Observation of stimulated Raman amplification in silicon waveguides

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Abstract: We report the first observation of Stimulated Raman Scattering (SRS) in silicon waveguides. Amplification of the Stokes signal, at 1542.3 nm, of up to 0.25 dB has been observed in Silicon-on-Insulator (SOI) waveguides, using a 1427 nm pump laser with a CW power of 1.6 W, measured before the waveguide. Two-Photon-Absorption (TPA) measurements on these waveguides are also reported, and found to be negligible at the pump power where SRS was observed.

OCIS codes: (230.7370) Waveguides; (250.3140) Integrated optoelectronic circuits; (250.4480) Optical amplifiers.

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1. Introduction

In the past few years, there has been important progress in the search for light emission and amplification in Silicon (Si). A variety of different approaches have been undertaken including the use of Si nanostructures [1], Er-doped Si-rich silica [2, 3], Si/SiO_2 [4] and Si/SiGe superlattices [5], and the use of surface texturing to enhance photoluminescence [6]. Blurring the distinction between direct and indirect band structure through the uncertainty principle, spatial localization increases the probability of band-to-band emission in the indirect bandgap silicon. Exploiting this phenomenon, stimulated emission has been demonstrated, in the 800 nm wavelength range, using a slab waveguide made of silicon nanocrystals embedded in a silica host [7]. The present authors have been investigating an entirely different approach, Raman scattering, for light generation and amplification in silicon [8]. The Raman phenomenon is attractive since it does not require nano-scale structures and hence, is compatible with conventional integrated optics. It does not require the silicon to be doped with special impurities such as Erbium, and it is tunable over all wavelength ranges of interest.

We have previously demonstrated spontaneous Raman emission in silicon waveguides and suggested the possibility of using Raman amplification in silicon to compensate for waveguide coupling and propagation losses [9]. The Raman effect in silicon is due to the scattering of light by the optical phonons of the crystal. The strongest Stokes peak (1^{st} order) is due to scattering from the three-fold degenerate optical modes at the center of the Brillouin zone [10]. The induced polarization, $\vec{P}_i$, responsible for spontaneous Stokes radiation associated with the "*i-th*" component of phonon displacement is $\vec{P}_i(\omega_s) = \varepsilon_o \chi_R \overleftrightarrow{R}_i \cdot \vec{E}(\omega_p)$, where χ_R is the scalar susceptibility and the Raman tensors $\overleftrightarrow{R}_i$ determine the polarization of the Stokes wave. Waveguides are typically fabricated parallel to $[1\bar{1}0]$ direction on a silicon $[001]$ surface, due to the favorable cleaving property in this orientation. In a coordinate system (x, y, z) rotated with respect to the crystallographic axes by 45^o rotation around $[001]$ axis, the Raman tensors have the following form [11],

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$$\overleftrightarrow{R}_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix}; \quad \overleftrightarrow{R}_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & -1 \\ 1 & -1 & 0 \end{pmatrix}; \quad \overleftrightarrow{R}_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \qquad (1)$$

The spontaneous scattering efficiency is defined as the percentage of scattered radiation per unit of solid angle per unit length. It is related to the Raman tensor as,

$$S = S_o \sum_{j=1,2,3} \left| \hat{e}_s \cdot \overleftrightarrow{R}_j \cdot \hat{e}_i \right|^2, \qquad S_o = \frac{k_o^4}{32\pi^2 n} V \chi_R^2 \qquad (2)$$

where $\hat{e}_i, \hat{e}_s$ are the polarizations of the incident and scattered radiation respectively, k_o is the Stokes wavevector, n is the index of refraction, and V is the scattering volume. The value of S_o was measured to be 4.1 x 10^{-7} $cm^{-1}Sr^{-1}$ [9]. In our scattering geometry, where the pump is in the TE_0 polarization ([110]) and the Stokes wave is measured in the TM_0 polarization ([001]), then $S = S_o$. Using Eqs. (1) and (2), it can be demonstrated that, with the pump in the TE_0 mode, then $S = S_o$ for a Stokes wave in the TE_0 mode as well. This result has been verified experimentally [12]. Therefore, the operation of a SOI-based Raman amplifier should be polarization insensitive, regardless of the polarization of the pump wave.

We have recently carried out a detailed Coupled-Mode Calculation (CMC) of Raman gain in silicon waveguides [11]. In this reference, the CMC equations for the evolution of the TE_0 and TM_0 modes [13], along the waveguide, are solved for the particular case where the third-order susceptibility includes the Raman gain coefficient, g_s. The results show that the threshold for SRS decreases monotonically with reduction in transversal waveguide dimensions. Also, the CMC results suggest that Raman-induced TE_0 –to-TM_0 coupling is negligible, in support of the assertion made in the previous paragraph on polarization independence of the SRS gain process. For the stimulated Raman effect in bulk material, the gain coefficient g_s, is obtained from the spontaneous efficiency from the well-known relation [14]:

$$g_s = \frac{8\pi c^2 \omega_p}{\hbar \omega_s^4 n^2(\omega_s)(N+1)\Delta\omega} S \qquad (3)$$

Where N is the Bose occupation factor (0.1 at room temperature), n is the refractive index, ω_p and ω_s are the pump and Stokes frequencies, respectively, and $\Delta\omega$ is the FWHM of the spontaneous lineshape. Substituting the measured value of S in silicon waveguides [9], we obtain $g_s = 3.7 \times 10^{-8}$ cm/W.

In this paper, we report the first observation of Raman amplification in silicon waveguides. SRS-induced optical amplification, with modest gain, is demonstrated in SOI rib waveguides. We also present unambiguous demonstration of Two Photon Absorption (TPA) in these structures and show that TPA occurs at higher pump powers compared to the SRS threshold.

2. Experimental Setup

Shown in Fig. 1 is the experimental setup used to measure SRS in SOI waveguides. The details of the setup are similar to those reported in a previous work by the authors [9]. The pump laser is a Cascaded-Raman-Cavity (CRC) fiber laser operating at 1427 nm. The output from the laser is coupled into the TE_0 mode of a SOI waveguide through a polarization beam splitter (PBS). The P-polarized input of the PBS is used to couple the signal beam into the TM_0 mode. The signal laser is an External Cavity Diode Laser (ECDL) with a linewidth of <300 kHz. The laser wavelength was scanned (0.2 nm/step) through a wavelength range from 1537.0 nm to 1547.0 nm. A variable optical attenuator (VOA) was used to regulate the amplitude of the signal beam. A polarizer (P) and a high pass filter are used to collect the field from the TM_0 mode coupled out of the waveguide.

To isolate the pump and signal interaction, a low frequency amplitude modulation is introduced in the pump beam, using a chopper (Ch) operating at 100 Hz. In the presence of a nonlinear interaction between pump and signal beams in the waveguide, this modulation will be transferred onto the CW signal beam within the waveguide. The interaction should possess the spectral characteristics of the Raman phenomenon. The effective Raman gain bandwidth (intrinsic linewidth, broadened by the finite pump linewidth) is approximately 350 GHz for maximum pump power (2 W after PBS). Given the 1427 nm pump used in our experiment, and the 15.6 THz optical phonon frequency, the gain bandwidth is expected to be centered at 1542.3 nm. An optically-broadband photodetector (PD) is used to measure the signal modulation. The signal from the PD is processed by a lock-in amplifier (LIA), which is locked to the chopper frequency. The average power is measured separately. A personal computer performs data acquisition and calculates the gain from the modulation amplitude and average power. The SOI rib waveguides have a length, L=1.8 cm, and a measured TM_0 modal area of A = 5.4 μm^2. Total insertion loss was measured to be 7 dB, including waveguide coupling losses (Fresnel reflection and mode mismatch) and propagation losses, γ = 1.5 dB/cm.

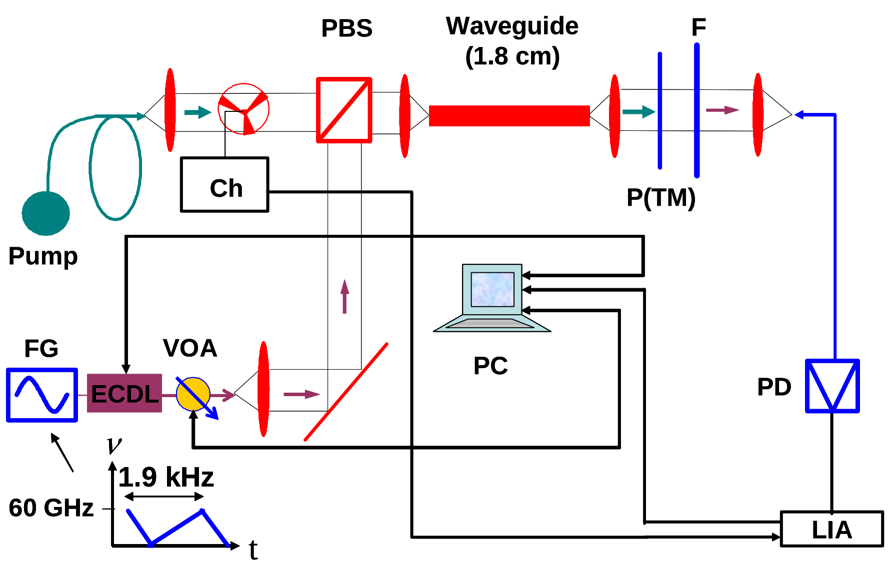

Fig. 1. Experimental setup: Pump-CRC fiber laser; Ch-Chopper; PBS-Polarization Beam Splitter; LIA- Lock-in amplifier; ECDL-External cavity diode laser (tunable); FG-Function generator (60 GHz freq. range); VOA-Variable optical attenuator; PD-optically-broadband photodetector. Thick lines represent electrical connections and wiring, thin lines represent free-space optical beams, and colored lines represent optical fiber.

Since the waveguide was not AR coated, Fabry-Perot (FP) fringes were clearly visible when a frequency modulation (FM) scan was performed with the ECDL. The free spectral range (FSR) corresponding to the waveguide-FP cavity modes is ~ 2.5 GHz. The depth of this modulation is about 15%. Since the amplitude of the fringes is comparable with the expected SRS modulation of the signal at the pump power levels used in the experiment, a special modification was needed in order to eliminate the FP effect. A function generator (FG) was used to modulate the ECDL frequency at a rate of 1.9 kHz, by sweeping the voltage input to the piezo-electric positioner of the ECDL. This, in turn, modulates the center frequency of operation of the laser by ± 30 GHz. The net effect of this is to average out the FP fringes.

3. Results

3.1 SRS observation

Shown in Fig. 2(a) is the measured signal power gain as a function of signal laser wavelength. The pump power, measured before the waveguide, was 0.64 W. Each data point was averaged 10 times from the LIA. Furthermore, 10 complete spectral scans are averaged. The characteristic wavelength dependence of the Raman process is clearly shown, and a signal amplification of 3% is obtained. For comparison, shown in Fig. 2(b) is the measured spontaneous emission. The gain peak in the stimulated emission occurs at 1542.3 nm, in excellent agreement with the position of the spontaneous peak. Additionally, the FWHM linewidth of 310 GHz is consistent with the measured value for spontaneous emission, at a comparable pump power. The spontaneous emission was measured using an optical spectrum analyzer, compared to a broadband photodetector used in the stimulated emission measurements. Hence, spontaneous radiation will appear as a flat background in the stimulated measurements, shown in Fig. 2(a), and does not contribute to the resonant behavior observed.

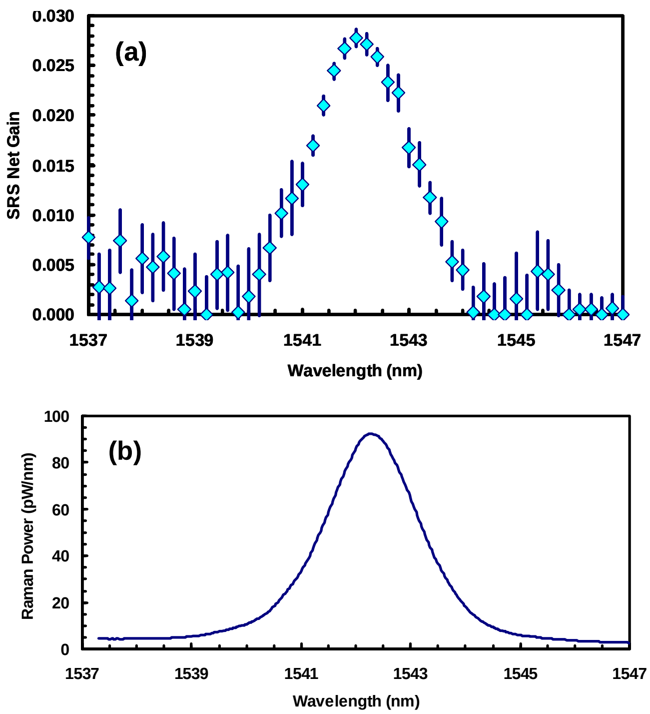

Fig. 2. (a) Measured spectral characteristic of the Stimulated Raman Scattering (SRS) in the silicon waveguide. The error bars are the standard deviation from this average. The pump power was 0.64 W at the front facet of the waveguide. SRS Net Gain is the ratio of the amplitude of the LIA output to the average signal power throughput. (b) Spontaneous Raman Spectra of the same waveguide with the same pump power as in (a).

In Fig. 3, the maxima of the signal wavelength scans are plotted versus the effective pump power (including the pass through the PBS and the coupling losses at the front facet of the waveguide). The maximum signal gain obtained is 0.25 dB, corresponding to ~ 6 % signal amplification. The slope of the curve is approximately linear, as expected for the gain of a Raman amplifier as a function of pump power.

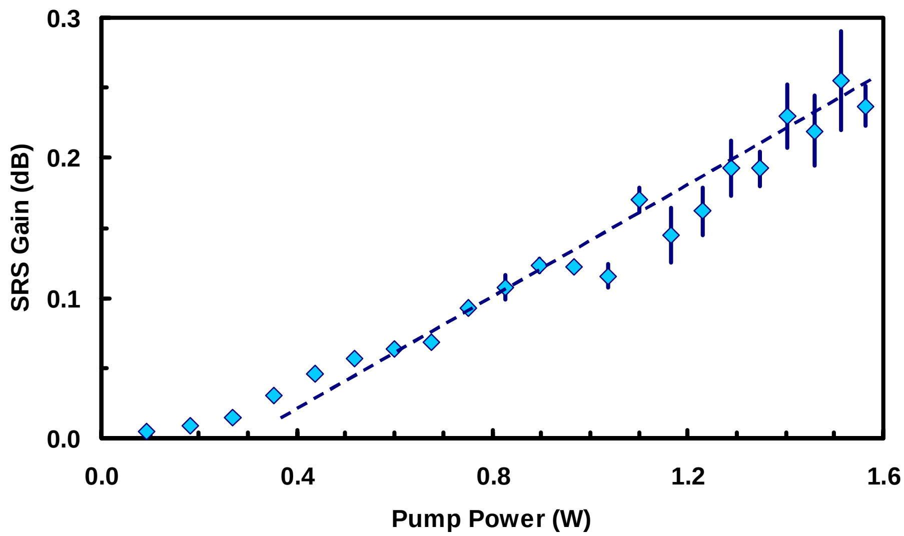

Fig. 3. The maxima from each spectral scan are plotted against effective pump power coupled into the front facet of the waveguide. A maximum of 0.25 dB (6%) amplification is obtained.

The amplified signal power expected from a waveguide of length, L, can be modeled as [8],

$$P_S(L) = P_S(0)\exp(-\gamma L + \frac{g_s\ P_p(0)}{A\cdot(1+\Delta\nu_p(P_p)/\Delta\nu_R)}L_{eff}). \tag{4}$$

Where P_S (L) is the amplified signal power, $P_S(0)$ and $P_P(0)$, the input power of the signal and pump, respectively. A and γ are as defined above, L_{eff}=(1-exp(-γL))/γ, is the effective waveguide length, and g_s is the SRS gain coefficient. The factor (1+ $\Delta\nu_p/\Delta\nu_R$) is an approximation describing the increase in Raman threshold due to the finite linewidth of the pump laser. The dependence of threshold on pump linewidth is well known in Stimulated Brillouin Scattering (SBS), in optical fibers [15]. Because of the extremely large Raman bandwidth in fibers (5-10 THz), this effect is neglected in modeling SRS in fibers. However, due to the narrow Raman linewidth in silicon ($\Delta\nu_R$ =105 GHz) the dependence of threshold on pump linewidth must be considered here. Additionally, the linewidth, $\Delta\nu_p$, of our pump laser increases with output power [16]. Based on the specifications provided by the manufacturer [16], the dependence of linewidth with pump power can be assumed to be linear, with a rate of 70 GHz/W. By using the total Stokes amplification obtained experimentally in Eq. (4), a value of $g_s = 2 \times 10^{-8}$ cm/W is found for the SRS gain coefficient. As described in Section 1, the value obtained by using the measured spontaneous scattering efficiency and Eq. (3), is $g_s = 3.7 \times 10^{-8}$ cm/W. While the two numbers are in reasonably good agreement, we offer the following discussion on possible mechanisms that can result in the measured gain coefficient being smaller than the expected value.

Reduction of SRS by Four Wave Mixing (FWM) is a well-known effect in nonlinear optics. The impact of this mechanism on g_s, depends strongly on the phase mismatch, Δk, between the waves involved. Complete suppression of SRS by FWM has been documented in fiber Raman amplifiers under phase-matching conditions [17]. The value of dispersion found in the literature for SOI waveguides of similar geometry [18] indicates that Δk does not correspond to a phase-matched condition for the current experimental setup. Nonetheless, a more detailed study of dispersion in the present waveguides is necessary before the effect of FWM on SRS can be accurately quantified.

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3.2 TPA measurement

The hypothesis of TPA quenching the SRS amplification should be ruled out by direct measurement of TPA on SOI waveguides. The experimental setup used for this measurement is depicted in Fig. 4. A passively mode-locked laser operating at a 25 MHz pulse-repetition rate, and with a 0.9 ps pulse-width, produces an input power level an order of magnitude higher than those used in previous reports of TPA in silicon [18, 19]. The laser operates at a center wavelength of λ = 1560 nm, which is well below the indirect bandgap of silicon; therefore, linear absorption can be considered negligible. The regime that this experiment then explores is that of indirect, simultaneous two-photon absorption [20]. Such an effect is of interest for ultrafast photo-detection in silicon.

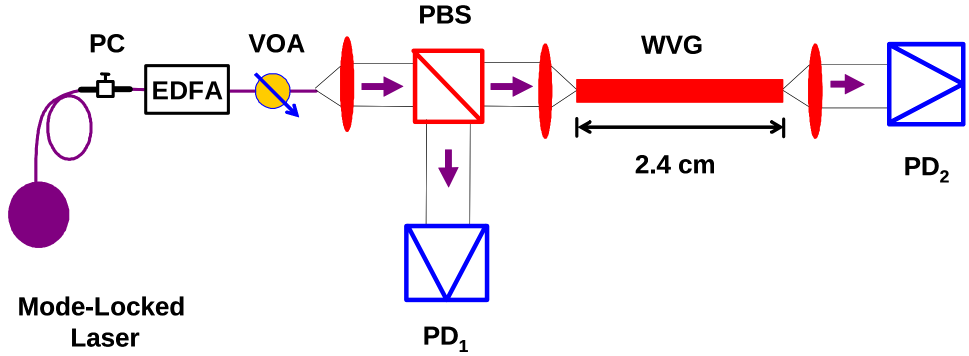

Fig. 4. Experimental setup for measuring TPA. The waveguide in this case is different from the one used for SRS. PC-Polarization controller; VOA-Variable optical attenuator; PBS – Polarization beam splitter; PD_1 and PD_2 photo-detectors (identical, Newport 1830-C).

Shown in Fig. 5 is a plot of the throughput peak power, P_{out} as a function of the input peak power, P_{in}. The effect of the nonlinear absorption is clearly visible for input power levels above 50 W. This is more than an order of magnitude higher than the power levels used to observe SRS.

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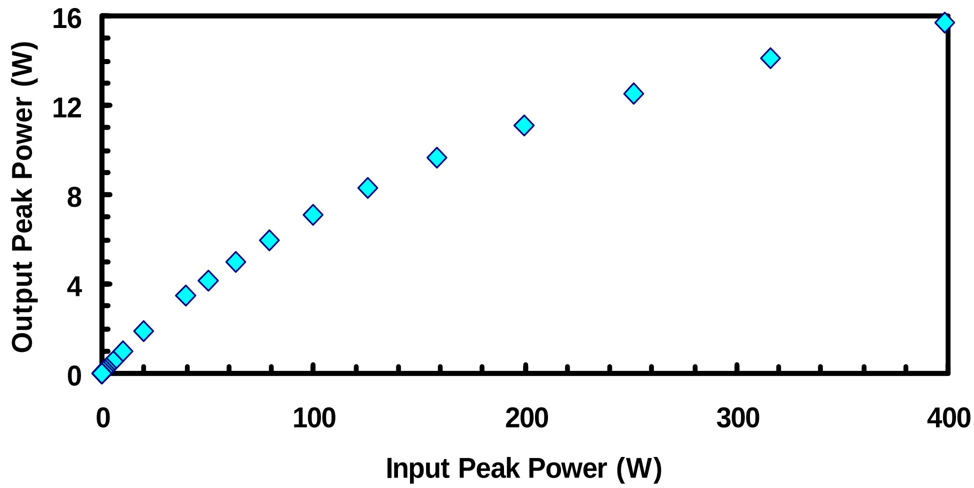

Fig. 5. Output power vs. input power results, using a mode-locked laser, and depicting a nonlinear relationship.

Under TPA-dominating conditions, the input power at the front facet of the waveguide, P_{in}, and the signal measured on PD_2, namely, P_{out}, are related by the following expression [20],

$$\frac{P_{in}}{P_{out}} = e^{\gamma L}\left(1 + \frac{\beta L_{eff}}{A} P_{in}\right). \tag{5}$$

Where γ (= 0.46 ± 0.1 cm^{-1}) is the propagation loss in the waveguide, *A* is the modal cross section (= 8.1 ± 1.0 × 10^{-8} cm^2), and β is the TPA coefficient (in cm/W). The result is plotted in Fig. 6, where the linear behavior of P_{in}/P_{out} versus P_{in} is clearly demonstrated up to 400 Watts of input power. The fact that spontaneous TPA in silicon is the dominant absorption process up to very high power regimes is of fundamental importance in the design of an ultra-fast silicon photodetector and/or imaging device, operating in the 1.5 µm region [21, 22]. The resulting value for β is then,

$$\beta = -\frac{c_1 A}{L_{eff}} e^{-\gamma L} = (4.4 \pm 1.0) \times 10^{-10}\ cm/W.$$

Where c_1 is the slope of the curve shown in Fig. 6 and the main elements in the error are the uncertainties in γ, and in *A*.

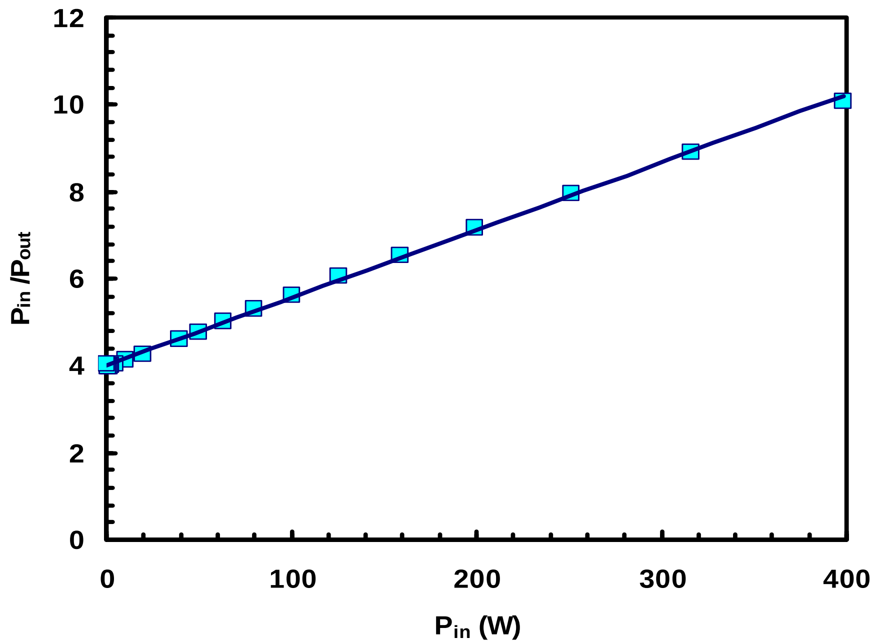

Fig. 6. TPA measurement result. The input power, P_{in}, is not corrected for coupling losses. The linear behavior is maintained up to ~ 400 W.

This value of TPA agrees with what has been reported in the literature and with an extrapolation of values measured at 1.06 µm [8].

Finally, comments should be made regarding effects that may be detrimental to SRS. Stimulated Brillouin Scattering (SBS) presents a serious problem for fiber-based Raman amplification. However, the Brillouin scattering coefficient for silicon is about two orders of magnitude smaller than the Raman coefficient [23]. Furthermore, as has been discussed above, the pump broadening reduction of the effective SBS gain is more pronounced than in the SRS case, due to the smaller bandwidth of the Brillouin signal. In conclusion, the possibility of SBS pump depletion is ruled out in SOI-based Raman amplification schemes. In the reports of light emission induced by photo-generated carriers in silicon nano crystals, the non-radiative Auger process has been mentioned as a detrimental effect [7]. In the case of SRS reported here, Auger recombination is not an issue because Raman emission does not involve a free carrier recombination process. Furthermore, silicon is transparent at the pump and signal wavelength and hence, notwithstanding TPA, photo-generation does not occur.

4. Conclusions

The purpose of this paper has been to report the first observation of stimulated Raman amplification in silicon waveguides. The observation was made at the technologically important wavelength window of 1500nm. The SRS gain coefficient extracted from the measurements is slightly lower than that expected from the measured spontaneous emission. A possible mechanism that can contribute to a reduction in SRS gain in silicon waveguides was discussed. Two-photon-absorption was measured, and it was shown to be negligible for the pump powers at which SRS was observed. While further waveguide optimization leading to a higher gain is necessary, this paper has highlighted the possibility of on-chip amplification and coherent light generation in silicon integrated optics.

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