A continuous-wave Raman silicon laser

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Abstract

- Achieving optical gain and/or lasing in silicon
  - Indirect band gap → very low light emission efficiency
- Stimulated Raman scattering
- Nonlinear optical loss
  - Two-photon absorption(TPA)-induced free carrier absorption(FCA)
    - Reverse-biased p-i-n diode
  - Limited to pulsed operation
    - Continuous-wave silicon Raman laser
- Laser cavity
  - Coating the facets of Si waveguide with multilayer dielectric films
- Stable single mode laser output
  - Side-mode suppression of over 55dB
  - Linewidth of less than 80 MHz
- Lasing threshold : p-i-n reverse bias / Laser wavelength : pump laser

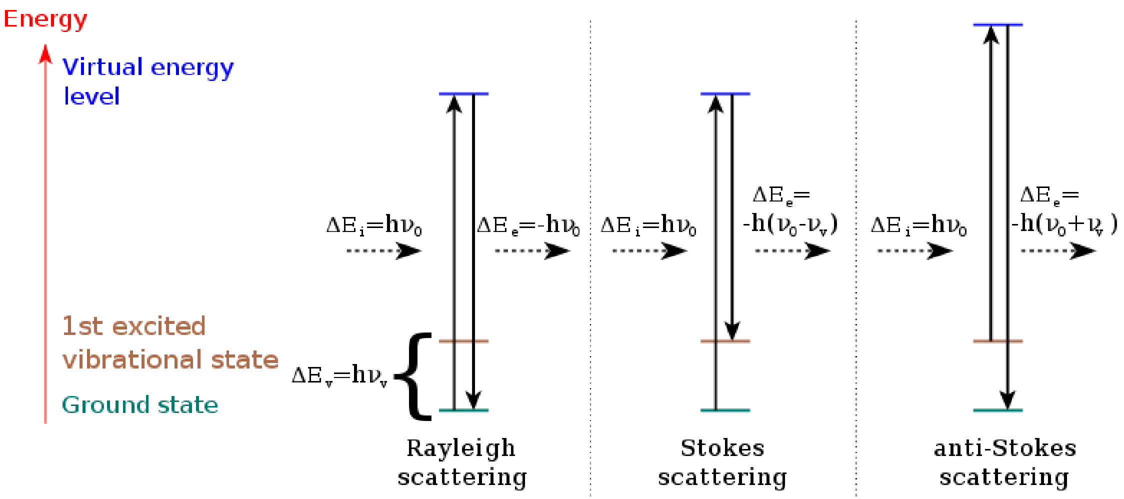
Background

I. Raman Scattering (or Raman effect)

- ❖ **Inelastic scattering of a photon**
- ❖ **A small fraction of the scattered light(≈1/10^7)**

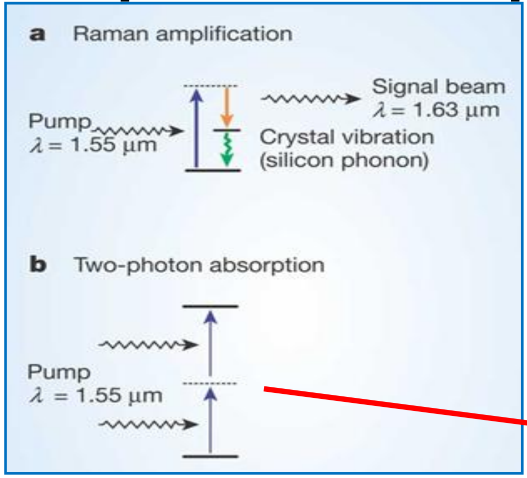
➡ **frequency different from incident photon : usually lower than**

> ➢ **Rayleigh scattering**
>
> − **When light is scattered from an atom or molecule, most photons are elastically scattered**
>
> − **Scattered photon = incident photon(same E & wavelength)**



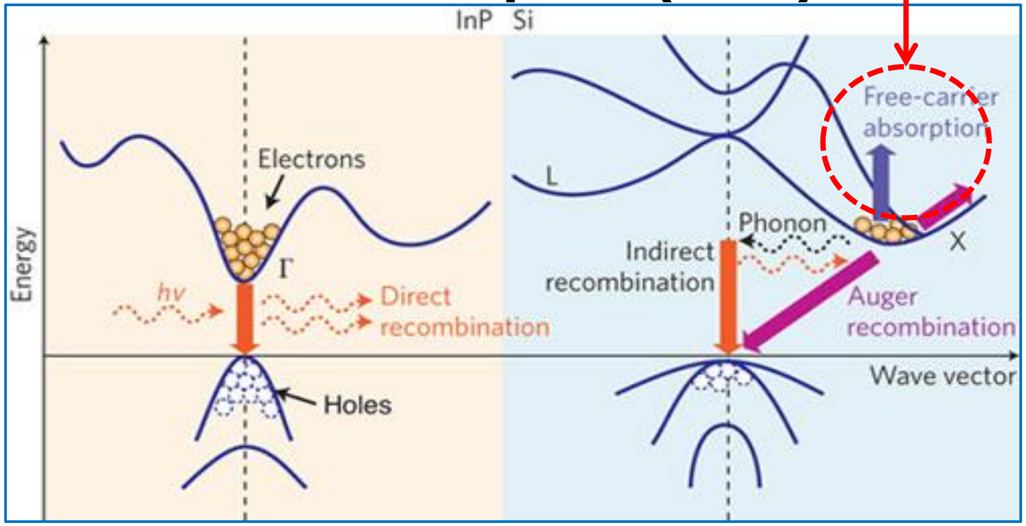
Background

II. Two-photon absorption(TPA)



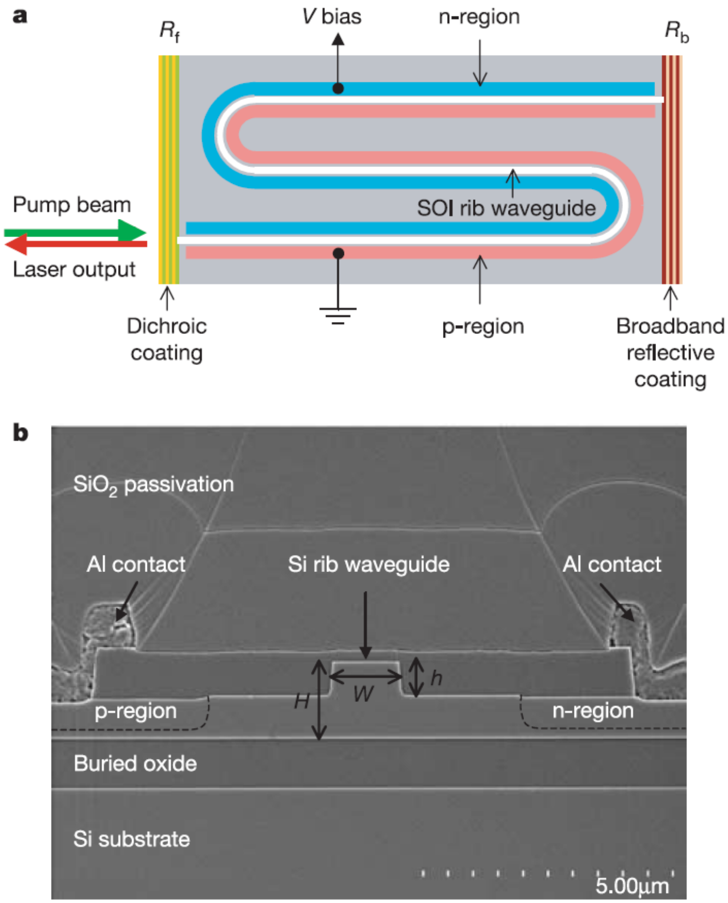
- ✓ *Simultaneous absorption of two photons of identical or different frequencies*
- ✓ *Nonlinear optical process*
- ✓ *TPA « OPA (One-photon absorption)*
- ✓ *Linear absorption* $\propto I_{light}{}^{2}$

III. Free-carrier absorption(FCA)



Laser Design

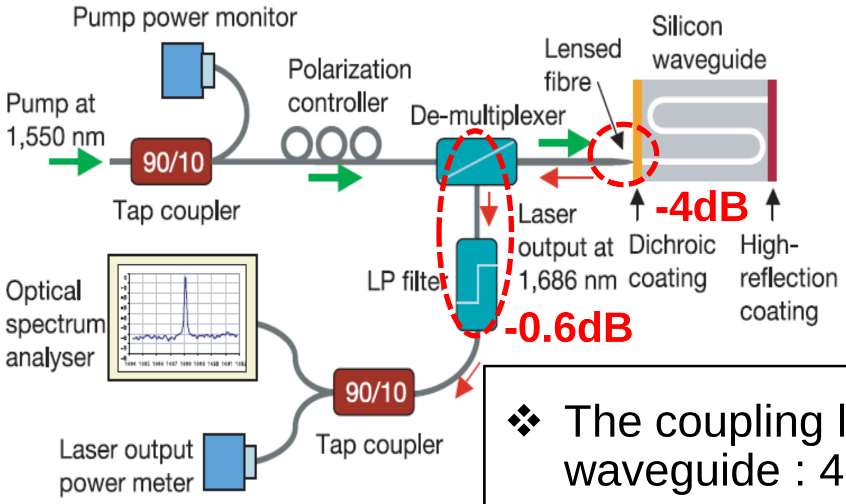
Laser cavity



- Low-loss SOI rib waveguide
- Coating the facets of Si waveguide with multilayer dielectric films
- R_f : 71%(1,686nm), 24%(1,550nm)
- R_b : 90%(1,686nm Raman & 1,550nm Pump)
- For minimizing optical power to achieve the lasing threshold ⇨ small cross-section
  - Not so small as to cause high transmission loss
- Width(W) : 1.5um / Height(H) : 1.55um / Etch depth(h) : 0.7um / Effective core area : 1.6um^2
- S-shaped waveguide
  - Total length : 4.8cm, Bend radius : 400um
    Transmission loss : 0.35 dB/cm
- p-i-n diode structure
  - To reduce nonlinear optical loss due to TPA-induced FCA

Laser Design

Schematic set-up



$$I_{\text{eff}} = I_i \frac{1-e^{-\alpha L}}{\alpha L} \frac{(1-R_{\text{f}})(1+R_{\text{b}}e^{-\alpha L})}{(1-\sqrt{R_{\text{f}}R_{\text{b}}}e^{-\alpha L})^2}$$

- The coupling loss between the lensed fiber and the waveguide : 4dB
- The insertion loss of the de-mux and long-wavelength pass filter : 0.6dB
- Cavity enhancement effect of the pump power → lower the lasing threshold
- When the pump laser is tuned to the resonance of the cavity : effective mean internal power (I_{eff})
- Power enhancement factor M=I_{eff}/I_i : 2.2
- At high power, α increases owing to TPA-induced nonlinear absorption, M reduces accordingly

Experimental results

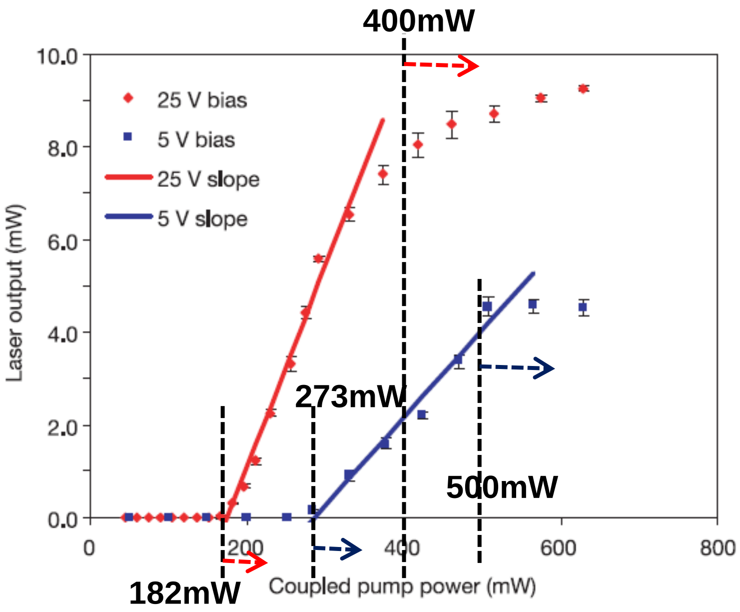
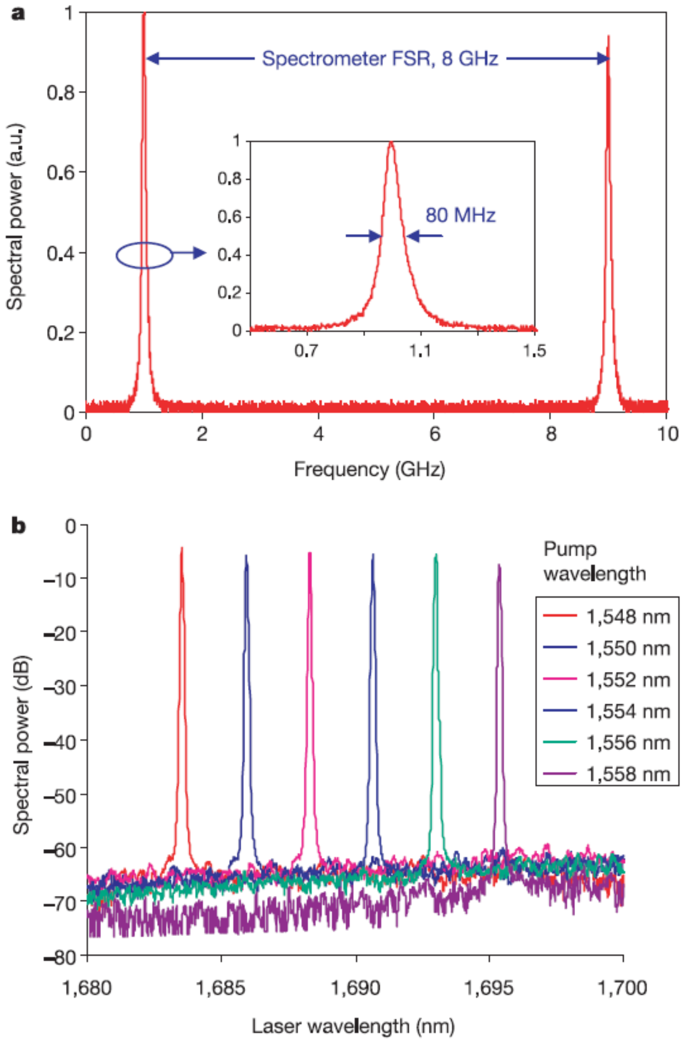


Figure 3 Silicon Raman laser output power as a function of the input pump power at a reverse bias of 25 and 5 V. The pump wavelength is 1,550 nm and the laser wavelength is 1,686 nm. The slope efficiency (single side output) is 4.3% for 25-V bias and 2% for 5-V bias. Error bars represent standard deviations.

- Raman laser frequency is 15.6THz lower than that of the pump laser
- Slope efficiency(single side output)
  - 25V reverse bias : 4.3% / 5V : 2%
- Lasing thresholds Power
  - 25V : 182mW / 5V : 273mW
- Higher reverse bias voltage lower -> lower threshold & higher laser output
  - Because the effective carrier lifetime is shorter ➡ lower nonlinear loss & higher gain
- Lasing saturation Power
  - 25V : 400mW / 5V : 500mW
- Nonlinear loss caused by TPA-induced FCA
  - Reduce the net gain at higher pump powers
  - Cavity enhancement factor M reduces ➡ lower the effective pump power in the cavity

Experimental results



- ❖ Confocal scanning Fabry-Perot spectrum analyser with free spectral range(FSR) of 8GHz(4.8cm cavity) & finesse of 100
- ❖ Pump power of 400mW & Reverse bias of 25V
- ❖ Single-mode output
  - − No other cavity modes with expected mode spacing of 0.9GHz
- ❖ 80MHZ linewidth by the resolution of the spectrum analyser
- ❖ 1,548~1,558nm pump laser in 2-nm steps
- ❖ Side-mode suppression of over 55dB
- ❖ Center wavelength corresponds to appropriate Stokes shift
- ❖ Small fluctuation is due to insertion loss of de-mux, long-wavelength pass filter, and gain of erbium-doped fiber amplifier

Conclusion & Summary

- **First demonstration of c.w. Raman lasing in silicon**
- **Improved by optimizing cavity mirror & length design**
- **Reduced threshold power by using smaller cross-sectional dimension & larger cavity enhancement**
- **Improved waveguide coupling efficiency by adding a mode converter**
- **Optimization of p-i-n diode design reduce the effective carrier lifetime to below 1ns**
- **Multilayer coating of cavity mirrors is replaced with waveguide Bragg reflectors, ring or microdisk resonator architectures**