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SPIE.

Event: SPIE OPTO, 2011, San Francisco, California, United States

Spontaneous and stimulated Raman scattering in planar silicon waveguides

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ABSTRACT:

Raman scattering in planar silicon on insulator (SOI) waveguides with 2 μm width, 220 nm height and 2 cm length is investigated. A cw Nd:YAP laser at 1340.6 nm with 7 GHz FWHM spectral width is used as the pump source. A lensed fiber of 2.5 μm focus diameter is used to couple the pump laser into the waveguide. The coupling efficiency is estimated to be around 10%. Spontaneous Raman scattering is observed with as low as 2.5 mW pump power inside the waveguide. The spontaneous Raman spectrum is measured by an optical spectrum analyzer. The first order Raman peak is measured at around 1441.4 nm corresponding to a Raman shift of 15.6 THz, while the FWHM of Raman spectrum is measured as around 100 GHz. Maximum Raman output of around 90 pW is obtained by around 22 mW pump. The stimulated Raman gain coefficient is estimated as around 56 cm/GW from the relationship between spontaneous Raman output power and pump power. A temperature dependence of Raman frequency shift of about 0.6 GHz/K is measured. The spontaneous anti-Stokes Raman scattering output peak at 1253 nm is also observed with around 35 mW pump. Stimulated Raman amplification measurement is carried out with a SLED white light source as probe signal. With 35 mW pump power, around 0.6 dB gain has been determined with both pump and probe being TE polarized.

1. INTRODUCTION

Silicon photonics is one of the most hotly research areas these days. Silicon-On-Insulator is believed to be the platform for next generation electronic Integrated Circuits. The silicon Integrated Circuits manufacturing is well developed. Silicon wafers have the lowest cost per unit area and the highest

crystal quality compared with other semiconductor materials. The availability of high quality SOI wafers is an ideal platform for creating planar waveguide circuits. The strong optical confinement offered by the high index contrast between silicon ($n \approx 3.5$) and SiO_2 ($n \approx 1.5$) makes it possible to scale photonic devices to several hundreds of nanometer level. Submicron-sized dimension will enhance the nonlinear intensity in the devices; it is easier to observe nonlinear optical phenomena, such as Raman and Kerr effects, in the chip-scale devices.

In this paper, Raman effect in planar silicon on insulator (SOI) waveguides with $2 \mu\text{m}$ width, 220 nm height and 2 cm length is investigated.

2. SPONTANEOUS RAMAN EMISSION IN PLANAR SILICON

In silicon the strongest Stokes peak corresponds to first order Raman scattering from the three fold degenerate optical modes at the center of the Brillouin zone [1]. It lies at 15.6 THz away from the pump and with a FWHM of 105 GHz at room temperature [2].

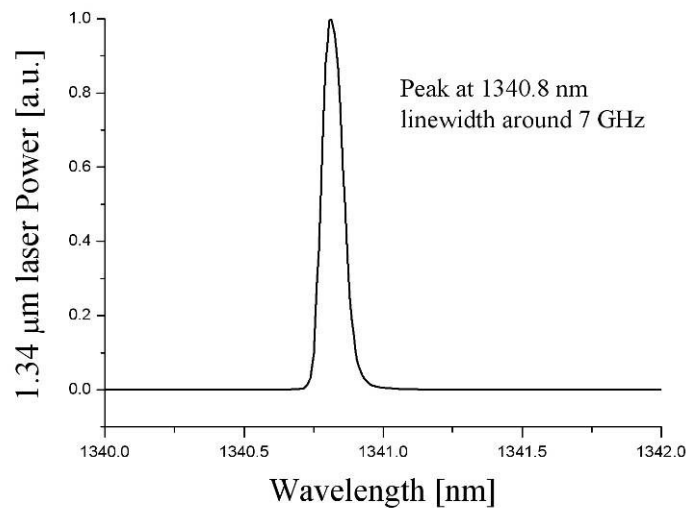


Fig.1 Spectrum of Nd:YAP laser at 1341 nm

In order to observe the Raman emission in silicon waveguide, a LD end pumped cw Nd:YAP laser working at 1341 nm is used as the pump source. The silicon waveguide is with $2 \mu\text{m}$ width, 220 nm height and 2 cm length. The spectrum of pump laser is shown in Fig.1. The pump laser is peak at 1340.8 nm has a bandwidth of around 7 GHz detected from the OSA. Maximum pump power of 350 mW at 1341 nm is achievable. A half-wave plate in combination with a polarizer are used together to change the input pump power to silicon waveguide. A fiber polarization controller is used to change the polarization of pump laser in the silicon waveguide. The experimental setup is shown in Fig. 2. The

1341 nm pump is coupled into the waveguide through a single mode tapered fiber. The $2\ \mu\text{m}\times 220\ \text{nm}$ silicon waveguide comprises a $5\ \mu\text{m}\times 220\ \text{nm}$ tapered waveguide in order to decrease the coupling loss from fiber to silicon waveguide. The coupling loss is estimated to around 10 dB from our previous experiments [3]. Spontaneous Raman scattering at around 1441.6 nm is generated, which corresponds to a silicon Raman shift of 15.64 THz. The measured Raman spectrum is shown in Fig.3. The figure shows both the wavelength and the frequency shift of the Raman output.

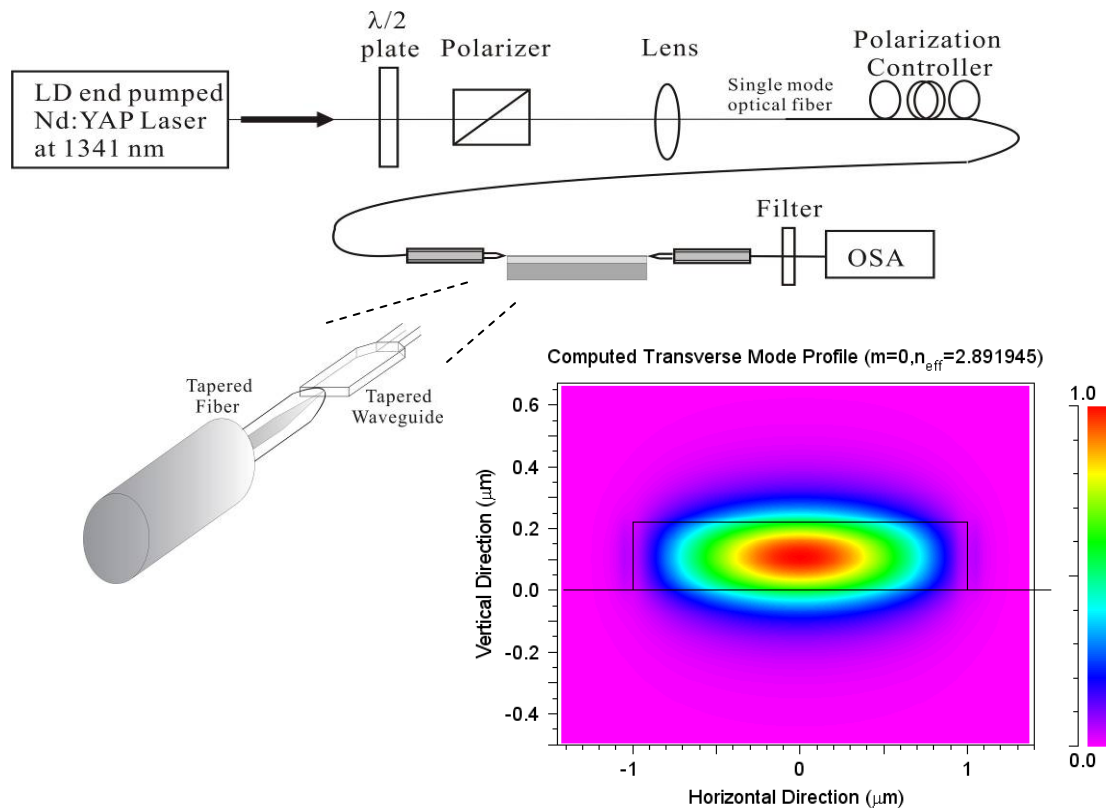


Fig.2 Experimental setup of Raman scattering measurement in silicon waveguide

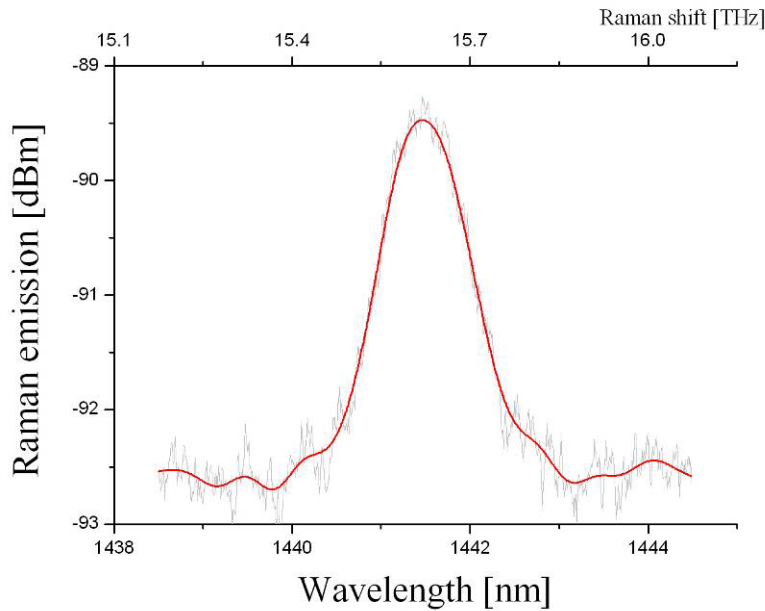


Fig.3 Raman spectrum of silicon waveguide

The forward Raman signal and the pump beam are then coupled into a receiving tapered fiber and are separated by a long pass filter. The signal is recorded by an optical spectrum analyzer (OSA) with 0.5 nm resolution. In the right down part of Fig.2 is the calculated mode profile in 2 μm silicon waveguide. The effective core area of the waveguide is defined as [4]

$$A_{eff} = \frac{\left[\iint I(x, y) dx dy \right]^2}{\iint I^2(x, y) dx dy} \quad (1)$$

where $I(x, y)$ is the transverse intensity profile of the fundamental mode of the waveguide. From the calculated mode profile, the effective core area is estimated as around $0.68 \mu\text{m}^2$.

Fig.4 shows the different results of two different pump polarization directions: TE pump and TM pump. The Raman shifts of both TE and TM pump are the same, which is measured as 15.64 THz.

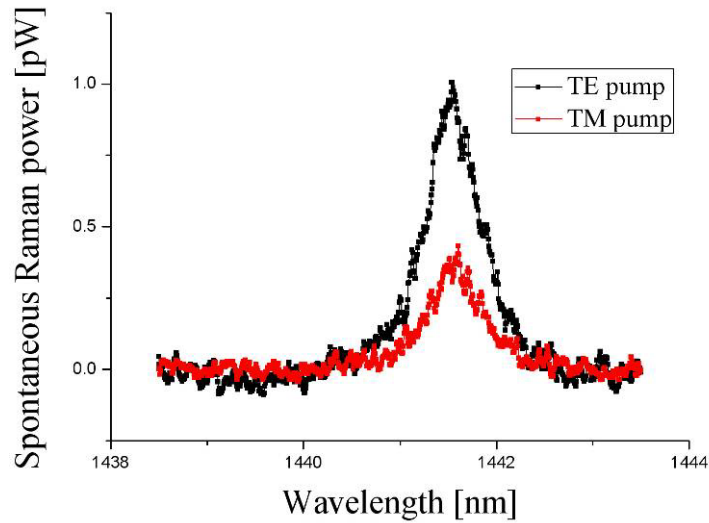


Fig.4 Spontaneous Raman spectra with TE and TM pump

Due to the much smaller bandwidth of pump laser compared with Raman gain bandwidth, the bandwidth of measured spontaneous Raman emission is near the same with the Raman linewidth of silicon. The output Spontaneous Raman bandwidths of both TE and TM pump are measured as around 100 GHz (*note: 100GHz are about 0.8nm -> so the OSA resolution should be as low as 0.2 nm*), which is within error compared with reported value 105 GHz. The power of spontaneous Raman emission with TE pump is around 3 times larger than with TM pump. This is because that the propagation loss of TE mode is smaller than of TM mode in such a small size silicon waveguide.

Fig.5 gives the spontaneous Raman spectra at various TE pump power. As low as 25 mW pump power, i.e. less than 2.5 mW pump power in silicon waveguide, the efficient Raman conversion is observed. This is because of the small bandwidth of our pump laser, as well as the small effective mode area within the silicon waveguide. The spontaneous Raman output power is linear dependent with pump power.

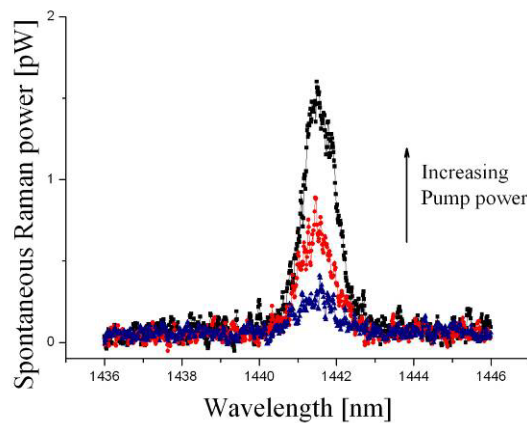


Fig. 5 spontaneous Raman spectra at various TE pump power

The temperature dependent Raman frequency shift is also studied. A TEC temperature controller is used to change the temperature of the waveguide from 290 K to 330 K. Here the absorption induced temperature rising is not considered, because the thermal conductivity of silicon at around 300 K is reported larger than $100 \text{ Wm}^{-1}\text{K}^{-1}$ [5]. The pump is TE polarized and the power is not changed during measurement at different temperatures. Fig.6 shows the measured results.

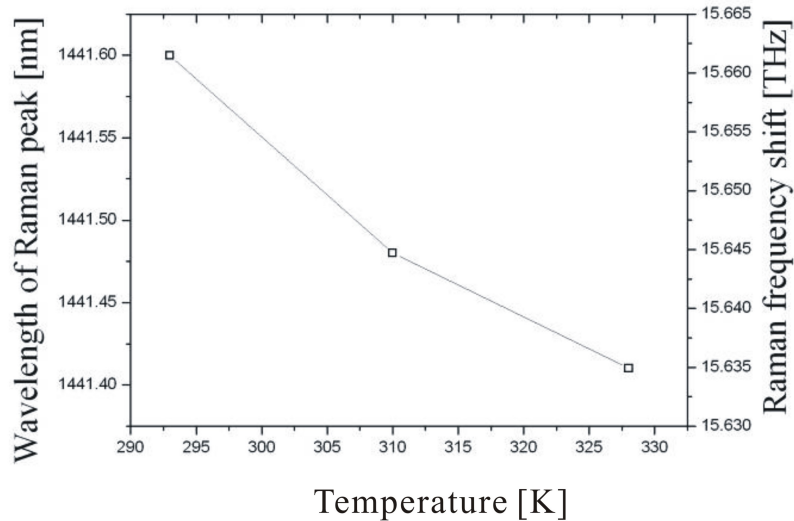


Fig.6 Raman frequency shift in silicon waveguide vs. temperature

From Fig.6, we see that with increasing temperature, the Raman frequency shift decreases. From the experiment we expect a temperature dependence of Raman shift of about 0.6 GHz/K, which is nearly the same as described in [6]. They also reported that the Raman linewidth increases around 0.1 GHz/K. But this has not been observed in our experiments, mainly due to the resolution limitation. The reason why Raman shift and linewidth are temperature dependent [7] is that rising in temperature results in an increase in the interatomic distance and a reduction of the phonon lifetime. The former leads to a decrease in the optical phonon frequency and correspondingly to an increase in the frequency of the Stokes component. The latter, which is interpreted as an increase in the damping coefficient in the context of a classical oscillator model, leads to broadening of the optical phonon linewidth.

The first order anti-Stokes Raman emission is also measured, shown in Fig. 7. The pink (*It will be in black and white*) line shows the first order anti-Stokes Raman emission, while the black line shows the first Stokes Raman emission with the same pump power. The ratio between the intensity of first anti-Stokes and first Stokes is measured as around 1/12, which can be predicted by Eq. (2)

$$\frac{I_{as}}{I_s} = \exp\left(-\frac{h\nu_{phonon}}{kT}\right) \approx 0.08 \quad (2)$$

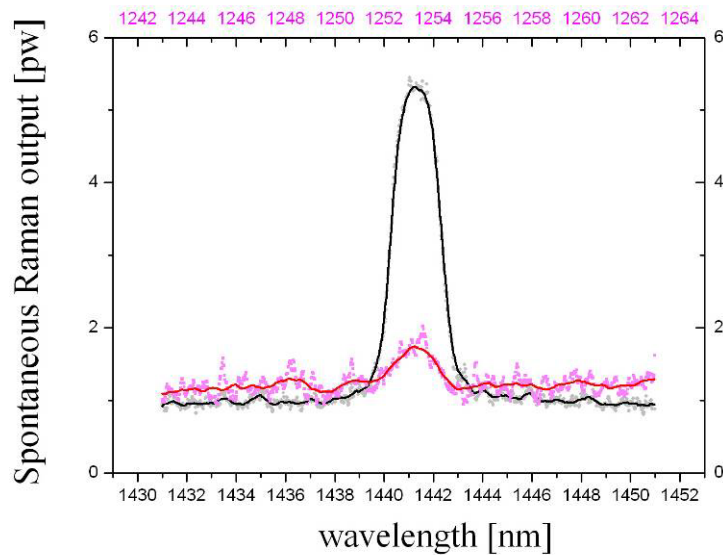


Fig. 7 Comparison of anti-Stokes and Stokes Raman emission in silicon waveguide

3. STIMULATED RAMAN EMISSION IN PLANAR SILICON WAVEGUIDE

At last we also measured the stimulated Raman amplification in such a planar silicon waveguide. The experimental setup is shown in Fig.8.

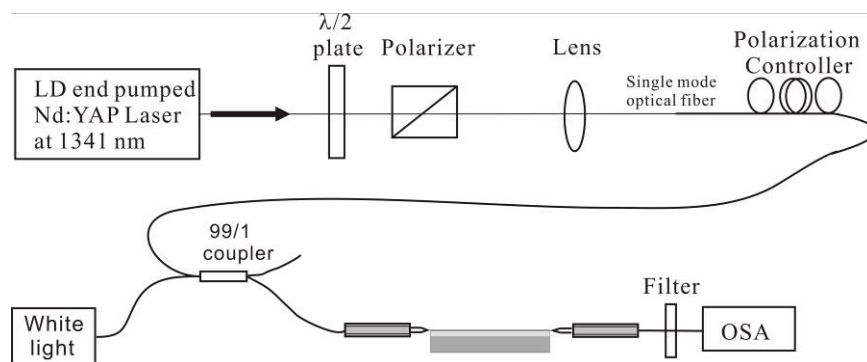


Fig.8 Experiment of stimulated Raman amplification in planar silicon waveguide

The cw 1341 nm Nd:YAP laser is used as the pump source again. A white light source which is centered at around 1440 nm is used as the probe source. A 99/1 coupler is used to couple the pump and probe together. The tapered fiber helps to couple the pump and probe into the silicon waveguide. The filter is used to block the pump wavelength from Raman emission. At first, the OSA measured the output of white light source without pump power. Then the OSA measured the output of white light source with pump power. We subtract these two outputs, and could obtain the amplification curve. Fig.

9 shows the experimental results. The blue (*b&w*) curve is measured spontaneous Raman spectrum, while the black curve is the measured Raman amplification. The resolution of OSA is used as 2 nm, that is to say the true amplification factor is around 2 times larger than measured by OSA considering the linewidth of spontaneous Raman emission is around 1 nm. We could see from the figure that the measured amplification curve fits well with the measured spontaneous Raman spectrum.

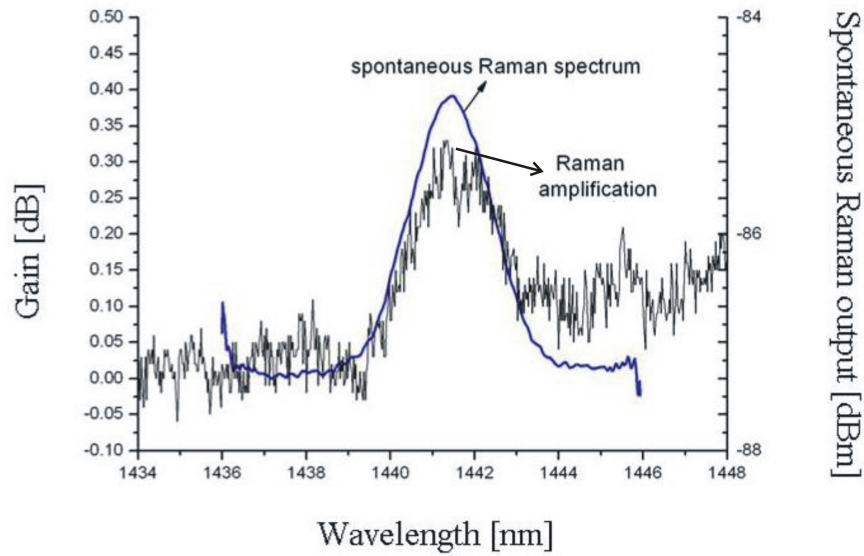


Fig. 9 Measured Raman amplification curve and spontaneous Raman spectrum curve

Fig. 10 shows the measured stimulated Raman gain dependent on the pump power at fiber output. With around 350 mW pump power, maximum of around 0.6 dB gain is obtained. The stimulated Raman gain coefficient is estimated to 35 cm/GW.

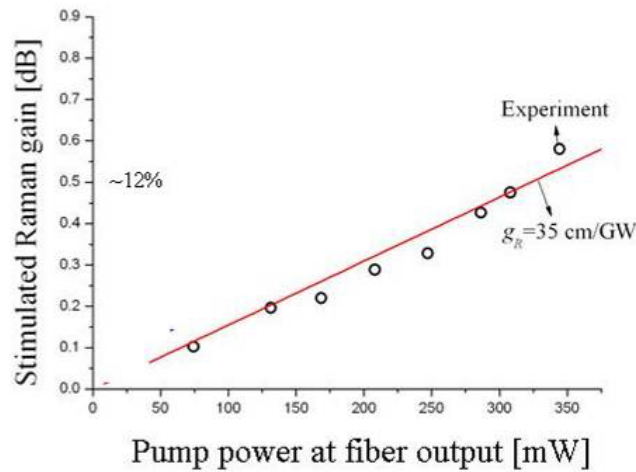


Fig. 10 Measured stimulated Raman gain dependent on pump power at fiber output

4. CONCLUSION

In this paper, we measured both spontaneous Raman output and stimulated Raman amplification of a silicon on insulator (SOI) waveguide with 2 μm width, 220 nm height and 2 cm length. With 1341 nm pump, the first stokes is measured at 1441.6 nm. The temperature dependence of Raman shift is measured as about 0.6 GHz/K. The first anti-stokes which centered at 1253 nm is also measured. At last we obtained the stimulated Raman amplification of such a small silicon waveguide. Maximum gain of around 0.6 dB is obtained at 350 mW pump.

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