

# Theoretical analysis of continuous-wave Raman gain/lasing in silicon wire waveguides without carrier extraction scheme

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**Abstract:** Stimulated Raman scattering in silicon waveguides are attractive for optical amplification/lasing due to high Raman coefficient and high optical pump intensity in the small waveguide core. In this paper, we investigate the effect of two-photon absorption and free-carrier absorption for continuous-wave light propagation in submicron size silicon wire waveguides. We also show that if the waveguide lengths and pump powers are optimized, the net continuous-wave Raman gain and thus lasing activities in such waveguides without any additional free carrier extraction schemes is possible.

**Keywords:** silicon photonics, silicon laser, wire waveguides, stimulated Raman scattering

**Classification:** Photonics devices, circuits, and systems

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## 1 Introduction

In recent years there has been much interest on sub-micron size silicon wire waveguides [1]. The ultra-small dimensions (e.g. 200 nm height by 450 nm width) and extremely strong optical confinement of such waveguides allows ultra-high optical intensity propagation. This leads to the manifestation of large nonlinear optical effects including two-photon absorption (TPA) and stimulated Raman scattering. Self-phase modulation (SPM) and nonlinear absorption in wire waveguides has been previously studied by the propagation of femtosecond pulses with high peak intensities in waveguides [2]. Stimulated Raman scattering, has recently shown potential for use in an optical amplifier because of the high Raman coefficient in crystalline silicon.

There are two kinds of commonly used singlemode silicon waveguides – large area rib structure and submicron size stripe structure (or wire waveguides). Most of reported silicon waveguide Raman amplifiers [3, 4, 5] and lasers [6, 7] are based on rib waveguide structures. In order to have significant net Raman gain in such waveguides, it is necessary to suppress the effect of optical loss originated from TPA generated free carriers [8]. Pulsed pumping [3] and reverse biased p-i-n diode structure to sweep out the free carriers [7] are the two commonly used approaches to solve this problem.

In this paper, we analyze the effect of TPA and the resulting free-carrier absorption (FCA) on the continuous-wave (cw) light propagation in submicron silicon wire waveguides at moderate power levels. We also show that it is possible to achieve cw-pumped Raman gain and lasing directly in such waveguides without any free carrier extraction schemes.

## 2 Propagation of cw pump

For the case of cw light propagation in wire waveguides, the loss due to photon absorption via TPA process is insignificant. However, the absorption of photons will create excess electron-hole pairs in the waveguides. The high carrier density in small waveguide area can lead to large loss and limit the maximum transmitted light.

To model this effect, we begin with the propagation of light along the waveguide and shown as below

$$\frac{dI}{dz} = -\alpha_{lin}I - \beta_2 I^2 - \sigma NI \quad (1)$$

where  $z$  is the propagation direction,  $\alpha_{lin}$  is the linear absorption,  $I$  is the optical intensity,  $\sigma$  is the free carrier absorption cross section,  $N$  is the carrier density and  $\beta_2$  is the TPA coefficient. The dependence of output power  $P(z)$  on the TPA coefficient is described in [9] as

$$P(z) = \frac{P(0)}{\exp(\alpha_{lin}z + \alpha_{fca}z)(1 + L_{eff}\beta_2 P(0)/A_{eff})} \quad (2)$$

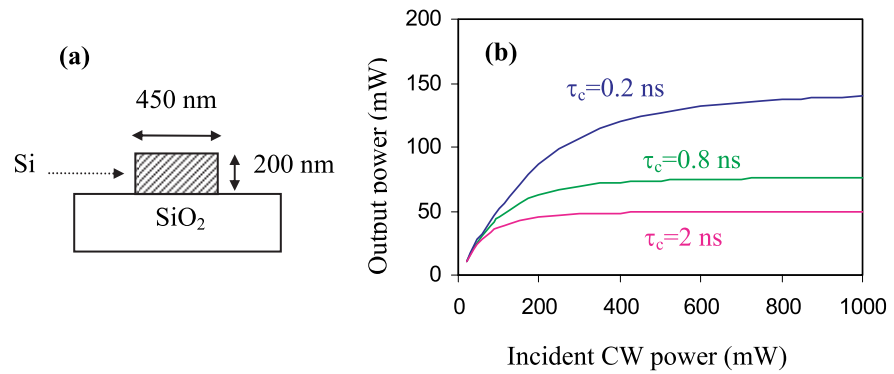
where  $\alpha_{fca}$  is the loss due to free carrier absorption,  $P(0)$  is the optical power at input facet,  $P(z)$  is the optical power at position  $z$ ,  $L_{eff}$  is the effective length and  $A_{eff}$  is the effective area of the waveguide mode. The generation rate of electron-hole pairs (EHP) is based on the interband two-photon absorption and the carrier lifetime  $\tau_c$

$$\frac{dN_A}{dt} = \frac{\beta_2 I^2(t)}{2h\nu} - \frac{N_A}{\tau_c} \quad (3)$$

where  $h\nu$  is the photon energy and  $N_A$  is the number of free carriers. The carrier lifetime in the waveguide is mainly characterized by EHP recombination time at both guiding layer (bulk recombination) and Si/SiO<sub>2</sub> interface (surface recombination). Surface recombination combined with rapid diffusion of carriers towards the Si/SiO<sub>2</sub> interface, results in a lowering of the measured lifetime compared to the bulk value. Based on the estimated carrier density from waveguide geometry and carrier lifetime, the free-carrier absorption (FCA) coefficient can be estimated from the classical Drude model, as described in [10].

Figure 1 (a) shows the wire waveguide geometry and dimensions used in the calculation. The calculated transmitted power as a function of input cw power launched into wire waveguide at different carrier lifetimes is plotted in Fig. 1 (b). For wire waveguides with same physical dimensions, the carrier lifetime can be different according to fabrication conditions. The value of  $\alpha$  in this calculation is 2.4 dB/cm [11]. Other values used in the calculation include  $\beta_2 = 0.8$  cm/GW [12] and  $A_{eff} = 0.1 \mu\text{m}^2$ .

It is clearly shown that maximum transmitted cw optical power is limited by nonlinear absorption. As shown in Fig. 1 (b), effective carrier lifetime plays an important role in the maximum transmittance inside the waveguides. Shorter carrier lifetime results in smaller carrier density, but saturation of maximum transmitted light still observed even though at the carrier



**Fig. 1.** (a) Silicon wire waveguide geometry. (b) Transmission of cw light at different carrier lifetime (0.2 ns, 0.8 ns and 2 ns).

lifetime of 0.2 ns. As shown in the calculation results, the output power becomes saturated at cw input powers exceeding 200 mW. The transmission saturation at such relatively low power level is an impediment for making high power nonlinear devices in silicon wire waveguides, such as waveguide Raman amplifiers. The carrier lifetime in silicon waveguides reported so far by various research groups are plotted in Table I. It is obvious that the lifetime decreases at smaller waveguide dimensions. This is due to the change in surface recombination rate and smaller diffusion time. Thus, it is promising to have Raman gain higher than nonlinear absorption loss in submicron size wire waveguides because of the shorter effective carrier lifetime.

**Table I.** Carrier lifetime in silicon waveguides.

Lifetime (ns)	Waveguide Type	Dimensions	Reference
82	Rib	$W = 4 \mu\text{m}$ , $H = 4 \mu\text{m}$	[8]
25	Rib	$W = 1.52 \mu\text{m}$ , $H = 1.45 \mu\text{m}$	[13]
1*	Rib	$W = 1.5 \mu\text{m}$ , $H = 1.55 \mu\text{m}$	[7]
0.77	Wire	$W = 0.22 \mu\text{m}$ , $H = 0.445 \mu\text{m}$	[4]

\* with reverse bias on p-i-n diode structure to sweep out part of free carriers.

### 3 Prospects of cw Raman amplification/lasing

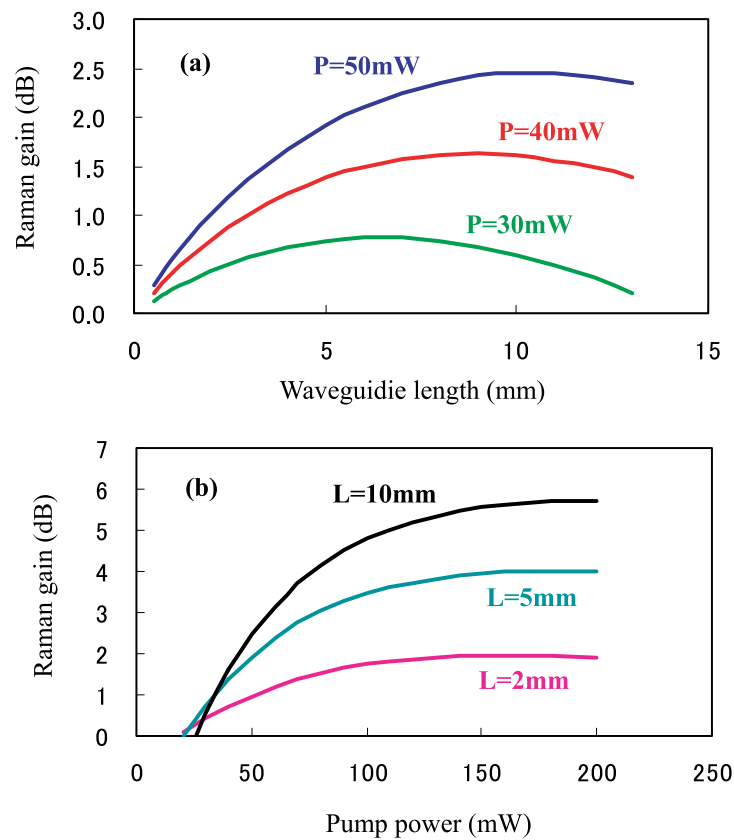
Although cw Raman laser has been demonstrated in silicon rib waveguides [7], it required external biasing voltage to sweep out the free carriers via a p-i-n diode structure. In wire waveguides, the carrier lifetime drops drastically when compare to rib waveguides. This helps to greatly reduce the total number of accumulated free carriers. Therefore, it should be possible to have net Raman gain in wire waveguides. If the achievable gain is sufficient to

compensate the cavity loss, we can realize a silicon Raman laser without any additional carrier extraction schemes.

The propagation of pump power along the waveguide can be described by Eq. (2). The amplified cw signal at the Stokes wavelength as a function of the waveguide propagation distance  $z$ , is calculated as

$$P_s(z) = P_s(0) \exp \left[ -(\alpha_{lin} + \alpha_{fca})z + \frac{g_s L_{eff} P_p(z)}{A_{eff}} \right] \quad (4)$$

where  $g_s$  is the Raman gain coefficient,  $P_s(z)$  and  $P_p(z)$  are the cw signal and pump power at waveguide position  $z$ . By using the same parameters as in [4], the Raman gain in various waveguide lengths and pump power levels are plotted in Fig. 2 (a) and 2 (b) respectively.



**Fig. 2.** (a) Raman gain against waveguide lengths at pump power levels of 30 mW, 40 mW and 50 mW; (b) Raman gain against pump powers at waveguide lengths of 2 mm, 5 mm and 10 mm.

As shown in Fig. 2 (a), the overall Raman gain increases to a maximum value and then drops. This is because the pump power depletes at the later section of the waveguides. The optical loss from nonlinear absorption is higher than the Raman gain. Thus the overall net Raman gain inside the wire waveguides will drop. However, the maximum achievable gain value can increase with coupled pump power. Shown in Fig. 2 (b) is the Raman gain at different pump power levels. With 200 mW pump power, it is possible to

achieve 6 dB Raman gain in a 10 mm wire waveguides. If the fabrication process is optimized to give better sidewall roughness, we can have smaller linear propagation loss and thus higher net Raman gain with the same waveguide dimensions should be possible. The curves in the graph also imply that longer waveguide and higher pump power are required to achieve higher Raman gain. The above calculated is based on the carrier lifetime reported in [4]. The free carrier absorption is the dominant nonlinear loss in cw Raman gain. The calculation results reveal that the overall Raman gain is higher than the free carrier absorption in wire waveguides. Thus net gain is achievable in those waveguides. From section 2, the influence of free carrier absorption will drastically increase if the carrier lifetime exceeds several nanoseconds. We believe that additional carrier lifetime reduction schemes are compulsory in rib waveguides, in which carrier lifetime is much longer than wire waveguides. It has been shown that it is possible to achieve net cw Raman gain in rib waveguides with p-i-n diode structure to sweep out the free carriers [7].

#### 4 Conclusion

In conclusion, we show that two-photon absorption and resultant free carriers can limit the maximum transmitted cw optical power in silicon wire waveguides. We also investigate the prospects of directly realizing Raman amplifiers/lasers in wire waveguides. The calculation results revealed that it is possible to achieve high Raman gain by reducing linear loss and increasing both waveguide lengths and pump powers.

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