Noise Figure of Silicon Raman Amplifiers

[1]Dimitrios Dimitropoulos, [1]Daniel R. Solli , [2]Ozdal Boyraz, and [1]Bahram Jalali

[1]Optoelectronic Circuit and Systems Laboratory,University of California, Los Angeles CA90095
[2]University of California, Irvine CA 92697

Abstract — Quantum mechanical Langevin calculations show nonlinear absorption significantly degrades the noise figure of silicon Raman amplifiers, and lifetimes in the 20ps range or less are needed to approach the theoretical limit of 3dB noise figure.

1. Introduction

The recent observation of high Raman gain [1] in silicon waveguides along with the demonstration of Raman lasers [2,3] have opened up new possibilities for low cost photonic components. For operation in the technologically important 1300-1550 nm wavelength range, the main challenge is the nonlinear optical loss that competes with the Raman gain in silicon. This loss is caused by absorption from free carriers that are created in the medium because of two-photon absorption (TPA) induced by the high intensity pump beam. In this paper, we show, for the first time, how the nonlinear losses affect the signal-to-noise ratio of a Raman amplifier. We develop a quantum mechanical model to determine the minimum noise figure of the silicon Raman amplifier as a function of the carrier lifetime, waveguide losses, and pump intensity.

2. The Noise Model

Our model consists of an equation for the quantum-mechanical operator describing the Stokes wave propagating along the silicon waveguide and an equation for the propagation of the pump intensity (1b):

$$\frac{d}{dx}\hat{a}_S = (g(x)/2)\hat{a}_S - (\gamma'(x)/2))\hat{a}_S + \sqrt{g(x)}\hat{N}_G^{+} + \sqrt{\gamma'(x)}\hat{N}_L \qquad (1a)$$

$$dI_P(x)/dx = -\gamma''(x)I_P(x) \qquad (1b)$$

Here $\hat{a}_S$ is the photon annihilation operator for the Stokes field and x is the position along the length of the waveguide. *g(x)* is the Raman gain along the waveguide and $\gamma'(x)$, $\gamma''(x)$ the loss coefficients for the Stokes and the pump wave, respectively. The coefficients sum up the linear propagation loss, the TPA loss and the free carrier absorption (FCA) loss for each wave. The last two terms in the equation are the Langevin noise sources, that represent sources of fluctuations for the optical wave due to the optical loss and the optical gain respectively. These operator sources obey the commutator relation:

$$[\hat{N}_L(x), \hat{N}_L^{+}(x')] = [\hat{N}_G(x), \hat{N}_G^{+}(x')] = \delta(x - x') \qquad (2)$$

These noise operators act on "noise reservoir states". A derivation of the noise sources for optical loss and gain can be found in [4].

We find the noise figure of the Raman amplifier by evaluating the mean output photon number and mean photon number fluctuation, at the end of the waveguide. The resulting expression is:

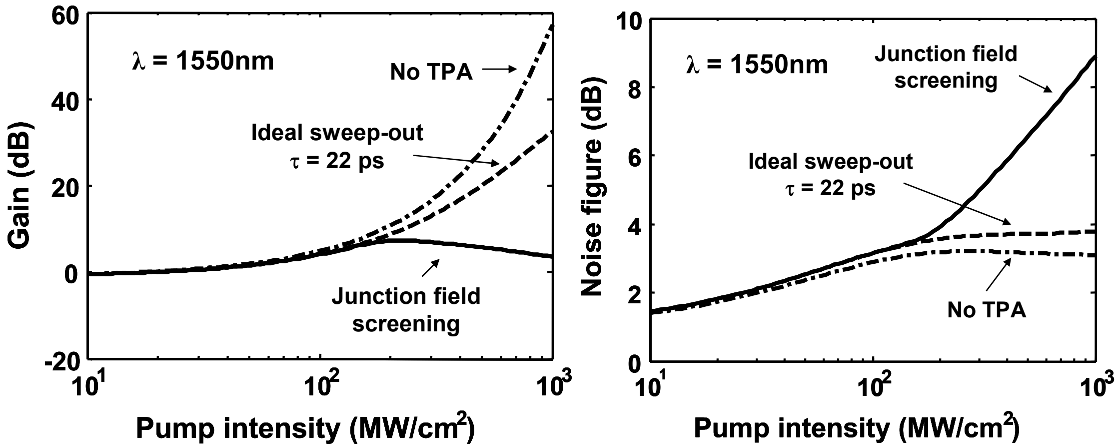
$$F = \frac{T + N_{loss} + N_{gain}}{T} + \frac{N_{gain}(T + N_{loss})}{T^2\langle n\rangle} \qquad (4)$$

where $T = \exp\left(\int_0^x dx''(g(x'') - \gamma'(x''))\right)$, $N_{loss} = \int_0^x dx'\,\gamma'(x')\exp\left(\int_{x'}^x dx''(g(x'') - \gamma'(x''))\right)$,

$N_{gain} = \int_0^x dx'\,g(x')\exp\left(\int_{x'}^x dx''(g(x'') - \gamma'(x''))\right)$ and $\langle n\rangle$ is the Stokes photon number.

3. Results

The above expressions are evaluated numerically for various values of the carrier lifetime, which is the critical parameter of the Raman amplifier. It is clear from the above expressions that the nonlinear loss not only degrades the net gain, but adds to the overall noise.



(a) (b)

Figure 1: (a) Amplifier gain and (b) noise figure vs. pump intensity for a device that uses a p-n junction for carrier sweep-out. Model parameters: length = 1 cm, Raman gain coefficient = 15 cm/GW, TPA coefficient = 0.7 cm/GW, free carrier absorption coefficient = 1.45×10^{-17} cm^2, linear loss = 1 dB/cm. Rib waveguide dimensions: width $w = 1.5\mu m$, core height $H = 1.55\mu m$, slab height $h = 0.75\mu m$, distance of the p and n doped regions from the rib edge $d = 2.25\mu m$.

We show in Figure 1 the gain and noise figure for a Raman amplifier where the sweep-out of the photogenerated carriers is achieved with a reverse biased p – n junction. In such a case the carrier lifetime is intensity dependent as shown in [5]. The reason is the increase in carrier generation rate at high pump intensities, an effect that leads to screening of the p-n junction field. A rib waveguide was assumed with dimensions given in the Figure caption. Drift-Diffusion simulations indicated that in the absence of field screening, i.e. at low pump intensity, the lifetime is 22ps. An increased pump intensity leads to a higher value of the lifetime due to field screening and this leads to a sever degradation in the amplifier noise figure (Fig. 1b). We also show results for two additional cases: (1) a fictitious case where the intensity dependence of lifetime is absent and a low intensity value of 22ps is used for the lifetime, and (2) an ideal case where TPA is completely absent. The impact of lifetime and TPA on the noise figure is clearly evident in Figure 1b. We note that the case of no TPA is valid for mid-IR wavelengths larger than ~2300nm. Two photons at these wavelengths do not have sufficient energy to cause interband transitions and nonlinear losses are absent as demonstrated in [6]. Therefore, for mid-IR wavelengths, the low noise figure approaching the theoretical limit of 3dB (Figure 1b dotted line) is achievable.

4. Conclusions

We have calculated the noise figure for a silicon Raman and have found that significant noise degradation is caused by the nonlinear losses in the near infrared wavelengths. The noise figure is a strong function of carrier recombination lifetime. In devices that use a p-n junction for carrier sweep-out, the onset of junction field screening is accompanied by a sharp increase in noise figure. The best performance for silicon Raman amplifiers is obtained at the mid-infrared wavelengths greater than ~2.3 μm, where TPA is absent. In this regime, an intrinsic low noise figure approaching the theoretical limit of 3dB is possible.

References

[1] O. Boyraz and B. Jalali, "Demonstration of 11 dB fiber-to-fiber gain in a silicon Raman amplifier," IEICE Electron. Exp. **1**, 429-434 (2004).

[2] O. Boyraz and B. Jalali, "Demonstration of a silicon Raman laser," Opt. Exp. **12**, 5269 (2004).

[3] H. Rong et al, "continuous-wave silicon Raman laser," Nature 2005.

[4] H.A. Haus, Electromagnetic Noise and Quantum Optical Measurements, Springer (2000).

[5] D. Dimitropoulos, S. Fathpour, and B. Jalali, "Limitations of active carrier removal in silicon Raman lasers and amplifiers," Appl. Phys. Lett. **87**, 261108 (2005).

[6] V. Raghunathan, R. Shori, O. Stafsudd, and B. Jalali, Journal of Physica Status Solidi (a) Rapid Research Letters, Vol. 203 (no.5), pp. R38-R40, March 2006.