Han, 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
6. R. Claps, V. Raghunathan, D. Dimitropoulos, B. Jalali, "Anti-Stokes Raman conversion in Silicon waveguides," Opt. Express, **11**, 2862-2872 (2003) http://www.opticsexpress.org/abstract.cfm?URI=OPEX-11-22-2862
7. T.K. Liang, H.K. Tsang; "Role of free carriers from two-photon absorption in Raman amplification in silicon-on-insulator waveguides," Appl. Phys. Lett., **84**, 2745-2747 (2004).
8. 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
9. J. I. Dadap, R. L. Espinola, R. M. Osgood, Jr., S. J. McNab, Y. A. Vlasov, "Spontaneous Raman scattering in a silicon wire waveguide," Proceedings of IPR 2004, Paper IWA4, (2004)
10. V. Raghunathan, D. Dimitropoulos, R. Claps and B. Jalali, "Raman induced wavelength conversion in scaled Silicon waveguides," IEICE Electron. Express, **12**, 298-304 (2004)
11. A. Liu, H. Rong, M. Paniccia, O. Cohen, and D. Hak, "Net optical gain in a low loss silicon-on-insulator waveguide by stimulated Raman scattering," Opt. Express **12,** 4261-4268 (2004) http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-18-4261
12. T.K. Liang and H.K. Tsang, "Pulsed-pumped silicon-on-insulator waveguide Raman amplifier," Proceedings of International Conference on Group IV Photonics, 2004, WA4
13. B. Jalali, V. Raghunathan, O. Boyraz, R. Claps and D. Dimitropoulos, "Wavelength Conversion and Light Amplification in Silicon Waveguides," Proceedings of International Conference on Group IV Photonics, 2004, WA3
14. Q. Xu, V. R. Almeida, and M. Lipson, "Time-resolved study of Raman gain in highly confined silicon-on-insulator waveguides," Opt. Express, **12**, 4437-4442 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-19-4437
15. P. A. Temple, C. E. Hathaway, "Multiphonon Raman Spectrum of Silicon," Phys. Rev. B, **7,** 3685-3697 (1973)
16. M. Cardona, G. Guntherodt, *Light Scattering in Solids II*, (Springer-Verlag, Berlin, 1982).

#5362 - $15.00 US Received 23 September 2004; revised 12 October 2004; accepted 13 October 2004

17. A. E. Siegman, *Lasers*, (University Science Books, Sausalito, CA, 1986)
18. G. P. Agrawal, *Nonlinear Fiber Optics*, (Academic Press, 1995).
19. P.Koonath, T.Indukuri and B.Jalali, "Vertically-coupled microdisk resonators realized using three-dimensional sculpting in Silicon," Appl. Phys. Lett. **85**, 1018 (2003).
20. Ming-Chang M. Lee and Ming C. Wu, "A MEMS-Actuated Tunable Microdisk Resonator," IEEE International Conference on Optical MEMS, 2003, MC3

1. Introduction

The need for low cost photonic devices has stimulated a significant amount of research in silicon photonics [1-2]. While a wide variety of passive devices were developed in the 1990's [3], recent activities have focused on achieving active functionality, mostly light amplification and generation, in silicon waveguides [1-2]. One approach that has been investigated for light generation and amplification is the Raman effect [4-6]. This approach relies on the fact that the Raman gain coefficient in silicon is rather strong (10^4 times higher than in fiber), making it possible to achieve gain over the length scales of an integrated waveguide [4].

Obtaining net Raman gain in silicon is challenging due to the losses induced by free carriers that are generated by the Two Photon Absorption (TPA) process in silicon [7-8]. One method for diminishing these losses is to reduce the free carrier lifetime through lateral scaling of waveguide modal area [8-10]. Another approach for reducing free carrier losses is to use pulsed pumping. To the extent that the pulse width is much less than the carrier lifetime and the pulse period is much larger than the lifetime, free carrier generation becomes negligible making it possible to obtain net gain [11-14]. Using this technique fiber-to-fiber net gain of 11 dB has recently been reported [13].

In this paper, we report the demonstration of a Raman laser in silicon. The laser consists of a silicon gain medium incorporated in a fiber loop cavity. It is pumped with 30 ps wide pump pulses at a 25 MHz repetition rate and is centered at 1540 nm. The laser produces output pulses at the Stokes wavelength of 1675 nm. A clear lasing threshold is observed at 9 W peak pulse power along with a slope efficiency of 8.5% above threshold. To the best of our knowledge, this is the first ever demonstration of a silicon laser.

2. Experimental results

A modelocked fiber laser operating around 1540 nm with a 25 MHz repetition rate is used as a pulsed pump laser. In the present experiment, to prevent excessive spectral broadening and the pulse distortion in the EDFA and in the fiber patchcords, the pulses are broadened to 30 ps in a spool of fiber before amplification to the desired peak power. A tapered Silicon-On-

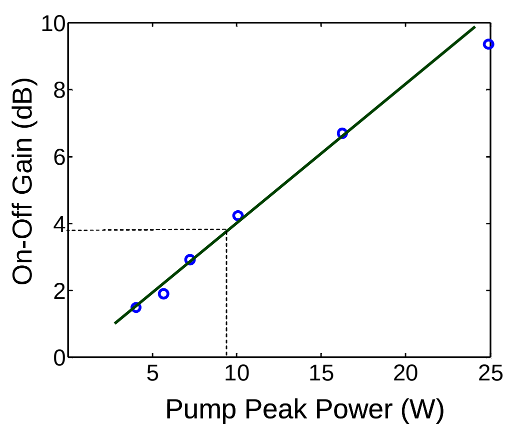

Fig. 1. Measured on-off gain in the silicon waveguide for a probe signal at 1675 nm. Pumping was done at 1540 nm with 30 ps pulses.

#5362 - $15.00 US Received 23 September 2004; revised 12 October 2004; accepted 13 October 2004

Insulator (SOI) rib waveguide with approximately 2 cm in length, and a total insertion loss (coupling plus propagation) of 0.8 dB, is used as a gain medium. We first characterize the Raman gain in the silicon waveguide, using a CW laser at 1675 nm (Stokes wavelength) as the probe signal. Gain is measured by observing the enhancement of the probe signal in the presence of the pump pulse. The results, shown in Fig. 1, indicate that the silicon waveguide provides up to 9 dB of on-off gain at 25 W of peak pump power.

The setup for demonstration of the silicon Raman laser is shown in Fig. 2. In this case, no

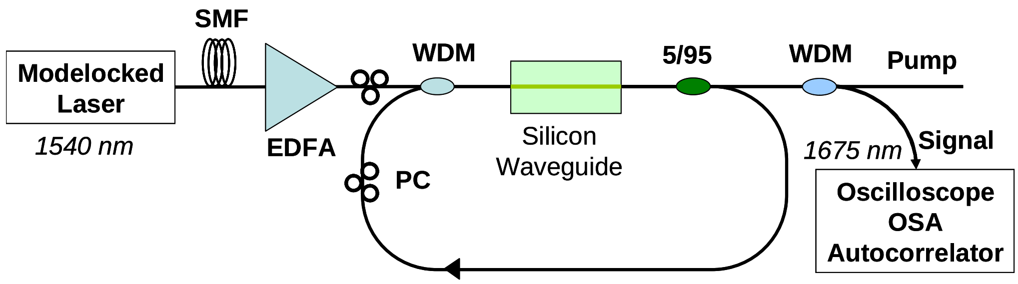

Fig. 2. Experimental set up used for silicon Raman laser demonstration. A ring cavity configuration is used as a resonator. A modelocked fiber laser at 1540nm is used as a pump laser. The lasing is obtained at the Stokes wavelength of 1675 nm.

probe signal is used. Pump pulses are coupled into the laser cavity by using a Wavelength Division Multiplexer (WDM) coupler [13]. The laser cavity is formed using a fiber ring configuration. Following the silicon waveguide a tap coupler with 5 to 95% splitting ratio is used to extract 5% of the power as the output. The 95% output of the tap coupler is looped back into the WDM coupler to form the ring cavity. Residual pump power is blocked by the WDM coupler. By measuring the propagation time of the modulated 1675 nm CW laser the cavity round trip time is measured and the cavity length (~ 8 m) is adjusted such that the cavity roundtrip time will match the pump pulse period of 40 ns. Two Polarization Controllers (PC) are inserted on the pump arm and in the cavity to adjust the relative polarizations of the pump and the laser. The pump polarization is set to TE polarization to obtain maximum coupling. The polarization state of the stokes is adjusted for maximum output power. The total cavity loss, including the silicon waveguide, measured at the Stokes wavelength (1675 nm) is measured to be 3.7 dB. A second WDM is used at the laser output to separate the pump and

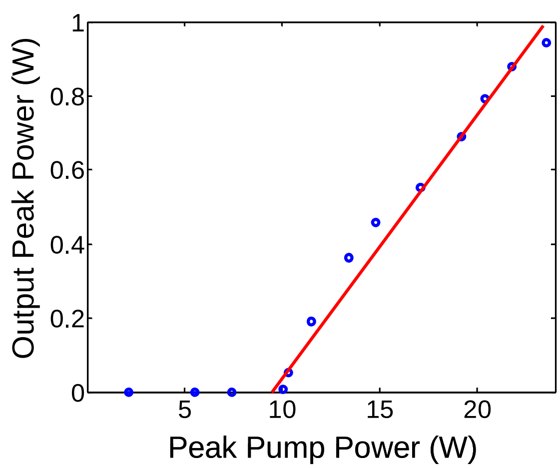

Fig. 3. Measured laser output power with respect to peak pump power. Lasing threshold is measured to be at 9 W peak power level. The slope efficiency is ~8.5%.

#5362 - $15.00 US
Received 23 September 2004; revised 12 October 2004; accepted 13 October 2004

signal wavelengths. The temporal characteristics of the laser are measured by a 40 GHz sampling oscilloscope, and separately with an autocorrelator. An Optical Spectrum Analyzer (OSA) is used to measure the spectrum.

The measured laser output power variation with respect to pump peak power is illustrated in Fig. 3. The peak pump power is varied from 0 to 25 W to characterize the lasing behavior and to determine the lasing threshold. Lasing, characterized by a sudden increase in emission at the Stokes wavelength of 1675nm, is obtained when the pump peak power level reaches 9 W. The threshold should occur when the waveguide gain compensates for the cavity loss. The threshold power of 9 W is consistent with the measured cavity loss of 3.7 dB and the measured Raman gain of ~3.9 dB at 9 W pump power (Fig. 1). After exceeding the threshold level the output increases almost linearly with the pump power. The slope efficiency, which is described by the ratio of the output peak power and the input peak pump power, is 8.5%.

Figure 4 presents the measured laser spectrum (4a) and that of the pump (4b). The spectral peak of the silicon Raman laser is at 1675 nm, which is precisely the expected location based on the optical phonon frequency (15.6 THz) in silicon [4, 15-16]. The 3 dB bandwidth of the laser is measured to be 0.36 nm (~38.5 GHz). The pump laser, on the other hand, is centered at 1540 nm with a 3 dB bandwidth of 0.7 nm (~88.5 GHz). [4, 15-16]. The narrower laser bandwidth can be explained by the gain narrowing, a well known behavior in lasers [17]. The spectral features and the asymmetric structure of the laser spectrum are

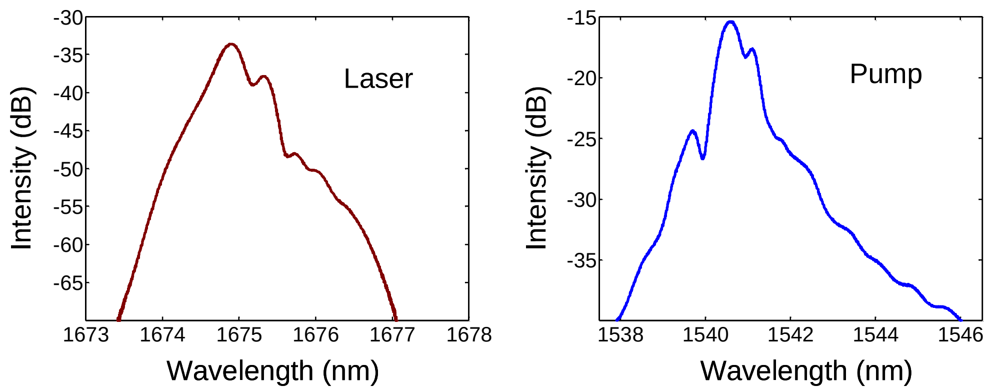

Fig. 4. Measured laser and pump spectra. The laser spectrum has 0.36 nm spectral bandwidth and is located 15.6 THz away from the pump laser. The pump-output separation is precisely the optical phonon frequency in silicon.

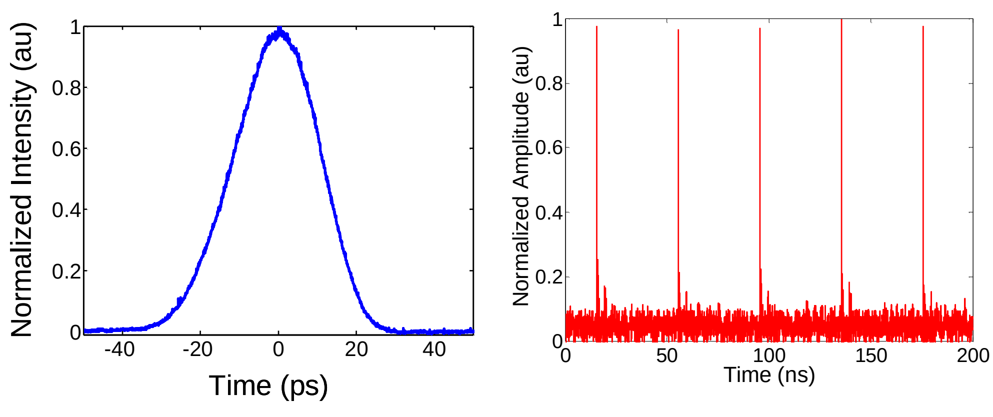

Fig. 5. Measured temporal profile of the laser output. (a) 25 ps pulse trace obtained by an autocorrelator at 1675 nm. (b) Oscilloscope trace shows 25 MHz pulse train at 1675 nm.

#5362 - $15.00 US Received 23 September 2004; revised 12 October 2004; accepted 13 October 2004

similar to the spectral features of the pump laser shown in Fig. 4(b). Raman scattering is a resonant phenomenon with an intrinsic bandwidth (FWHM) of ~100 GHz [4, 15-16]. Figure 5(a) shows the measured temporal profile of the laser output, at the Stokes wavelength of 1675 nm, measured using an autocorrelator. The pulse width at FWHM in this measurement is 25 ps. The actual pulse width is calculated to be 17.7 ps based on the Gaussian approximation. By using the measured 0.36nm spectral bandwidth, the time bandwidth broaduct ($\Delta\tau.\Delta\nu$) of the laser is calculated to be 0.68 and it is not transform limited. This conclusion will not materially change if we assume Sech pulse shapes. The walkoff between pump and the laser in the gain medium and complex spectral shape of the pump laser are belived to be main reasons for non-transform limited pulses. Figure 5(b) shows the output pulse train at 25 MHz, measured using the 40 GHz oscilloscope. The small features 4.2 ns after the pulses are caused by the ringing in the photodetector circuitry.

A comment must be made regarding the role of the Raman interaction in the fiber that constitutes the laser cavity. The Raman effect in fibers has a broadband gain spectrum (> 10 THz) with a primary peak located at 13.2 THz down shifted from the pump, and a secondary peak at 14.7 THz. These correspond to wavelengths of 1652 nm and 1666 nm for our pump wavelength of 1540 nm. In contrast, the peak of the narrow gain spectrum of silicon, and the observed emission (Fig. 4(a)) lies at 1675 nm. At this point in the gain spectrum of fiber, the gain coefficient is reduced to approximately 30% of its peak value. Furthermore, the measured peak gain coefficient in fiber is $1x10^{-13}$ m/W for 1 μm pump wavelength [18]. Assuming a linear dependence on pump wavelength [18] and using the known gain spectrum of fiber [18] we obtain a peak gain coefficient of $g_R = 0.7x10^{-13}$ m/W at 14.7 THz away from the pump wavelength of 1540 nm. With the known effective area of 80 μm^2 for single mode fiber, the total gain in the fiber for 10 W pump power is calculated to be the 0.31 dB. This gain will be far less than the cavity loss of 3.7 dB and hence insufficient to cause lasing [18]. When considering that the observed peak emission occurs 15.6 THz away, the Raman gain coefficient in fiber would be $0.3x10^{-13}$ m/W corresponding to a total gain of 0.13 dB [18].

3. Summary

In this paper, we have reported the first demonstration of a silicon Raman laser. Pulsed operation is necessary in order to avoid accumulation of free carriers that are generated due to TPA. The results show that free carrier induced limitations can be solved by using pulsed pumping. On the other hand using pulsed pumping scheme will add constraints to the practically of the device due to high cost of pump lasers. Under CW operation, the free carrier losses can significantly reduce the net Raman gain and hence prevent lasing. The steady state carrier density depends on the lifetime in the waveguide, which diminishes upon reduction in waveguide cross section [8-10]. This trend bodes well for the prospects for a CW silicon Raman laser. Additionally, carrier sweep out using a p-n junction can be useful [7]. Recently, high quality silicon micro disk resonators have been reported by us and others [19-20]. This technology can form the basis for a fully integrated silicon Raman laser. A silicon Raman laser can be a valuable tool for extending the wavelength range of III-V injection lasers to longer wavelengths that are important for sensing applications.

Acknowledgments

This work is supported by DARPA. The authors are grateful to Dr. Jagdeep Shah for his support of this work. They also acknowledge D. Dimitropoulos for technical discussions.