

Demonstration of 11 dB fiber-to-fiber gain in a silicon Raman amplifier

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Abstract: We report the demonstration of 11 dB fiber-to-fiber optical gain in a silicon Raman amplifier. Pulsed pumping is employed to reduce the TPA induced free carrier losses resulting in net signal amplification. The influence of free carriers is elucidated by observing the dependence of gain on pulse energy.

Keywords: Waveguides, optical amplifiers, silicon photonics, Raman

Classification: Photonic devices, circuits and systems

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1 Introduction

The need for low cost optical interconnects has stimulated 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]. Creation of active devices in silicon is challenging due to the near-absence of nonlinear optical properties caused by the symmetric crystal structure, and the lack of efficient optical transitions due to the indirect band structure.

In the context of light amplification and generation, silicon dioxide films containing silicon nanostructures and/or Erbium (Er) have received the bulk of the attention [1]. We have undertaken a different approach to light generation and amplification in silicon, namely through Raman the effect [4, 5]. Further, we have demonstrated wavelength conversion through parametric Raman scattering [6, 7].

Although stimulated Raman amplification was demonstrated in 2003, realization of net gain has been difficult to achieve due to the losses introduced by free carriers that are generated by the Two Photon Absorption (TPA) process [8, 9]. There are two potential solutions to this predicament. The first solution relies on the fact that the effective carrier lifetime, and hence the steady state carrier density, diminishes upon reduction of modal area [7-10]. Using this concept, an efficient Raman conversion has been demonstrated in highly scaled waveguides with $0.1 \mu\text{m}^2$ modal area [10]. Another approach is to keep a low average power and hence the free carrier density by using pulsed pumping [11, 12]. This technique will be effective as long as the pulse width is shorter than the recombination time, and the pulse period is larger than the lifetime.

In this paper, we report measurement of net fiber-to-fiber gain of 11 dB in a silicon waveguide by using pulsed pumping technique. To the best of our knowledge this is the highest gain ever reported in silicon. Additionally, the effect of free carrier accumulation on net Raman gain is evaluated ex-

perimentally by changing the pump pulse width. The results clearly indicate that as the pulse energy is raised (by increasing the pulse width) free carrier accumulation increases and lowers the net gain. Pumping with counter propagation geometry is also measured. It is shown that because of the limited interaction time between the pump and the signal, the measured gain is limited to 0.2 dB in this case

2 Experimental results

Figure 1 shows the experimental setup used for the pulsed Raman gain measurement. A modelocked fiber laser operating around 1540 nm with 25 MHz repetition rate is used as a pulsed pump laser. Following the laser, a bandpass filter (BPF) is used to limit the spectral bandwidth and standard single-mode fiber is employed to broaden the pump pulse. Specifically, the gain is measured with 50 ps and 200 ps pump pulses in this particular experiment. After amplifying pump it is combined with a CW signal at 1675 nm using a WDM coupler. The wavelength of CW signal is controlled by temperature tuning to move the signal wavelength with respect to the Raman resonance peak located at 1675 nm. The polarization states of the pump and the CW signal are adjusted by polarization controllers (PC) before combining to maximize the gain at the output. A silicon-on-Insulator (SOI) waveguide is used as the Raman gain medium. The waveguide has a length of approximately 2 cm. The fiber-to-fiber small signal insertion loss is measured to be 0.8 dB including the propagation loss and coupling loss. After the waveguide, the signal and the pump laser are separated by a WDM coupler. The signal is then detected by a 40 GHz photodetector and measured by an oscilloscope.

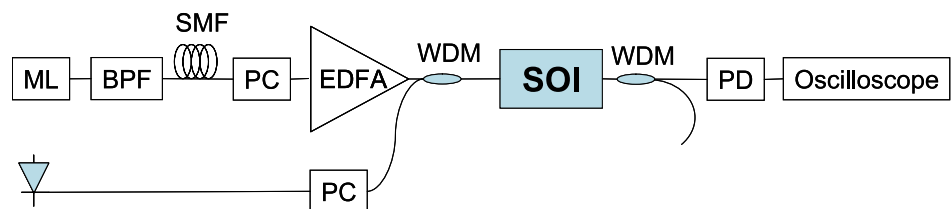


Fig. 1. The experimental setup used for pulsed Raman gain measurement. A modelocked pump laser around 1540 nm amplifies the CW signal at 1675 nm by Raman effects in silicon.

The Results of fiber-to-fiber net Raman gain measurements are presented in Fig. 2. In this set of measurements 50 ps pump pulses are used. Figure 2 (a) shows the enhancement of the signal power caused by the pump pulse. A 12.2 dB of amplification is observed for a pump peak power of 40 W. To obtain the net fiber-to-fiber gain, the device insertion loss must be taken into account. Using the measured 0.8 dB insertion loss value, a net fiber-to-fiber gain of 11.4 dB is obtained. Figure 2 (b) shows the dependence of net fiber-to-fiber gain on the peak pump power when the latter is varied from 0

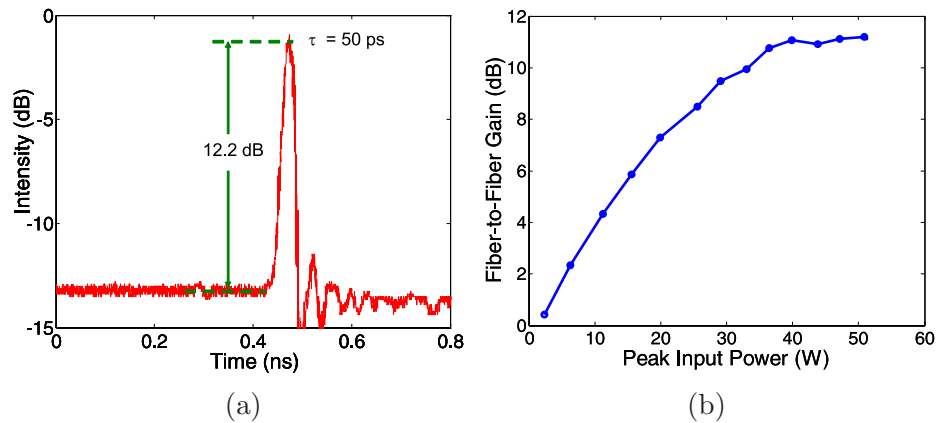


Fig. 2. Measured fiber-to-fiber net gain results in silicon waveguide. 11 dB fiber-to-fiber gain is measured around 40 W peak power levels by using 50 ps input pump pulses.

to 55 W (by changing the output power of the EDFA). The gain saturates at around 40 W of peak pump power. This behavior is attributed to pulse breakup and excessive spectral broadening of the pump laser in the pigtail fiber at these power levels. This is a well known phenomenon [13] and the spectral broadening was clearly observable in our experiments. Raman gain is a resonant phenomenon whereas the TPA induced free carrier loss is a wideband effect. Hence by tuning the signal laser to on- and off-resonance, we can independently measure the free carrier loss. The maximum free carrier loss so measured is 0.8 dB at the peak pump power level (~ 40 W). The low loss indicates that the pulsed pumping scheme has been effective in diminishing the free carrier effect.

The effect of free carrier accumulation on the stimulated Raman amplification in silicon waveguides is further studied by comparing the gain measurements with 50 ps and 200 ps pump pulses. As shown in Figure 3, 6.6 dB of gain is measured when pulses are 50 ps wide. The gain decreases to 3.8 dB at the same peak power level when 200 ps pump pulses are used. The reduction in gain can be attributed to increase in free carrier accumulation for longer pulses. This effect is unambiguously evident in the time domain measurements shown in Figure 4. Figure 4 (a) represents the time domain results obtained using 200 ps pump pulses. An attenuation caused by accumulation of free carriers is evident after the trailing edge of the pump pulse. On the other hand there no such effect is observed in Figure 4 (b) when shorter (50 ps) pulses are used. In both cases, the peak pulse power in the waveguide was 15 W. The results are expected since the amount of free carrier accumulation depends on the pulse energy which is proportional to the pulse width [11, 14]. The fast oscillations observed in Figure 4 (b) are due to the ringing the optical receiver circuitry when excited with a short pulse. To verify this, the pump beam is attenuated to the same power level as the signal beam and is directly coupled to the photodetector (i.e. no waveguide is present). As it is shown in the inset of Figure 4 (b) similar oscillations is

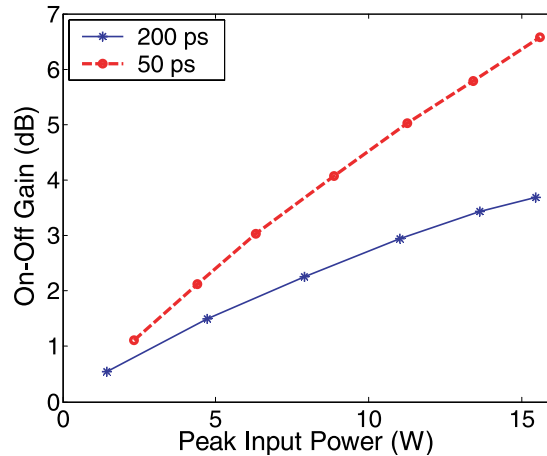


Fig. 3. Comparison of measured on-off gain by using 50 ps and 200 ps input pump pulses. As the pulse width increases the free carrier loss limits the maximum achievable gain.

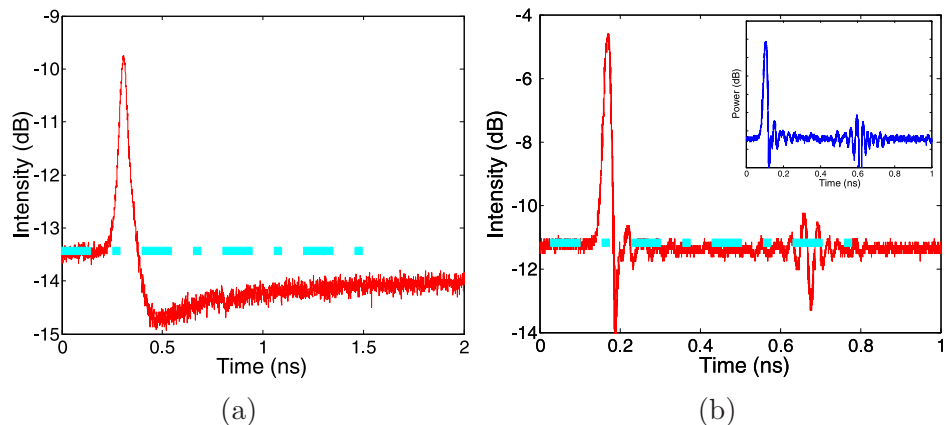


Fig. 4. Measured gain by using a) 50 ps pulses b) 200 ps pulses. As it is shown in figure, the free carrier loss dominates at longer pulse widths.

observed on the detected pump pulses.

3 Discussion

The free carrier accumulation is the main obstacle for obtaining net stimulated Raman gain in silicon waveguides by using CW pumping [11, 12]. Pulsed pumping scheme with pulse period larger than the carrier recombination time and pulse width shorter than the carrier lifetime is an alternative approach to obtain net gain. A high and record net optical gain of 11 dB is demonstrated in this paper. However, practical application of pulsed pumping is limited. First, in order to take advantage of pulsed pumping scheme, the pulse period should be comparable or larger than the carrier life time. This is a limitation when the high data rate is desired. Typically the carrier lifetime in silicon waveguides varies from few nano-seconds to few tens of nano-seconds. Thus, the maximum data rate cannot exceed Gb/s due to lim-

itation of carrier lifetime. Additionally, this method requires synchronization between pump pulses and the data signal. This requirement adds additional complexity to the applications. However, for specific low data rate applications pulsed pumping is a promising method for on-chip Raman amplification. For high speed applications different techniques like carrier sweeping by p-n junction could be implemented to reduce free carrier accumulation and to obtain high gain.

4 Summary

A high and record fiber-to-fiber Raman gain of 11 dB has been demonstrated in a silicon waveguide. The experimental results obtained for varying pump pulse widths indicate that as the pulse energy increases, free carrier accumulation limits the maximum achievable net gain. It is also shown that counter propagating pumping scheme, employed in fiber Raman amplifiers, is not no useful in silicon Raman amplifiers.

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