Numerical Analysis of CW Raman Amplifier in Silicon-on-Insulator Nano-Waveguides

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Abstract: Numerical analysis of continuous wave (CW) on-off optical Raman gain in Silicon-On-insulator (SOI) nano-waveguides has been investigated. Two types of waveguide structures rib and strip waveguides have been incorporated. The waveguide structures have designed to be 220 nm in height. Three different widths of (350, 450, 1000) nm were studied. At telecommunication wavelength of 1550 nm, Raman amplification was calculated to be about 65 dB in rib SOI waveguide. The obtained Raman amplification is the heist reported value at relatively low pump power. High Raman gain amplification in SOI nano-waveguides presents an important step towards integrated on-chip optoelectronic devices.

Keywords: Silicon photonics, Raman Amplifier, Optical Waveguides, Photonic Integrated circuits.

1. Introduction
Silicon photonics technology has made rapid progress and especially based on SOI (silicon on insulator) attracted great deal attention in recent years. It is seen as the Key enabling technology for integration of highly complex optical circuit [1]. CMOS (complementary-metal-oxide-semiconductor) technology is sufficiently advanced to fabricate virtually all silicon photonics components [2]. This offers an efficient technique to produce such devices with low cost, in addition to, the possibility to integrate Si photonics devices and electronic control functions together. Which opens a wide range of applications from telecommunication to chip-to-chip interconnects on chip communication, also possible applications in emerging areas such as biomedical and sensing devices [3]. Silicon with bandgap of 1.12 eV is transparent at wavelengths used typically for optical communication transmission rang from 1270 nm to 1625nm. It has many of important properties which make it a good material, such as wafers of silicon are incredibly pure and low defect density, also has high thermal conductivity, which is Useful for an active device substrate. Furthermore, Therefore it presents as an ideal platform for electronics and integrated optics focused on achieving active functionality, mostly light amplification, modulation and wavelength conversion in silicon waveguides.
The approach that has been investigated for light generation and amplification in our work is the Raman Effect. Raman amplification process used to amplify signal wave via Raman interaction with the pump power. The Raman Scattering process is inelastic scattering. When light beam propagates inside an optical silicon waveguide, the photons are scattered to new frequencies causing change in the energy of scattered photons. In this interaction, the energy may be losing leading to Stokes shift or gains energy resulting anti-Stokes shift. See Figure 1A. Stimulated Raman scattering SRS process in silicon-on-insulator waveguides (SOI) is an attractive way of amplifying optical signal based on Raman Effect as shown in Figure (1).

![Figure 1](image1.png)

**Figure 1.** a) Schematic of Spontaneous Raman scattering phenomenon
b) Stimulated Raman scattering phenomenon [4].

Small cross sections with low loss waveguides are required for the realization of high performance devices. Surface roughness produces strong scattering and high propagation loss because of the high index contrast between the waveguide core and the cladding [5],[6]. For example, the losses of silicon waveguides tend to increase with reduction in dimension of cross-section. SOI waveguide fabrication processes by CMOS technology promise submicron cross section with low loss waveguides [5]. Raman net gain of 13 dB has been achieved by using a pulsed pump power at peak pulse power of 39 W with a pulse width of 3 picosecond and a repetition rate of 25 MHz in SOI waveguides with 2 μm² modal areas and a length of 25 mm [7]. A micrometer-sized laser was recently satisfied on a continuous-wave (CW) Raman Si laser based on a photonic-crystal high-quality (Q)-factor nanocavity, with a resonator size of 10 μm and an ultralow threshold of 1 μW, it generated from the most widely used silicon material in the electronics industry [8]. A Raman silicon laser has been achieved by using a high-quality (high-Q) nanocavity design at optically-pumped sub microwatt threshold [9].

In this work, Raman amplification in SOI Nano-waveguides has been investigated by numerically solved coupled equations, which describe the evaluation of the pump and Stokes wave via commercial software. Different dimensions of waveguide structures were relied of (3, 6, 8, 10, 12, 16, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85) mm in length, widths of (350, 450, 1000) nm, and compatible height with CMOS process of 220 nm. Two types of waveguide structures rib and strip waveguides have been incorporated. The inner core (in the order of hundreds of nanometers) is designed with a high refractive-index silicon material surrounded by a low-refractive-index of silica cladding offering high light confinement.

## 2 Simulation Part

Mode profiles were calculated for all of our rib and strip waveguide structures by using FullWave commercial software. We suppose that our waveguide structures are covered with a SiO₂ layer to reduce the contamination effect. Refractive indices of 3.47 and 1.45 for Silicon
and SiO₂ were adopted in the mode profile calculations. The calculations show the possibility of coupling or exciting only the fundamental mode into waveguide structure of 350 nm in width, and coupling more than the fundamental mode in the waveguide widths of 450, 1000 nm. The results of our simulation have been shown in figures (2, 3), where only the fundamental mode has been presented. The effective refractive indices are shown in the figures calculated by the software. The right side shows the computed mode profile for both figures. The left side shows the rib and strip waveguides. The effective area of the core waveguide is defined as [10]:

\[
A_{\text{eff}} = \frac{\iint I(x,y)\,dx\,dy}{\iint I^2(x,y)\,dx\,dy}
\]

(1)

Where \( I(x, y) \) is the transverse intensity of the fundamental mode (TE mode) of a waveguide (the integration is over the transversal plane). Considering only the calculation of the transverse mode profile for the fundamental mode, the effective core area could be estimated for each waveguide.

\[\text{Figure 2.} \text{ a) Basic structure of rib waveguide. b) Computed transverse Mode profile of Stokes radiation in the SOI waveguide (always z is the propagation direction)}\]

\[\text{Figure 3.} \text{ a) Basic structure of strip waveguide. b) Computed transverse Mode profile of Stokes radiation in the SOI waveguide.}\]
The effective core areas could be estimated for each waveguide, as shown in Figure – 4- and table -1-. Assuming that only the fundamental mode coupled out of the waveguide at stokes radiation, the value of the full width at half maximum (FWHM) of the outcoupled mode profile can be determined from the vertical and horizontal cut transverse mode profile, as shown in Figure - 4 - .

Table 1: The calculated effective core area ($A_{eff}$), effective refractive indices ($n_{eff}$), group index ($n_{gr}$) of waveguides with 350, 450 and 1000 nm in width, 220 nm in height for rib and strip waveguide.

| Rib/Strip − width Slab − height | $N_{eff}$ at 1550nm | $A_{eff}$ ($\mu$m$^2$) at 1550nm | $N_{gr}$ at 1550nm |
|---------------------------------|---------------------|---------------------------------|-------------------|
| 350nm, 0nm                      | 2.102149            | 0.113977                        | 4.45              |
| 450nm, 0nm                      | 2.386479            | 0.126323                        | 4.31              |
| 1000nm, 0nm                     | 2.746367            | 0.244736                        | 3.7059            |
| 350nm, 50nm                     | 2.276466            | 0.138204                        | 4.01              |
| 450nm, 50nm                     | 2.464671            | 0.112799                        | 4.08              |
| 1000nm,50nm                     | 2.7524445           | 0.252889                        | 3.6896            |

3  Coupled Equation of Raman Propagation and Simulation Results

3.1 Mathematical Model.
A weak signal and strong pump are launched into the optical waveguide, leading to amplify the signal due to the Stimulated Raman Scattering process. The difference in the energy between the pump and signal is called vibration state ($\Omega = \nu_p - \nu_s$), which determines the frequency shift of the pump and Stokes ($\nu_{p,s}$) and shape of the Raman gain curve[4].

Figure 4. The computed transverse fundamental mode profile of Stokes radiation SiO$_2$-covered for rib waveguide width (W) of 450nm, a) horizontal cut and b) Vertical cut.
Figure 5. Schematic diagram of a basic silicon Raman amplifier [10].

Figure 5 shows the schematic of the SOI Raman amplifier setup we analyze in this paper. It consists of the SOI waveguide of length \( L \), into the left-hand side of which pump and Stokes power light source and right-hand side of which Stokes output.

We use a simple model for the SOI Raman amplifier; we describe the amplifier in terms of the longitudinally varying optical powers. By taking into account pump depletion due to stimulated Raman scattering [11]. We generalize the differential equations are describing the longitudinal distributions of the pump power \( P_p \) and the signal power \( P_s \) inside the SOI waveguide structure are given in [12],[13], [14].

\[
\frac{1}{P_p} \frac{dP_p}{dL} = -\left[ \alpha_p + \varphi \lambda_p^2 N_{eff}[z] \right] - \left( \frac{\beta}{A_{eff}} \right) P_p \\
\frac{1}{P_s} \frac{dP_s}{dL} = -\left[ \alpha_s + \varphi \lambda_s^2 N_{eff}[z] \right] - \left( \frac{g_s - 2\beta}{A_{eff}} \right) P_s
\]

Where \((\alpha_p, \lambda)\) is the linear absorption coefficient for pump and signal wavelengths, \((\beta)\) is the two photon absorption coefficient, \( z \) is the longitudinal coordinate system, and \( \alpha \) represents the linear Waveguide losses, \((g_s)\) is the Raman gain coefficient. \((A_{eff})\) is the effective area of the waveguide, calculated to be 0.11, 0.12, and 0.24 \( \mu m^2 \) for strip waveguides and 0.1, 0.11, and 0.25 \( \mu m^2 \) for rib waveguides, respectively. Where \((\Delta N)\) is the density of electron hole pairs given by[15]:

\[
\Delta N = \beta \left( \frac{P}{A_{eff}} \right)^2 \left( \frac{\tau_{eff}}{2h\nu_p} \right)
\]

Where \( \nu_p \) is the frequency of pump beam, \((h)\) is Planck’s constant and \((h\nu_p)\) is the photon energy, and \((\tau_{eff})\) is an effective recombination lifetime for the free carries.

From Equation (2) the on-off (pump-on-pump-off) Raman gain is given in[16]:

\[
G_{on-off} = \frac{P_s(L=Z)}{P_s(0)}
\]

Raman net gain for considered as in [17]:

\[
G_{net} = \frac{P_s[L=Z]}{P_s[0] \exp \left( -L \alpha_s \right)}
\]

Where \( P_s[L] \) is the signal output power, which is obtained in equation (3), \( L \) is the waveguide length.
3.2 Simulation parameters
We base the simulations in this section on the parameters given as: Raman-gain of $g = 70 \text{ cm/GW}$ and TPA coefficients $\beta_{p,s} = 0.5 \text{ cm/GW}$ [18], pump and Stokes wavelengths of $\lambda_p = 1450 \text{nm}$ and $\lambda_p = 1550 \text{ nm}$, respectively, and effective areas taken from Table 1. The amplifier has a various lengths and widths.

Table 2: linear loss ($\alpha_{p,s}$) in the Silicon waveguide structure.

| linear losses of $\alpha_{p,s}$ (dB/cm) | Reference |
|----------------------------------------|-----------|
| 0.5                                    | [19]      |
| 1                                      | [10], [13]|
| 2.8                                    | [20]      |
| 3.6                                    | [21], [22]|
| 4                                      | Estimated |
| 5                                      | Estimated |

3.3 Results and discussion
The most important factor in determining the Raman gain in SOI waveguides is the effective carrier lifetime ($\tau_{\text{eff}}$), which plays an important role reaching maximum transmittance CW power into the silicon waveguide structures. It is clearly shown in figure 6 that maximum transmitted CW power is limited by nonlinear losses, where shorter carrier lifetime results smaller carrier density leading to increase Raman gain. The effective carrier lifetime in figure (6) are reported by various research groups (see Table 3). As shown in the calculation results, the output power starts dropping at input pump power exceeding 1 W. Due to the fast free carrier recombination mechanisms and smaller diffusion time at sub-microns silicon waveguides size, the effective carrier lifetime ($\tau_{\text{eff}}$) becomes short, which is promising to have high Raman gain.

![Figure 6. Output pump power characteristics for silicon Raman amplifiers with various effective carrier lifetimes for a) Strip, b) Rib waveguides.](image)

Table 3: Effective (Carrier) lifetime in Si Waveguide.

| Carrier Lifetime (ns) | Reference |
|-----------------------|-----------|
|                       |           |
Figure 7. On-off CW Raman gain versus input pump power of the SOI waveguides with various widths of (350, 450, and 1000) nm and length of 3 mm, a) Strip waveguide, b) Rib waveguide

Figure 7 shows the on-off Raman gain as a function of the input pump power of a passive strip and rib waveguides at various widths of (350, 450 and 1000) nm with a fixed length of 3 mm. At these dimensions, maximum pump-on-pump-off Raman gain of about 36.9 dB was obtained for all our SOI structures but at different input pump powers. For the waveguides of (W = 350 and 450) nm, maximum gain was of about 0.85 W input pump power. While for the waveguide of W = 1000 nm, input pump power of about 1.8 W was required to achieve maximum gain. It found that there is a tolerance of about 1 W input power between the waveguides of (W= 350, 450) nm and the waveguide of W=1000 nm starting Raman gain reduction. Also figure 7 shows that the Raman gain increases sharply with increasing the pump power for the waveguides of (350 and 450) nm in widths, because of the relatively small waveguides effective area. Then drops dramatically at pump power of about 0.9 W, nonlinear losses become more significant with increasing the coupled pump power. While Raman gain for the waveguide of 1000 nm is raising linearly with increasing the pump power reaching maximum Raman gain, then drops at pump power of about 2 W. These results improve the high dependence of waveguide dimensions on the nonlinear losses due to two photon absorption induced free carrier absorption in silicon waveguides as well as Raman amplification. The equivalent in the values of Raman gain between the strip and rib waveguides at the same length is due to the agreement of the effective area, where the mode distributions are nearly the same (see figures 2 and 3).
Figure 8. on-off Raman gain versus various waveguide lengths at 850 mW pump power and different waveguide widths of 350, 450 and 1000 nm., a) Strip waveguides, b) Rib waveguides,

Figure 8 shows the calculated on-off Raman gain at various waveguide length, which computed by solving the mathematical mode equations for strip and rib waveguides of (350, 450, 1000 nm) in widths. The overall on-off Raman gain increases to a maximum value with the optimum lengths and then drops. It is obvious in figure 8 that short lengths in the range of several millimeters of (W= 350 and 450) nm SOI waveguides are enough to satisfy the maximum value of the on-off Raman gain. Maximum on-off Raman gain at pump power of 850 mW and optimum waveguide length of 6 mm was calculated to be (39.8, 40.4) dB in a strip waveguides of 350 and 450 nm widths respectively. While these values were found to (45, 47.7) dB for the rib waveguides of 350 and 450 nm widths, respectively see (figure 8 a, b). 12 to 16 mm lengths are the optimum waveguide lengths (L) to obtained maximum Raman gain for a waveguide 1000 nm in widths at 850 mW pump power. Maximum on-off Raman gains of strip and rib waveguides with (W= 1000 nm and L=16 were calculated to be (65.5 and 64.9), respectively. These results show the tradeoff between the waveguide effective area and waveguide length. The pump power depletes by lengthening the relatively small waveguides due to the linear loss because of the sidewall roughness. In addition to linear loss due to generated free carriers,

Figure 9. Raman net gain as a function of the input pump power at various waveguides of (W = 350, 450 and 1000) nm, a) Strip waveguides. b) Rib waveguides.

Since the Raman net gain is calculated without taking in considering the linear losses. Figure 9 shows the calculated Raman net gain for our previously considered SOI waveguides. Laser action could be achieved by introducing optical feedback, in addition to high Raman net gain [10].
Our results in figure (10), shows that the Raman gain decreases by increasing the linear losses ($\alpha_p, s$). From hand, the maximum possible gain can be increased equally well by decreasing the linear losses (for example, by waveguide sidewall smoothing to reduce surface scattering [24]).

In the other hand, scaling down the waveguide dimensions has a significant effect to reduce the nonlinear absorption in SOI waveguides. The previous results show that there is a tradeoff between the linear losses and nonlinear loss into SOI waveguides leading to an increase in Raman gain.

4. Conclusion

In summary, Numerical analysis using beam propagation method was investigated to calculate CW Raman amplification in sub-micron SOI nano-waveguides at telecommunication wavelength. Two different waveguide structures (Strip and Rib) were simulated. Raman amplification was calculated to be 65.5 dB in rib SOI waveguide of 1000 nm in width and 16 mm in length. The obtained Raman amplification is the heist reported value at relatively low pump power 0.85 W. Silicon photonics technology is an important step towards integrated on-chip optoelectronic devices. Farther development, silicon photonics components and circuits on SOI platform for example, ring resonator, photonic crystal as well as arrayed waveguide gratings.

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