# Pump to Signal RIN Transfer in Silicon Raman Amplifiers

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**Abstract:** The pump to signal RIN transfer in chip-scale silicon Raman amplifiers is investigated in the presence of nonlinear losses. Pump RIN frequency components as high as 1.5 GHz will be transferred to the signal.



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## 1. Introduction

Miniaturization of optical devices in highly nonlinear, high index contrast silicon waveguides attracted considerable attention in recent years. For instance, stimulated Raman scattering has been used to demonstrate light amplification and lasing in silicon waveguides [1-6], which generally can be realized in kilometers long fibers with similar efficiency. Despite of their high efficiency, the practical realization of these nonlinear silicon devices requires optimization of power levels to avoid nonlinear losses originating from two-photon absorption (TPA) and TPA-induced free carrier absorption (FCA) [1,2,4]. In addition to efficiency, the noise performance of the devices should be carefully evaluated. Recently, noise figure in silicon Raman amplifiers has been investigated [7] where the pump noise is excluded.

Small amplitude perturbations residing on the pump wave characterized as the relative intensity noise (RIN) are transferred to the Stokes wave during Raman amplification. In fibers, the long interaction length and averaging due to large group velocity dispersion induced "walk off", mitigates the RIN transfer at noise frequencies above 10 MHz and 10 kHz in co-pumped and counter-pumped configurations, respectively [8]. However, noise components below the cut-off frequency are amplified and appear as fluctuations in the output signal. Here the pump-to-signal RIN transfer in chip scale silicon Raman amplifiers is investigated.

## 2. Principle of pump to signal RIN transfer in silicon Raman amplifiers

Assuming that pump and signal waves travel in the waveguide with different group velocities, we can write the nonlinear losses and interaction between two waves as following on a reference plane traveling with the pump wave:

$$\frac{\partial I_s}{\partial z} - d_{\pm}\frac{\partial I_s}{\partial t} = -\alpha_s I_s - \alpha_s^{FCA} I_s - \beta_{TPA} I_s^2 - 2\beta_{TPA} I_{p\pm} I_s + g_R I_{p\pm} I_s \qquad (1)$$

$$\frac{\partial I_{p\pm}}{\partial z} = \mp\alpha_p I_{p\pm} \mp \alpha_p^{FCA} I_{p\pm} \mp \beta_{TPA} I_{p\pm}^2 \mp 2\beta_{TPA} I_s I_{p\pm} \mp \frac{\omega_p}{\omega_s} g_R I_s I_{p\pm} \qquad (2)$$

The parameters $I_{s,p}$ represent the signal and the pump intensities, $g_R$ is the Raman gain coefficient, $\alpha_{s,p}$ are the linear loss coefficients, $\omega_{s,p}$ are the angular optical frequencies, $\beta_{TPA}$ is the TPA coefficient. The upper and lower signs of $\pm$ and $\mp$ correspond to the co-propagating and counter-propagating configurations, respectively. The TPA induced free carrier absorption is given as $\alpha_l^{FCA}(z) = 1.45\times10^{-17}(\lambda_j/1550)^2 N$ ($j=s,p$, $\lambda_j$ in nanometer) for a steady state free carrier density of $N(z)=\tau\,\beta_{TPA}\,I^2(z)/(2hv)$ (cm$^{-3}$) generated by both CW pump and Stokes intensities[6], where $\tau$ is the free carrier lifetime, and $hv$ is the photon energy. Here total intensity, $I$, is assumed to be $I^2(z)=(I_p+I_s)^2$, including free carriers generated by both degenerate and non-degenerate TPA effects . The pump to signal RIN transfer is mainly determined by the free carrier loss and the "walk-off" between pump and the signal as: $d_{\pm} = 1/v_p \mp 1/v_s$,

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where $v_{s,p}$ are the group velocities of the Stokes and pump waves in the waveguide. The "walk-off" for the co-propagation case is mainly attributed to the group velocity dispersion (GVD) in the waveguide, and it is linearly proportional to local GVD value of $D$ and wavelength separation $\Delta\lambda$ and hence $d_+ \approx D\Delta\lambda$. In the counter-propagating case, the "walk-off" is mainly due to the opposing velocities and it is estimated to be $d_- \approx 2n_g/c$, where $n_g$ is the average group index and $c$ is the speed of light in vacuum.

Assuming that the intensity fluctuations have sinusoidal time dependence and the modulation indices can be separated, we can write the intensity of the pump and Stokes wave at any location along the silicon waveguide as:

$$I_s(z,t)=\bar{I}_s(z)[1+M(z,t)]=\bar{I}_s(z)[1+m(z)\exp(i\Omega t)] \quad (3) \qquad I_{p\pm}(z,t)=\bar{I}_{p\pm}(z)[1+N_\pm(z,t)]=\bar{I}_{p\pm}(z)[1+n_\pm(z)\exp(i\Omega t)] \quad (4)$$

where m(z) and $n_\pm(z)$ are the perturbing complex spatial modulation indices, and Ω is the angular frequency of the modulation. Substituting Eqs. (3) and (4) into Eqs. (1) and (2) we obtain the following differential equations for the complex spatial modulation indices:

$$\frac{dm}{dz}=i\Omega d_\pm m+(g_R-2\beta_{TPA})\bar{I}_p n_\pm-\beta_{TPA}\bar{I}_s m-\gamma_s^{FCA}(2\bar{I}_s^2 m+2\bar{I}_{p\pm}\bar{I}_s m+2\bar{I}_{p\pm}^2 n_\pm+2\bar{I}_{p\pm}\bar{I}_s n_\pm) \quad (5)$$

$$\frac{dn_\pm}{dz}=\mp\left(2\beta_{TPA}+\frac{\omega_p}{\omega_s}g_R\right)\bar{I}_s m\mp\beta_{TPA}\bar{I}_p n_\pm\mp\gamma_p^{FCA}(2\bar{I}_s^2 m+2\bar{I}_{p\pm}\bar{I}_s m+2\bar{I}_{p\pm}^2 n_\pm+2\bar{I}_{p\pm}\bar{I}_s n_\pm) \quad (6)$$

where $\gamma_{p,s}^{FCA}=\alpha_{p,s}^{FCA}/I^2=1.45\times10^{-17}(\lambda_{p,s}/1550)^2\tau\beta_{TPA}/(2h\nu_{p,s})$. If we assume quadratic modulation terms can be neglected due to small fluctuations, i.e. $|m|^2$, $|n_\pm|^2$, $|m \bullet n_\pm|$«1, and hence. The RIN transfer can be calculated for co-propagating and counter-propagating configurations as [8]:

$$T_+(L,\Omega)=\frac{|M(L,\Omega)|^2}{|N_+(0,\Omega)|^2} \quad (7) \qquad T_-(L,\Omega)=\frac{|M(L,\Omega)|^2}{|N_-(L,\Omega)|^2} \quad (8)$$

From Eqs.(5)-(6) , we can be numerically calculated RIN transfer functions for co-propagating and counter-propagating configurations, respectively.

### 3. Results and discussions

The calculations are performed with 1cm long waveguide parameters presented in reference [7] with the pump intensity varying from 10 to $10^3$ MW/cm$^2$. We assume 1 dB/cm linear loss, Raman gain coefficient $g_R$=15 cm/GW and TPA coefficient $\beta_{TPA}$=0.7 cm/GW. To include the effect of the "walk-off" and GVD, GVD is assumed to be $D$ = -910 ps/(nm•km) [9].

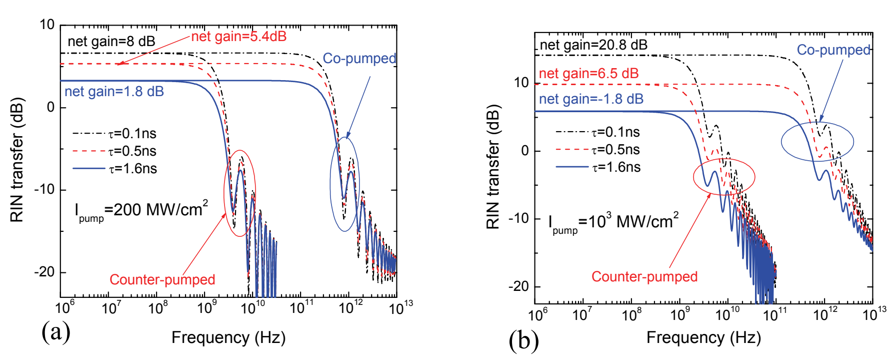
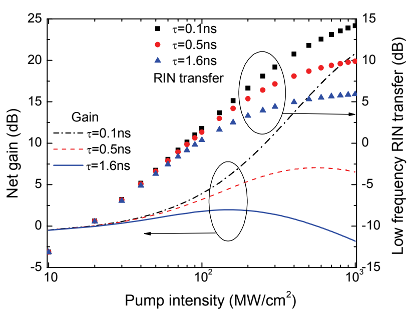



Fig.1. RIN transfer spectra for co-pumped and counter-pumped silicon Raman amplifiers pumped at (a) 200 MW/cm$^2$ and (b) $10^3$ MW/cm$^2$. Modal parameters: $L$=1 cm, $\alpha_s$=$\alpha_p$=1dB/cm, $g_R$=15 cm/GW, $\beta_{TPA}$=0.7 cm/GW, $D$=-910 ps/(nm•km), pump at 1418 nm, signal at 1550 nm, and $\tau$: free carrier lifetime.

Fig. 1(a) and (b) show the magnitude of the pump to signal RIN transfer for pump intensities of 200 MW/cm$^2$

and $10^3$ MW/cm$^2$ in a waveguide with free carrier lifetime values of 0.1, 0.5 and 1.6 ns. Since the RIN transfer depends on the Raman gain, the low frequency RIN transfer decreases noticeably with increasing free carrier lifetime, i.e with increasing FCA and decreasing net Raman gain. As expected, the high frequency RIN transfer decreases due to the averaging induced by the group velocity difference. However, the –3 dB cut-off frequency for GVD averaging in a co-pumped Raman amplifier is ~400 GHz. The same value decreases to ~1.5 GHz in a counter pumped Raman amplifier. These results are several orders of magnitude higher than those expected from fiber Raman amplifiers (<10MHz). The main reason is that there is not sufficient "walk-off" within a 1 cm long silicon waveguide to average the effect of the pump intensity noise. Therefore, the RIN transfer noise of silicon Raman amplifiers should be considered even at the high bit rate systems.

Fig. 2(a) illustrates the low frequency RIN transfer and net Raman gain for pump intensities varying from 10 to $10^3$ MW/cm$^2$. For free carrier lifetimes above 0.5 ns, net Raman gain enters into saturation and then decreases as pump intensities increased because of nonlinear losses induced by FCA. However, the RIN transfer is determined by the local gain. This means the pump noise is still transferred into the signal through the stimulated Raman scattering process with or without a net amplification at the end. In the above calculations, we assume that the Stokes intensity $I_s$ is much smaller than the pump intensity $I_p$. Fig.2 (b) shows the low frequency RIN transfer and net Raman gain at pump intensity of $10^3$ MW/cm$^2$ due to pump depletion.



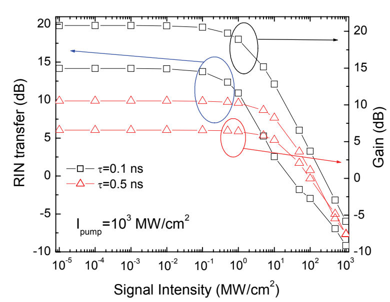




Fig.2 Low frequency RIN transfer and net Raman gain versus (a) pump intensity and (b) signal intensity

## 4. Conclusion

We show that due to the short waveguide length and small "walk off", pump fluctuation averaging occurs inefficiently in silicon Raman amplifiers and RIN frequency components as high as 1.5 GHz are transferred to the signal. This occurs in counter propagating pump-signal configuration which provides the lowest possible cut-off frequency. For co-propagating case, all RIN components of the pump at frequencies of practical interest are transferred to the signal.

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