Demonstration of directly modulated silicon Raman laser

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Abstract: The first Raman laser with intra-cavity electronic switching is demonstrated. Digital control of intra-cavity gain is attained by using a diode gain cavity. In contrast to traditional Raman lasers, the Raman laser reported here is made from pure silicon and can be directly modulated to transmit data. Room temperature operation with 2.5W peak laser output power is demonstrated.

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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

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#6183 - $15.00 US Received 4 January 2005; revised 21 January 2005; accepted 22 January 2005

Until recently, the indirect bandgap of Silicon had prevented the realization of long the awaited silicon laser. Raman scattering, which is approximately 10^4 times stronger in silicon than that in silica glass, has been proposed as a means to bypass the electronic band structure limitation of silicon [1]. Using this effect, the first silicon laser was recently demonstrated [2]. The Raman effect is widely utilized in fiber based amplifiers and lasers [3]. In general, the Raman lasers require another laser to pump them, and for that reason, they are considered a tool for extending the wavelength range of other lasers [4-5]. However, the lack of on-chip electronic switching capability casts a shadow over the usefulness of a Raman laser in optoelectronic applications.

A typical laser consists of an optical gain element placed inside a resonant cavity. In the case of a Raman laser, atomic vibrations provide energy transfer from the pump to a new wave (Stokes wave). Lasing at the Stokes wavelength occurs when the amplification per round trip exceeds the loss per round trip. The output of the laser can be switched or modulated electronically if the intra-cavity loss can be altered. The optical loss in silicon is a linear function of free carrier (electrons and holes) density [6-7] and this can be altered by many orders using a diode. This offers a unique ability to electronically switch the silicon laser output using a diode laser cavity. This is where a semiconductor (silicon) Raman laser has a unique advantage over conventional counterparts that are made from insulators (silica) to achieve on-chip lasing and switching. The free carrier effect has previously been used to create silicon light valves to modulate the light generated by non-silicon lasers [7-9].

The purpose of this paper is to report the proof-of-concept demonstration of electronic switching in a Raman laser. To the best of our knowledge, this is the first such demonstration. The silicon device achieves digital control of intra-cavity gain using a diode laser cavity. In contrast to the traditional Raman lasers, this laser can be directly modulated to transmit data, and can be part of a silicon optoelectronic integrated circuit.

For the demonstration purpose, a laser was constructed using a silicon chip and a fiber loop cavity [2] as it is illustrated in Fig. 1. The chip contains a waveguide plus a p-n junction diode (inset of Fig. 2). The p-n junctions are 8μm away from the edge of the rib waveguide and they do not induce additional propagation loss due to this large gap. The waveguide is 2 cm long, has input and output tapers, and has a total insertion loss of 1dB. The modal area is

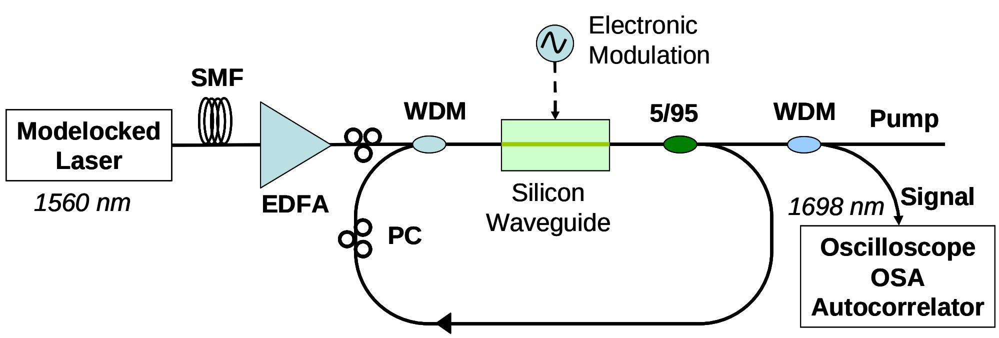

Fig. 1. The experimental setup used for electronically switched silicon Raman laser. A diode laser cavity is used as a gain medium. By using an external current supply the laser output is electronically controlled.

approximately 5 μm^2. We used 30ps pump pulses at 20MHz repetition rate and at a wavelength of 1560nm. These were generated by broadening 1 ps pulses generated by a Calmar Optocom modelocked fiber laser in a piece of standard single mode fiber. 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 for Stokes wavelength while blocking the residual pump wave. The length of the fiber was

Received 4 January 2005; revised 21 January 2005; accepted 22 January 2005

chosen such that cavity roundtrip time equals the pump pulse period. The relative polarization of the pump and Stokes were adjusted for maximum efficiency using two polarization controllers. The total cavity loss, including the silicon waveguide, measured at the Stokes wavelength (1675 nm) is measured to be 3.7 dB. At the output port, a second WDM coupler is used to separate the pump and signal wavelengths. To switch the laser on and off a function generator is connected to the diode laser cavity. A sampling oscilloscope, an autocorrelator and an Optical Spectrum Analyzer (OSA) are used to measure the output characteristics of the laser.

The observed threshold characteristics of the laser are shown in Fig. 2. Data is plotted in logarithmic scale to elucidate the near threshold behavior. The lower abscissa shows the peak power of pump pulses while the upper abscissa displays the average pump power. Below threshold, the output power is around -40 dBm level and is limited by the noise floor of the optical spectrum analyzer used in the experiment. Once the lasing threshold is reached, there

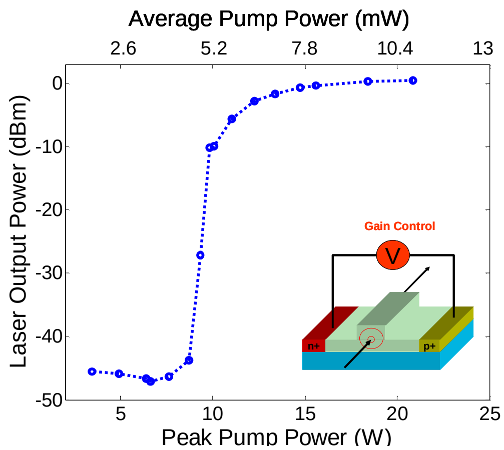

Fig. 2. Input-output characteristic of the silicon Raman laser exhibiting a sharp threshold at 9W peak pump pulse power. Inset shows the geometry of the device used in our experiments.

is a sudden 1000 fold (30 dB) increase in the output power. Above threshold the output power increases linearly as expected, and a high peak output power of 2.5 W is obtained when the peak pump power is 20 W. The slope efficiency, defined here as the ratio of peak output power and peak pump power, is calculated to be 12.5%. Broadening of pump pulses due to self phase modulation was evident at high powers and can also account for the observed saturation behavior. As shown in Figure 3, Coherent Anti-Stokes Raman Scattering (CARS) was also measured in our experiment [10]. The peak emission was at a wavelength of 1443 nm which corresponds to the pump frequency after it is up-converted by the 15.6 THz optical phonon frequency of silicon. Since the CARS generation depends on the presence of Stokes frequency, the anti-Stokes frequency will be turned off when the laser is switched off. Thus, dual wavelength lasing with simultaneous switching can be possible in silicon. The laser presented here is modelocked, the CARS line width, >20GHz, and the laser linewidth, ~40 GHz, are broader than a typical CW laser as expected. The amplitude of the anti-Stokes wave was approximately $\sim10^{-5}$ times lower than the Stokes wave. The efficiency of the CARS process depends on phase matching and drops sharply away from the phase matched condition. This explains the low anti-Stokes conversion efficiency as no attempt was made to affect phase matching in the silicon waveguide.

#6183 - $15.00 US Received 4 January 2005; revised 21 January 2005; accepted 22 January 2005
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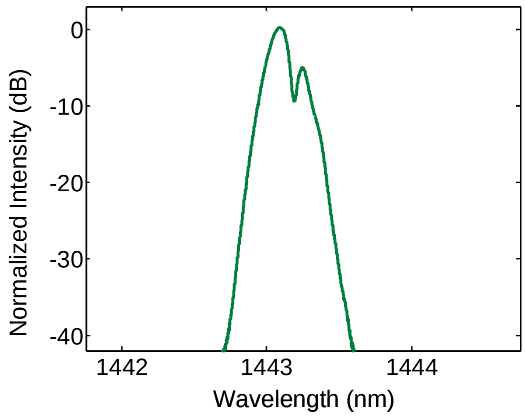

Fig. 3. Measured coherent anti-Stokes emission at 1443 nm. Wavelength of anti-Stokes emission matches the expected 15.6 THz up shifting of the 1560 nm pump laser.

A key attribute of the silicon Raman laser is its electronic modulation capability. Optical loss in silicon and hence the net optical gain in the laser cavity is proportional to the free carrier density in silicon, with a dependence that is described as: $\Delta\alpha = 1.7\times10^{-17}\cdot\Delta N$, where $\Delta\alpha$ is the change in loss caused by ΔN change in free carrier density [7-8]. The linear dependence of free carrier density on diode forward current provides direct electronic modulation of the intra cavity gain. The laser will be turned off when the loss induced by diode current exceeds the gain per round trip in the cavity. Hence the device will function as a "normally on" switch that is turned off when forward bias is applied to the p-n junction diode. Figure 4 shows the switching characteristics of the laser when a digital electrical waveform with 2.5 mA peak current and 200 ps rise/fall time is applied to the diode. The output pulse train of the laser is switched on and off as expected, with a measured turn-on time of 1µs and a turn-off time of 500ns. The turn off time will depend on the rate of carrier injection and hence on the switching time of the diode, whereas the turn on time will depend on the photon lifetime in the laser cavity. For a ring laser cavity, the roundtrip time is defined by $c/(n\cdot l)$ where c is the speed of light, n is the refractive index and l is the cavity length. Because of the 5% coupler use to extract the output from the cavity, we expect the photon lifetime to be 20

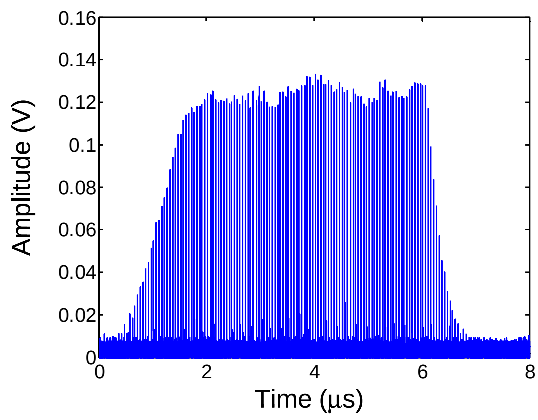

Fig. 4. Demonstration of electronic switching of the silicon Raman laser. 2.5 mA peak current with 200 ps rise and fall times is applied to the on-chip diode.

#6183 - $15.00 US Received 4 January 2005; revised 21 January 2005; accepted 22 January 2005
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times the cavity round trip time which corresponds to a value of 20x50ns = 1μs. Figure 5 shows the laser output with 1 MHz modulation applied to the p-n junction diode. While the modulation speed is limited in these experiments, the results clearly demonstrate the electronic switching feature of the silicon Raman laser.

The use of a monolithic silicon micro-cavity bodes well for high speed switching of the laser, since both the rise and fall times scale with the cavity size. Passive silicon micro disk

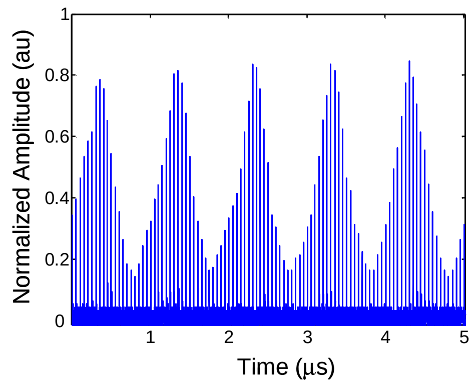

Fig. 5. Electronic modulation results of the silicon Raman laser.

and micro ring cavities have recently been demonstrated [11-13] and represent the natural evolution of the silicon Raman laser. As an example, a micro ring with circumference of 1mm results in a roundtrip time of 10 ps, or an equivalent turn-on time of 200ps. This assumes that the diode's current can be switched within this time scale. Because of its capacitance scale with device dimensions, the electrical switching time of the diode will also scale with device dimensions, a fortuitous trend as it relates to high speed performance. Using MOS structure as it is reported in silicon modulators [9] can in principle be also used to improve switching speed of the laser. Moreover, the index change due to free carrier injection will alter the effective cavity length and hence the resonance frequency of the micro cavity resonators and result in faster switching speeds. Switching time of the diode can be further increased by operation in the depletion mode as opposed to the injection mode. Depleting the gain medium will also enable Continuous Wave (CW) operation of the laser. In the present experiment, the laser was operating in the pulsed mode in order to mitigate losses associated with free carriers that are generated by two photon absorption [14-15]. CW operation can be achieved by using p-n junction to deplete such carriers. While the present device is not optimized for this function preventing the laser from CW operation, an optimized version can attain electronically switched CW operation. In this configuration the diode will operate in depletion mode and the laser would be a "normally switched off" switch.

In summary, we have proposed and demonstrated intra-cavity switching in a silicon Raman laser. Direct modulation and switching is a unique feature of the silicon Raman laser that is not shared by traditional silica Raman lasers.

Acknowledgments

This work is supported by DARPA. The authors are grateful to Dr. Jagdeep Shah for his support of this work.