Demonstration of CW Raman Gain with Zero Electrical Power Dissipation in p-i-n Silicon Waveguides

Sasan Fathpour, Ozdal Boyraz, Dimitri Dimitropoulos, and Bahram Jalali
Electrical Engineering Department, UCLA, Los Angeles, CA 90095
jalali@ucla.edu

Abstract: Electrical power dissipation has been an unfortunate penalty paid for achieving net CW gain in Silicon Raman amplifiers and lasers. We report the first observation of net CW gain with zero electrical power dissipation.

Stimulated Raman scattering in silicon has been proposed as a mean to bypass the indirect bandgap of silicon and to create waveguide amplifiers [1,2] and eventually led to the demonstration of the first optically pumped laser in silicon [3]. Extension to CW operation has been difficult due to absorption by free carriers that created by Two Photon Absorption (TPA). Active sweep-out of carriers using a p-n junction was proposed [4,5] and CW laser operation has been recently demonstrated using this technique [6]. However, voltages of 5-25V have been necessary for active removal of free carriers [6] resulting in on-chip *electrical* power dissipation, an adverse effect that is entirely absent in traditional Raman devices. With the chip power dissipation being the primary problem faced by the silicon electronics industry, this effect will undoubtedly diminish the prospects of Raman amplifiers being integrated into future silicon photonic integrated circuits. In this work, we demonstrate that net CW Raman gain can be achieved by actively removing the free carriers, but with zero on-chip electrical power dissipation.

The device is a lateral p-i-n waveguide fabricated on a silicon-on-insulator wafer with p^+ and n^+ wells straddling the silicon rib that supports an optical mode with an area of approximately 2 μm^2. The linear propagation loss is measured to be ≤0.5 dB/cm in these waveguides by using the Fabry-Perot fringes technique.

The gain measurements were conducted on a Newport SmartTable system by using a CW pump laser at 1427 nm and a CW probe laser tuned to the Stokes wavelength of 1542 nm. The measured gain versus coupled pump power at different bias conditions is shown in Fig. 1. As expected, the accumulation of free carries results in a net optical loss at the Stokes wavelength when the diode is open circuited. When a zero bias (short circuit) is applied, the induced electric field removes the free carriers reducing their effective lifetime. The measured photo-generated current varies from 30 to 60 μA at zero bias, depending on the pump power range of Fig. 1. The maximum on-off gain is measured to be ~1.5 dB at 500 mW pump power level in this configuration. With the measured waveguide loss of 0.5 dB/cm, a net Raman gain of 0.5 dB is obtained. Although the diode is actively removing the free carriers, as evidenced by the measured pump-induced reverse current, there is no electrical power being dissipated on the chip because the terminal voltage is maintained at zero. While pump-on/pump-off gain has been previously reported in zero biased p-i-n waveguides [7] and in nanowires [8], the net gain in those waveguides was negative. Therefore, the present result is the first demonstration of positive net gain achieved in the absence of on-chip electrical power dissipation.

Numerical drift-diffusion simulations using ATLAS verify that at zero bias, the depletion region extends into the waveguide core. The value of electric field at this bias in the core region is about 10^3 V/cm, which corresponds to a drift velocity of ~ 10^6 cm/s in silicon. This value of drift velocity is about one order of magnitude higher than the diffusion velocity of undoped silicon for the dimensions of the present device (1.3×10^5 cm/s). Therefore, simulations verify that active removal of TPA induced free carriers is being achieved at zero voltage.

A maximum gain of 1.8 dB is measured at a reverse bias voltage of 20V (Fig. 1). In fact, the gain does not improve much for voltages beyond 10V reverse bias. The saturation of gain with bias is most likely due to saturation of the drift velocity, a well known feature of carrier transport in silicon that occurs at an electric field of 2×10^4 V/cm. This hypothesis is supported by the fact that the calculated average electric field at 10 V in our device is 2.02×10^4 V/cm, in agreement with the known saturation field in silicon.

While it is shown that electrical power dissipation can be avoided, other questions remain regarding the CW Raman amplifiers and lasers that employ a p-i-n junction for carrier sweep out. In the present experiments, it was found that it was necessary to maintain the chip at room temperature by mounting it on a thermoelectric (TE) stage. In the absence of the TE cooler, the device under bias would undergo thermal runaway leading to damage or failure. At this point, it is not clear whether this is a fundamental attribute of these structures or whether the observed phenomenon can be avoided through device optimization. Nonetheless, because of high pump powers encountered in Raman devices, and the inherent generation of phonons in stimulated Raman scattering, thermal behavior of any diode used for carrier sweep-out should be carefully investigated. From this point of view, eliminating the need for the diode by using waveguides with intrinsically low carrier lifetime [8] is an attractive approach.

References

[1] 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).
[2] R. Claps, D. Dimitropoulos, V. Raghunathan, Y. Han, and B. Jalali, "Observation of stimulated Raman amplification in silicon waveguides," Opt. Express **11,** 1731-1739 (2003).
[3] O. Ozdal and B. Jalali, “Demonstration of a silicon Raman laser,” Optics Express **12**, 5269-5273 (2004).
[4] 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).
[5] R. Claps, V. Raghunathan, D. Dimitropoulos, and B. Jalali, “Influence of nonlinear absorption on Raman amplification in Silicon waveguides,” Opt. Exp. **12**, 2774-2780 (2004).
[6] H. Rong, R. Jones, A. Liu, O. Cohen, D. Hak, A. Fang and M. Paniccia, “A continuous-wave Raman silicon laser,” Nature **433**, 725-728 (2005).
[7] R. Hones, H. Rong, A. Liu, A. W. Fang, and M. Paniccia, “Net continuous wave optical gain in a low loss silicon-on-insulator waveguide by stimulated Raman scattering ,” Optics Express **13**, 519-525 (2005).
[8] R. L. Epinola, J. I. Dadap, R. M. Osgood, Jr., S. J. McNab, and Y. Vlasov, “Raman amplification in ultrasmall silicon-on-insulator wire waveguides,” Optics Express **12**, 3713-3718 (2004).

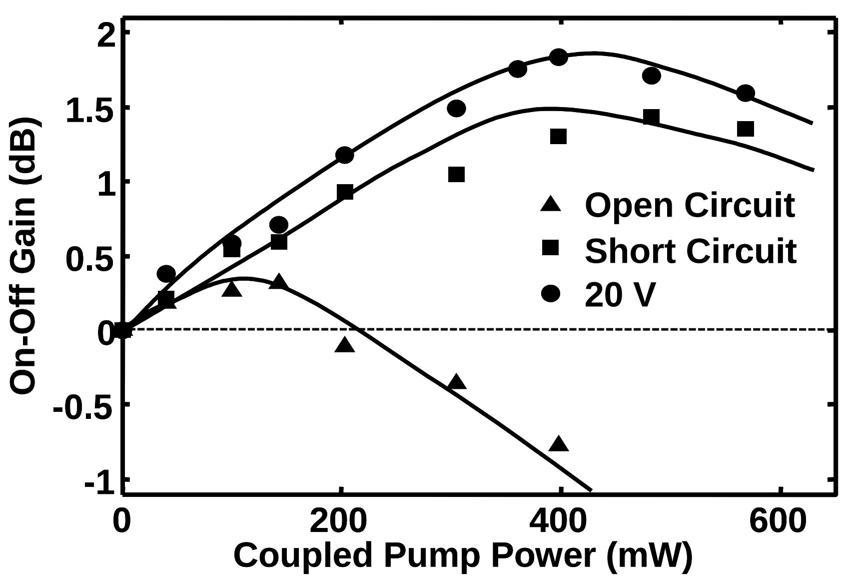

Fig. 1: Measured on-off Raman gain in silicon-on-insulator waveguides with a straddled p-i-n diodes at different biases: open circuit, short circuit and 20 V.