Energy Harvesting in Silicon Raman Amplifiers

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Abstract
A method to recover power lost to two photon absorption is described. Approach is applicable to both Raman and Kerr based devices. CW Raman amplification with negative electrical power dissipation is experimentally demonstrated in silicon.

Introduction

For some time now, Silicon-on-Insulator (SOI) has been recognized as an efficient platform for the realization of both electronic and photonic devices [1]. One of the most attractive features of the SOI material system is the prospect of full integration of optical and electronic devices on the same substrate. While lots of progress is being made in Si photonics, no attention has been paid so far to the power dissipation of photonic devices. This is important because heating and thermal management is the central problem faced by VLSI industry. The problem is so severe that it threatens to bring to halt the continued advance of VLSI as described by the Moore's law [2]. This is highlighted by the recent momentous shift of the microprocessor industry away from increasing the clock speed and in favor of multi-core processors [3]. Hence, low power dissipation in photonic devices is crucial if photonics is to merge with VLSI electronics. This paper addresses this issue in the context of silicon photonic devices that operate based on nonlinear optical effects, such as Raman amplifiers and lasers. The approach is also applicable to other nonlinear optical devices such as wavelength converters that operate based on the Kerr effect.

Second order optical nonlinearities are absent in silicon, however, 3rd order processes do exist and can be exploited to create active photonic devices. An example of such processes, Stimulated Raman scattering (SRS) has been proposed as a mean to bypass the indirect bandgap of silicon and to create waveguide amplifiers [4-6]. The approach led to the first demonstration of lasing in silicon [7]. Similarly both Raman [8] and Kerr [9, 10] nonlinearity have been used to perform wavelength conversion.

A common feature of all such devices is the high optical intensity that is required to cause nonlinear interaction within the waveguide. At such high intensities, two photon absorption (TPA) occurs, resulting in loss of photons. Even worse, the generated free carriers can cause severe absorption if carrier accumulation takes place [11]. For example, in Raman devices, CW amplification and lasing has been difficult due to carrier accumulation. Active sweep-out of carriers using a p-n junction was proposed [12] and CW laser operation has been recently demonstrated using this technique [13]. However, the carrier removal has been achieved at the expense of significant electrical power dissipation (25V and 10's of mA current levels). We have recently demonstrated CW Raman gain with zero electrical power dissipation [14]. In this paper, we demonstrate that it is actually possible to obtain negative electrical power dissipation in such devices. This is achieved by operating the diode in the 4th quadrant of the current-voltage transfer function. In this mode, TPA generated carriers are swept out by the built-in field of the junction, yet the device produces electrical power. The concept becomes clear if one considers this device to be a nonlinear optical equivalent of a solar cell.

Experiment

A schematic of the fabricated devices is shown in Fig. 1. The device is a lateral p-i-n waveguide fabricated on a SOI wafer with p^+ and n^+ wells straddling the silicon rib that supports an optical mode with an area of approximately 2 μm^2. Waveguide lateral tapers were used to reduce coupling losses. The facets were polished but were left uncoated. The experimental results presented in the following are for 2.2-cm long waveguides with W=1.5 μm and d=1.9 μm.

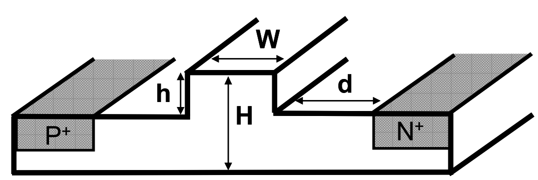

Fig. 1: Schematic of the silicon-on-insulator electrooptic modulator with a straddling p-n junction.

The Raman gain measurements were performed on a Newport SmartTable™ optical table in order to minimize vibration induced errors. The pump laser is a New Focus external-cavity tunable diode at 1539 nm amplified with an EDFA with a linewidth of 0.1-0.2 nm. The Stokes signal is a 1673 nm DFB laser by ILX Lightwave biased at an output power of ~4.5 mW. The pump and Stokes beams are coupled in and out of the waveguide with two identical objective lenses (M=20X, 0.40 NA), after combining them in a wavelength division multiplexing (WDM) coupler. The electrical

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loop that biases the *p-i-n* junction consists of a power supply, a 1 kΩ series resistor and a current meter.

Results and Discussions

Figure 2 presents the measured pump-on/pump-off Raman gain at different pump powers and biasing conditions. As expected, the accumulation of free carries results in a net optical loss at the Stokes wavelength when the diode is open-circuit. When a reverse bias is applied, the induced electric field removes the TPA-induced free carriers, hence reducing the carrier effective lifetimes. A maximum on-off gain of ~4 dB is obtained at a reverse bias of 15 V. Higher reverse voltages do not increase the gain considerably, which may be due to saturation of the drift velocity. It is also observed that a Raman gain of 2.7 dB is attained when the diode is short-circuit (0 V). This Raman gain at zero bias is higher than our previous report where no lateral mode-converting tapers was involved [14].

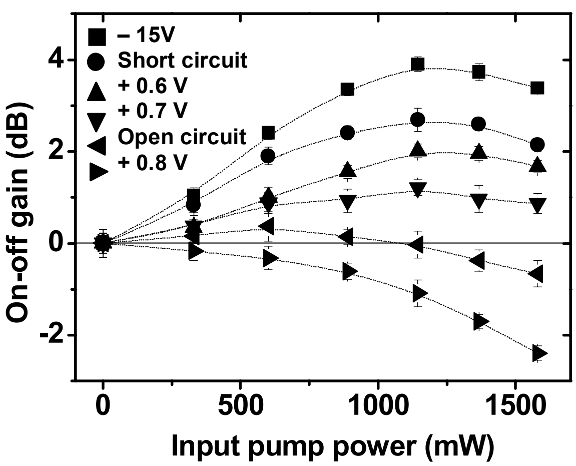

Fig. 2: Measured on-off Raman gain versus pump power in the devices of Fig. 1 at different biasing conditions.

As seen in Fig. 2, Raman gain as high as 2.0 dB is achieved when the device is forward-biased at voltages ≤0.7V. The importance of this biasing regime is that power dissipation is negative because the product of current and voltage is negative. Figure 3 shows the *generated* power for biases of 0.6 and 0.7 V at different pump intensities, extracted from the measured current and voltage across the diode. The photovoltaic effect is also clearly observable in the measured current-voltage (*I-V*) characteristics (presented in Fig. 4). The attenuation of pump intensity via TPA creates free carriers in the Si waveguide. The photogenerated carriers contribute to a current component that delivers electrical power to the external circuitry. Therefore, the sweep-out of TPA generated free carriers is exploited to generate electrical power.

Sweep-out of carriers and reduction of the effective lifetime has been the motivation for utilizing a reverse-

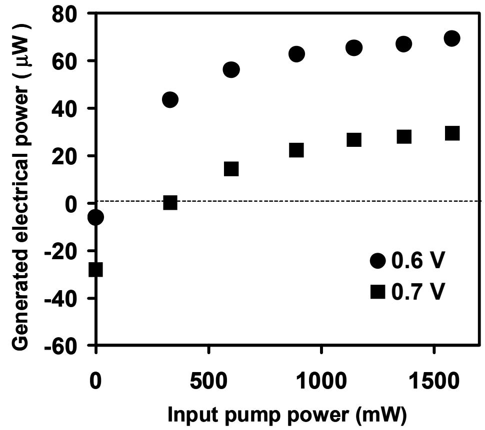

Fig. 3: Generated electrical power at different pump powers for two biases in the fourth quadrant.

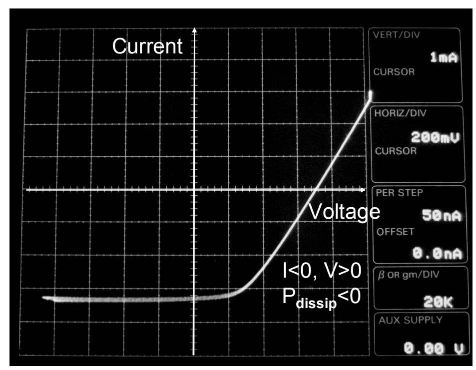

Fig. 4: The current-voltage characteristics of the p-n junction measured with a curve-tracer for an optical illumination of ~1.1 W.

biased p-n junction in Raman amplifiers [11-13]. The forward-bias employed in the present work might seem counterintuitive. The key idea is that reduction of the effective lifetime can be achieved as long as the diode current is negative. In other words, a negative voltage is not a prerequisite for carrier sweep out. We conducted 2-D numerical drift-diffusion simulations on structures identical to the fabricated devices using ATLAS (from Silvaco International), according to the methodology described elsewhere [15]. It was verified that the effective lifetime of biases in the fourth quadrant is still about one order of magnitude lower than the open-circuit value. It was verified that the effective carrier lifetime in the fourth quadrant is only a few percent higher than the value in typical reverse bias. Therefore, *collection* of photogenerated carriers in the fourth quadrant of current-voltage transfer function is enough in decreasing the free-carrier loss.

Finally, we point out the limitations of the proposed approach. At very high optical intensities, the built-in field of the junction is insufficient to remove the high density of carriers that are generated via two photon absorption. In such cases, a reverse bias has to be applied to increase the field resulting in net electrical power dissipation. Hence there exists a tradeoff between the amount of gain (and hence output power) and the electrical power generation/dissipation.

Conclusions

Two photon absorption and the resulting free carrier scattering are omnipresent problems in silicon photonic devices that operate based on nonlinear optical interactions. It is shown that active removal of these carriers can be achieved while generating modest amounts of net electrical power.

Acknowledgement

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