Influence of nonlinear absorption on Raman amplification in Silicon waveguides

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Abstract: We model the TPA-induced free carrier absorption effect in silicon Raman amplifiers and quantify the conditions under which net gain may be obtained. The achievable Raman gain strongly depends on the free carrier lifetime, propagation loss, and on the effective Raman gain coefficient, through pump-induced broadening.

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

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1. Introduction

Stimulated Raman Scattering has been recently proposed as a means to achieve optical gain in silicon guided wave devices [1-3]. The motivation stems from the fact that the stimulated Raman scattering coefficient is approximately 10^4 times higher than that in silica fiber [1]. The effect is further enhanced by the tight optical confinement in silicon waveguides, resulting in large intensities in the waveguide core. The initial demonstration of spontaneous Raman emission [2] was followed by the demonstration of stimulated amplification at 1542nm, with a modest gain of 0.25dB [3]. However, a net positive gain is yet to be reported, since the observed gain was much smaller than waveguide insertion losses of 7 dB [3].

Two-Photon-Absorption (TPA) is a potentially detrimental phenomenon that reduces the efficiency of nonlinear guided wave devices. In silicon, TPA has been shown to be negligible from the point of view of pump depletion [1]. This is plausible since the TPA coefficient in silicon, β, is relatively small compared to III-V semiconductors that have also been considered for nonlinear guided wave devices [3-11]. Another potentially detrimental manifestation of TPA, as it relates to Raman gain, is absorption by TPA-generated free carriers. This effect, which was not included in our previous calculations [1], is a broadband, pump-induced absorption that competes with the Raman gain. Free Carrier Absorption (FCA), caused by TPA, has been identified as a limiting factor in all-optical switching in III-V semiconductor waveguides [9-11]. It has also been discussed as a potential limit to achievable Raman gain in GaP waveguides [12], although a Raman gain of 24dB was demonstrated in these waveguides [13]. More recently, TPA-induced FCA has been measured in silicon waveguides in the context of spontaneous Raman emission [4], and in transmission of ultra short pulses in silicon waveguides [6]. In this paper, we model the TPA-induced FCA in silicon Raman amplifiers and quantify the conditions under which useful gain may be achieved.

2. Analysis and discussion

The following analysis applies to single mode, silicon-on-insulator (SOI) waveguides with modal area, *A*, and length, *l*, as shown in Fig. 1. Previous Coupled-Mode Calculations (CMC) for these waveguides have shown that the one-dimensional approach, using the propagating field intensities to calculate nonlinear optical phenomena, is adequate [14]. The evolution of pump and signal field intensities, $I_P(z)$ and $I_S(z)$, along the waveguide propagation direction, z, is governed by the following expressions [10]

$$dI_P/dz = -(\alpha_P + \alpha_P^{FCA}(z))I_P - \beta I_P^2, \tag{1.1}$$

$$dI_S/dz = -(\alpha_S + \alpha_S^{FCA}(z))I_S + (g_R - 2\beta) I_P I_S. \tag{1.2}$$

Where β is the TPA coefficient in silicon, g_R is the Raman gain coefficient, and $\alpha_{P,S}$ is the linear propagation loss coefficient for the pump/signal wavelength. We note that Eq. (1.1)

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assumes no pump depletion effects due to stimulated Raman conversion. This approximation is only valid in the low signal amplification regime, which is the case considered here. In the calculations that will follow, an input Stokes signal of 0.1 μW has been used. Even at a high gain of 30 dB, and an input pump power between 0.5 and 1.0 Watt, pump-depletion is negligible. The terms in Eq. (1.1) and Eq. (1.2), involving the coefficients, $\alpha^{FCA}_{P,S}$ (z), take into account the FCA mechanism. The magnitude of FCA depends on free carrier concentration through the relation: $\alpha^{FCA} = 1.45 \times 10^{-17}(\lambda/1.55)^2 \cdot \Delta N$, where, λ is the wavelength in microns, and ΔN is the density of electron-hole pairs [15, 16]. The latter is related to the pump intensity by

$$\Delta N = \beta \cdot I_p^2 \cdot \tau_{eff} /(2 \cdot h\nu). \quad (2)$$

Where $h\nu$ is the photon energy, and, τ_{eff}, is the effective recombination lifetime for free carriers. We note that Eq. (2) assumes that carriers diffuse uniformly over the modal area. The latter assumption overestimates the carrier density, since carriers will diffuse over the device volume, beyond the modal region. It is well known that the recombination lifetime in SOI is much shorter than that in a bulk silicon sample with comparable doping concentration. This lifetime reduction is due to the presence of interface states at the boundary between the top silicon and the buried oxide layer. This effect depends on the method used for preparation of the SOI wafer and the film thickness, with reported values ranging between 10ns – 200ns [4, 17, 18].

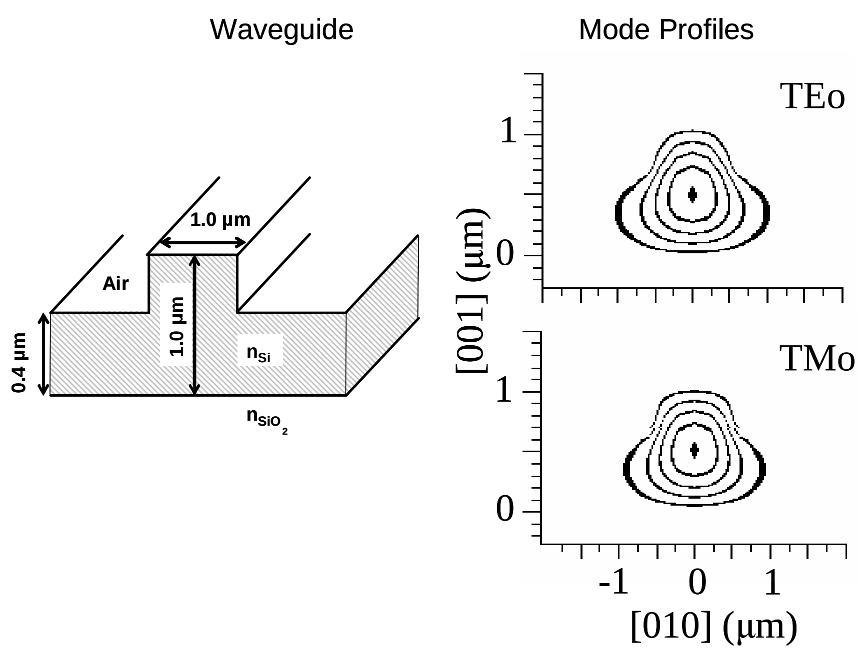

Fig. 1. Schematic diagram of the SOI waveguides considered for the calculations.

Integration of Eq.(1.1) and Eq.(1.2) was carried out numerically and the effective Raman gain, defined as, $10 \cdot \log[I_s(L)/I_s(0)]$, is plotted in Fig. 2. The results are shown for values of τ_{eff} ranging from 1 ns to 100 ns. The length of the waveguide was taken to be, L = 2 cm, and a propagation loss of $\alpha_P = \alpha_S$ =1 dB/cm, was assumed. We have used a TPA coefficient of β =

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0.7 cm/GW, which is closer to the upper end of the 0.4-0.9 cm/GW range reported in the literature [3-6], and a Raman gain coefficient of g_R = 76 cm/GW [2, 19]. Also included in Fig. 2 is the plot of the Raman gain obtained without FCA. It is clear that, for lifetimes of 10ns or larger, FCA limits the achievable gain. However, in the regime between 1 to 10 ns, reasonable gain may be expected in a 2 cm long waveguide.

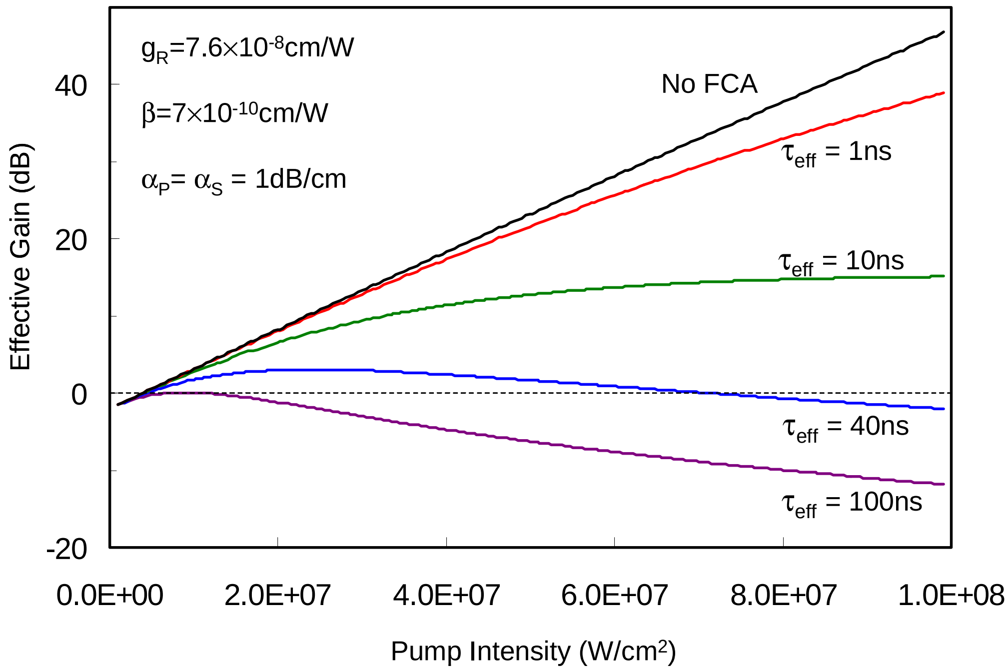

Fig. 2. Effective gain, calculated for different values of effective recombination lifetime.

To obtain an estimate for the value of τ_{eff}, free carrier diffusion needs to be considered in addition to the recombination lifetime. Through diffusion, shown in Fig. 3, carriers move out of the modal area, resulting in an effective lifetime that can be shorter than the recombination lifetime in SOI. If τ_r is the recombination lifetime, and τ_t is the transit time, then $1/\tau_{eff} = 1/\tau_r + 1/\tau_t$. The lower bound for the effective lifetime can be obtained by considering the case of a slab waveguide. The effective diffusion velocity of free carriers in this slab is approximately given by, $v_D = D/L_D$, where L_D is the diffusion length, $L_D = \sqrt{D\tau_r}$, and D is the ambipolar diffusion coefficient in silicon [20]:

$$D = \frac{(n+p)D_n \cdot D_p}{nD_n + pD_p}. \tag{3}$$

Here, n/p is the electron/hole concentration, and $D_{n,p}$ is the diffusion coefficient. Under high level injection of electron-hole pairs, $n = p$, and Eq. (3) becomes $D = 2D_n \cdot D_p /(D_n + D_p)$. Assuming a doping concentration of 10^{15} cm^{-3}, then D_n = 40 cm^2/s and D_p = 10 cm^2/s, so that D = 16 cm^2/s.

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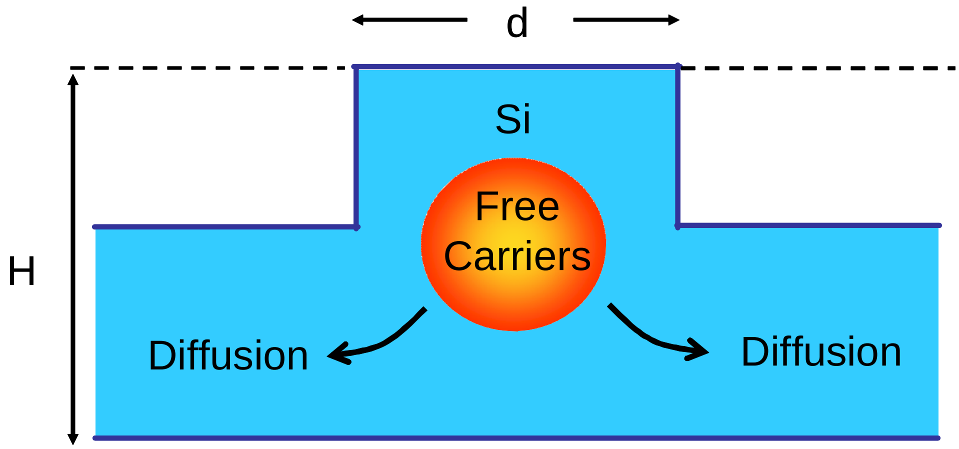

Fig. 3. SOI rib waveguide, with photo-generated free carriers within the rib section. The carriers diffuse into the slab, effectively reducing the carrier density within the optically active area.

The parameter, τ_r, is the recombination time of the free carriers in the SOI film. In general, it follows the relation: $1/\tau_r = 1/\tau_r^{bulk} + S/H$, where *S* is the surface-recombination velocity at interface between the top silicon and the buried oxide. Since τ_r^{bulk} is ~ 1µs, it can be safely assumed that τ_r = H/S, for H sufficiently small. The value of *S* depends on the method used to prepare the SOI wafer but is typically in the 10^3 cm/s range [21]. For *H* = 1µm, and an optical mode of width *w* ~ *1*µm, and recalling the expression for the diffusion velocity, v_D, the time it takes for carriers generated at the center of the mode, to transit out of the modal area, is

$$\tau_t = \frac{w}{2} \cdot \frac{1}{v_D} \approx \frac{w}{2} \cdot \sqrt{\frac{H}{SD}} \approx 4\, ns.$$

It is apparent that diffusion will reduce the effective lifetime for sufficiently small *w*. For the case considered, assuming τ_r = 100 ns, then τ_{eff} will be reduced to ~ 4 ns due to diffusion. For a rib waveguide the effective lifetime will be longer than the above value due to the partial confinement of carriers by the rib. As the slab height is reduced, diffusion from the waveguide rib into the slab is diminished. An upper bound on τ_{eff} is obtained by considering a channel waveguide, where diffusion into the slab does not occur. In this case, τ_{eff} will simply be given by τ_r (assuming the sidewalls are well passivated and do not introduce significant recombination centers). Figure 4 shows a plot of the total optical gain obtained for different values of the effective Raman coefficient, $g_{R.}$ Calculations are performed for an effective lifetime of τ_{eff} = 8ns. Variations of g_R account for the reduction in the Raman gain coefficient by the finite linewidth of the pump laser. This effect has been observed experimentally, where the 100 GHz intrinsic Raman bandwidth was broadened to ~ 250GHz by the pump laser used [3]. Figure 4 indicates that the reduction of the Raman gain coefficient, by pump-induced broadening, has a detrimental effect on the total gain that can be achieved. From this point of view, a narrow linewidth (<<100GHz) pump laser is preferred as it leads to the maximum Raman gain coefficient.

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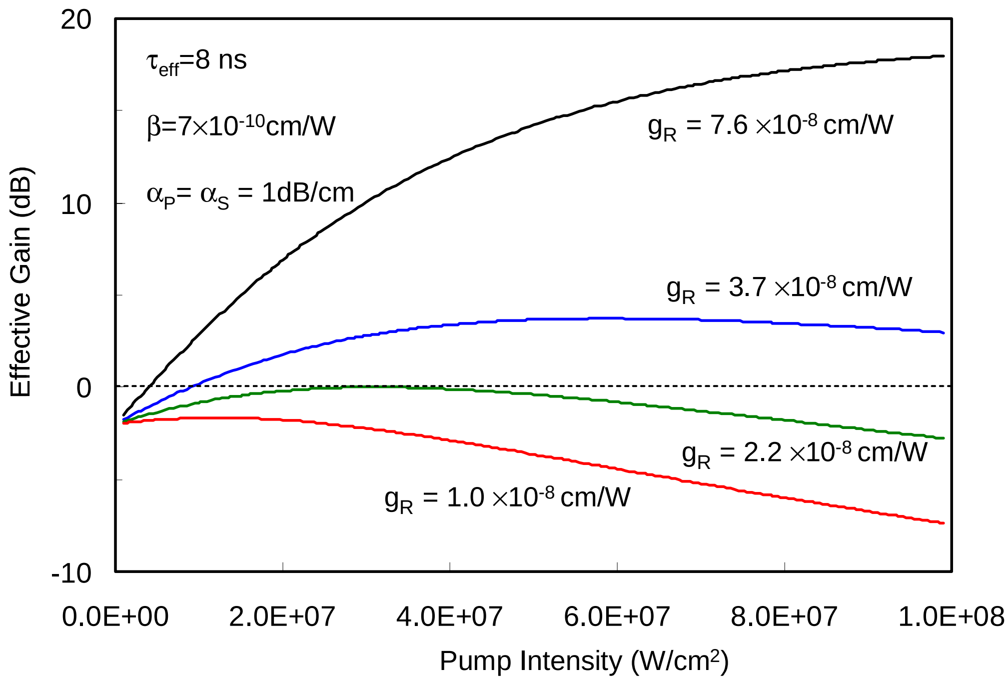

Fig. 4. Effective gain as a function of input pump intensity, for different values of Raman gain coefficient in silicon. Pump-broadening is responsible for the reduction in Raman gain.

Another parameter that will significantly impact the amplifier gain is the passive propagation loss of the waveguide. Figure 5 shows the expected gain versus pump intensity, for waveguide propagation losses ranging from 0.1 dB/cm to 5 dB/cm. The results suggest that, in order to have appreciable gain, propagation losses must be kept below 1.0 dB/cm. For SOI waveguides, the loss typically increases with reduction in transverse dimension, due to increase in surface scattering. However, waveguides with submicrometer dimension and losses below 1dB/cm have been demonstrated by using surface smoothing techniques [22].

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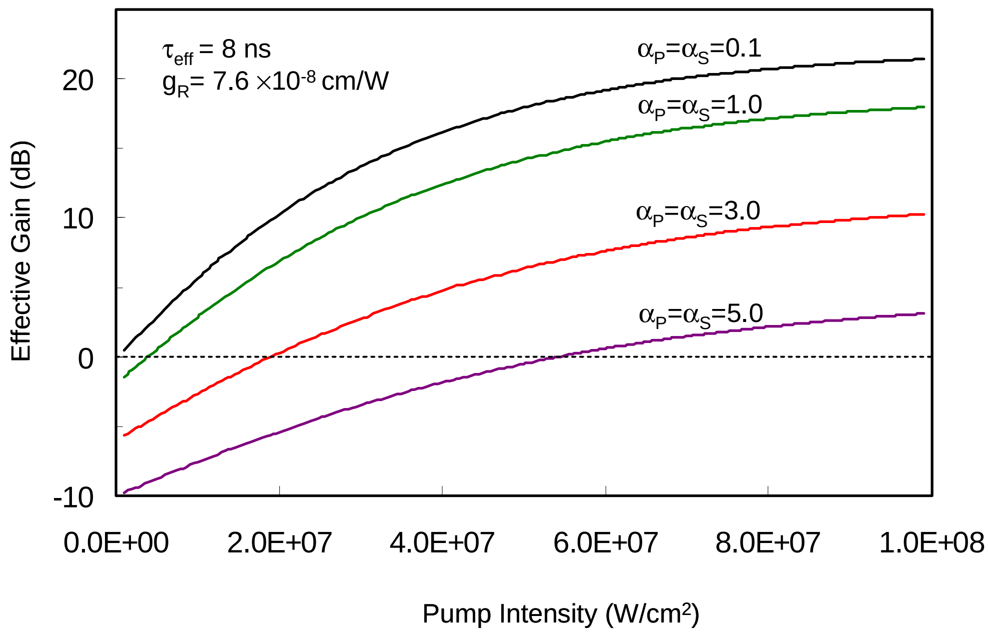

Fig. 5. Effective gain curves for different values of linear propagation loss in the waveguide.

3. Conclusions

In summary, it is clear from the above analysis that achievable Raman gain strongly depends on the effective free carrier lifetime, propagation loss, and on the effective Raman gain coefficient through pump-induced broadening. In a rib waveguide with submicron modal area, the effective lifetime will be significantly lower than the recombination lifetime in the SOI film, due to diffusion of photo-generated carriers into the slab regions that surround the rib. This phenomenon enhances the achievable gain by reducing the steady state carrier density and diminishing the role of FCA. Further reduction in carrier density could be achieved using a reverse bias p-n junction to deplete the carriers. The use of a narrow linewidth pump is preferred in order to achieve the maximum gain. However, it should be noted that pump induced gain broadening does have the beneficial effect of increasing the gain bandwidth. This may be necessary in a multi-channel application.

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