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Research Article

Maximization of Gain in Slow-Light Silicon Raman Amplifiers

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We theoretically study the problem of Raman gain maximization in uniform silicon photonic-crystal waveguides supporting slow optical modes. For the first time, an exact solution to this problem is obtained within the framework of the undepleted-pump approximation. Specifically, we derive analytical expressions for the maximum signal gain, optimal input pump power, and optimal length of a silicon Raman amplifier and demonstrate that the ultimate gain is achieved when the pump beam propagates at its maximum speed. If the signal's group velocity can be reduced by a factor of 10 compared to its value in a bulk silicon, it may result in ultrahigh gains exceeding 100 dB. We also optimize the device parameters of a silicon Raman amplifier in the regime of strong pump depletion and come up with general design guidelines that can be used in practice.

1. Introduction

The rapid progress in the field of silicon photonics realized during recent years draws the reality of all-optical signal processing on a nanoscale closer than ever [1–3]. Of paramount importance for the integration of optical functionalities on a silicon platform is the problem of efficient signal amplification through stimulated Raman scattering (SRS) [4–9]. Even though the Raman gain coefficient is relatively large for the silicon material, its use for signal amplification is hampered considerably by its large two-photon absorption (TPA) coefficient ($\sim 0.5 \text{ GW/cm}^2$) in the wavelength region near 1550 nm [10] and the effects of free-carrier absorption (FCA) that come into play once free carriers are generated via TPA.

Several techniques have been successfully employed to mitigate the nonlinear losses and increase the Raman gain in silicon-on-insulator (SOI) waveguides. The most straightforward method lies in the reduction of free-carrier lifetime. It is typically implemented through a reverse-bias p-i-n diode, which uses silicon waveguide as an intrinsic region and removes carriers from the region near its mode center through the applied static electric field [11–13]. This approach has been used to make silicon Raman amplifiers (SRAs) operating continuously. In the pulsed regime, in ad-

dition to gain enhancement, this technique allows operation of an SRA at a bit rate as high as 100 Gbit/s. Once free carriers are efficiently removed and they stop affecting optical propagation, TPA becomes the only nonlinear effect that limits performance of an SRA [14].

Signal gain can also be improved by successively optimizing both the length of the SOI waveguide and the input pump intensity [15, 16]. Existence of the unique length that provides the maximum gain for given material parameters is evident from the following consideration. If the waveguide is too short, signal does not have enough time to build up its energy through interaction with the pump. In a very long waveguide, on the other hand, the gain approaches zero, as the signal is constantly exposed to TPA and linear losses that decay with optical intensity slower than the SRS does. This means that the silicon waveguide should end at the point where the gain peaks. Inside an SRA of optimal length, the signal gain can still have a local minimum, in the event that FCA-induced energy dissipation predominates signal amplification near the input facet of the waveguide. If that is the case, one can increase the gain by reducing the intensity of the input pump beam. The existence of an optimal pump intensity for a fixed length of SRA can also be understood with a similar argument.

Another way of enhancing the amplified signal lies in engineering (tapering) the lateral cross-section of a SRA [17–22]. The objective of tapering is to provide an optimal balance between the nonlinear losses and SRS, which is possible because they scale differently with the effective mode area. By developing a semianalytical method for calculating the optimal tapering profile of an SRA, we have shown that linear tapering of the amplifier is capable of increasing gain almost up to its ultimate limit that is reached with an irregular optimal tapering [17].

A somewhat more challenging, but quite efficient, gain-improvement technique relies on the slow-light enhancement of nonlinear optical phenomena in silicon photonic crystal (SPhC) waveguides [23–29]. A reduction in the group velocities of the pump and signal beams inside a SPhC waveguide leads to an increase in beams intensities and allows them to stay longer inside the amplifier, thereby improving the efficiency of the SRS process. This speed reduction, unfortunately, also results in the enhancement of TPA and FCA, making the problem of gain maximization in slow-light SRAs more intricate compared to that in ordinary SRAs. The only attempt to analyze gain scaling with group velocity and find the optimal parameters for a SPhC-based SRA belongs to Krause et al. [30]. In this paper, we extend this study and present an exact solution to the problem of gain maximization in slow-light SRAs within the undepleted-pump approximation. We also perform a numerical optimization of various SRA parameters in the regime of strong pump depletion, in order to come up with the design guidelines that can be applied in practice.

2. Formulation of the Problem

Consider amplification of a continuous wave (CW) signal at the frequency ω_s by a CW pump at the frequency ω_p inside a SPhC waveguide, which is characterized by the slow-down factors S_s and S_p at frequencies ω_s and ω_p , respectively. If the pump copropagates with the signal, then their “slowed-down” intensities $Q_{p(s)}(z) = S_{p(s)}I_{p(s)}(z)$, where $I_{p(s)}(z)$ are the ordinary intensities, satisfy the following system of coupled differential equations [23, 30]:

$$\begin{aligned} \frac{1}{S_p Q_p} \frac{dQ_p}{dz} &= -\alpha_p - \beta_p Q_p - \gamma_p Q_s \\ &\quad - \xi_p [Q_p^2 + 4Q_p Q_s + (\omega_p/\omega_s) Q_s^2], \\ \frac{1}{S_s Q_s} \frac{dQ_s}{dz} &= -\alpha_s - \beta_s Q_s + \gamma_s Q_p \\ &\quad - \xi_s [Q_p^2 + 4Q_p Q_s + (\omega_p/\omega_s) Q_s^2]. \end{aligned} \quad (1)$$

In these equations, the terms characterized by the coefficients $\alpha_{p(s)}$, $\beta_{p(s)}$, and $\xi_{p(s)}$ account for linear losses, TPA, and FCA of the pump and signal beams, respectively. The FCA coefficients are defined as

$$\xi_{p(s)} = \frac{\sigma_0 (\omega_0/\omega_{p(s)})^2 \tau_c \beta_p}{2\hbar \omega_p}, \quad (2)$$

where $\sigma_0 = 1.45 \times 10^{-21} \text{ m}^2$, $\omega_0 = 2\pi c/(1.55 \mu\text{m})$, τ_c is the effective free-carrier lifetime, and \hbar is the reduced Planck's constant. The nonlinear parameters, γ_p and γ_s , have been defined such that they describe both the cross-TPA and SRS effects. Assuming that the pump frequency exceeds the signal frequency exactly by the Raman shift $\omega_p - \omega_s = \Omega_R \approx (2\pi)15.6 \text{ THz}$, we have

$$\gamma_p = g_R + 2\beta_p, \quad \gamma_s = \frac{(g_R - 2\beta_s)}{\eta}, \quad (3)$$

where g_R is the Raman gain coefficient and $\eta = \omega_p/\omega_s$.

Equations (1) are similar in form to the coupled-intensity equations obtained without the slow-light effects [31–33], but they contain two additional parameters S_p and S_s . Strictly speaking, these parameters are related to each other, since they both depend on geometric and material characteristics of the same photonic crystal. However, owing to a great number of such characteristics and the possibility of varying most of them in different ways within wide limits, we may think of the slow-down factors for pump and signal modes as independent of each other. These factors can be adjusted to take different value (from 1 to as large as 1000) by engineering the dispersion of the SPhC waveguide [29, 34]. We also assume that the input pump intensity I_{p0} may take any value between zero and infinity because it can be varied by changing either the pump power or the SRA cross-section.

Hence, the problem of gain maximization in a slow-light SRA, for a given intensity of the input signal, consists of searching for the optimal values of the waveguide length L , input pump intensity I_{p0} , and slow-down factors S_s and S_p . If some of these parameters are fixed by practical needs or restricted by fabrication capability, the optimization problem becomes simpler because it involves fewer than four parameters.

3. Exact Solution: Undepleted-Pump Approximation

The signal gain can be readily optimized analytically in the undepleted-pump regime, which usually holds for relatively short SRAs with $g_R \lesssim 10 \text{ GW/cm}^2$ and for low input signal powers. We now consider this scenario in detail, for it is quite instructive and helps us to illuminate the peculiarities of the optimization problem in the general case.

In the approximation of an undepleted pump, valid as long as $Q_p \gg Q_s$ everywhere inside the SPhC waveguide, (1) reduces to

$$\frac{1}{S_p Q_p} \frac{dQ_p}{dz} \approx -\alpha_p - \beta_p Q_p - \xi_p Q_p^2, \quad (4a)$$

$$\frac{1}{S_s Q_s} \frac{dQ_s}{dz} \approx -\alpha_s + \gamma_s Q_p - \xi_s Q_p^2. \quad (4b)$$

Equation (4b) shows that the signal gain grows with increasing S_s , confirming that one can improve the performance of an SRA by slowing down the signal mode as much as possible [30]. The situation is less clear with the optimal

slow-down factor for the pump. Indeed, when the input pump intensity is fixed, an increase in the time the pump spends inside the amplifier may result in either increase or decrease in the value of Q_p , which, in turn, may enhance or reduce the local signal gain. Therefore, the three parameters to be optimized in the undepleted-pump regime are the amplifier length, the input pump intensity, and the slow-down factor for the pump field.

To find the values of the three optimal parameters, we use the implicit solution of (4a) and (4b). It can be written compactly with the shortened notations $Q_0 \equiv Q_p(0)$ and $Q_L \equiv Q_p(L)$ in the form of the following coupled equations [35]:

$$\frac{\alpha_p + \beta_p Q_L + \xi_p Q_L^2}{\alpha_p + \beta_p Q_0 + \xi_p Q_0^2} = \frac{Q_L^2}{Q_0^2} \exp(2\alpha_p S_p L + \beta_p Q_0 L_{\text{eff}}), \quad (5a)$$

$$L_{\text{eff}} = \frac{\mu}{\beta_p Q_0} \ln\left(\frac{\mu F_L + 1}{\mu F_L - 1} \frac{\mu F_0 - 1}{\mu F_0 + 1}\right), \quad (5b)$$

where $\mu = (1 - 4\alpha_p \xi_p / \beta_p^2)^{-1/2}$, $F_j = 1 + 2\xi_p Q_j / \beta_p$, and L_{eff} is the effective length of the amplifier.

Using (4b), (5a), and (5b), it is easy to show that the signal gain G_s is given by the relation

$$\left(\frac{S_p}{S_s}\right) \ln G_s = -(\alpha_s - \eta^2 \alpha_p) S_p L + (\gamma_s + \eta^2 \beta_p) Q_0 L_{\text{eff}} - \eta^2 \ln\left(\frac{Q_0}{Q_L}\right). \quad (6)$$

We maximize G_s with respect to the three optimization parameters, L , I_{p0} , and S_p , by requiring that the following three derivatives vanish:

$$\frac{\partial G_s(L, I_{p0}, S_p)}{\partial L} = 0, \quad (7a)$$

$$\frac{\partial G_s(L, I_{p0}, S_p)}{\partial I_{p0}} = 0, \quad (7b)$$

$$\frac{\partial G_s(L, I_{p0}, S_p)}{\partial S_p} = 0. \quad (7c)$$

Upon employing (4b)–(6), these requirements lead to the following three relations:

$$\alpha_s - \gamma_s Q_L + \xi_s Q_L^2 = 0, \quad (8a)$$

$$Q_0 + Q_L = \frac{\gamma_s}{\xi_s}, \quad (8b)$$

$$\frac{S_p}{S_s} \ln G_s = \frac{\gamma_s - \xi_s(Q_0 + Q_L)}{\alpha_p + \beta_p Q_0 + \xi_p Q_0^2} (Q_0 - Q_L) - (\alpha_s - \gamma_s Q_L + \xi_s Q_L^2) S_p L. \quad (8c)$$

The combination of (8a)–(8c) leads to the equality $\ln G_s = 0$, which is in conflict with (6). This implies that not more than two of the parameters L , I_{p0} , and S_p can be

optimized at the same time. Next, substitution of (8b) into (8c) results in

$$\ln G_s = -(\alpha_s - \gamma_s Q_L + \xi_s Q_L^2) S_p L. \quad (9)$$

This equation is not satisfied in real SRAs since, according to (4b), it requires pump power to be constant along the amplifier. Consequently, the gain provided by an SRA of a given length peaks simultaneously with either the slow-down factor S_p or the input pump intensity. The optimal parameters of an SRA depend on the optimization scenario. In what follows, we consider the three possible optimization schemes.

3.1. Optimal L and I_{p0} for a Fixed S_p . When the slow-down factor of the pump is fixed, (8a) and (8b) yield the critical values for the quantities Q_0 and Q_L of the form

$$Q_0 = \frac{\gamma_s + \sqrt{\gamma_s^2 - 4\alpha_s \xi_s}}{2\xi_s}, \quad Q_L = \frac{\gamma_s - \sqrt{\gamma_s^2 - 4\alpha_s \xi_s}}{2\xi_s}. \quad (10)$$

It is evident from these expressions that the inequality $\gamma_s^2 > 4\alpha_s \xi_s$ must be satisfied to allow for amplification of signal. This inequality sets the upper limit for the product $\alpha_s \tau_c$ [30]. For $\gamma_s^2 > 4\alpha_s \xi_s$, one can see from (4b) that the derivative dQ_s/dz remains positive as long as $Q_0 > Q_p > Q_L$. The expressions in (10) simply determine the pump intensities corresponding to the onset and the end of local net gain and thus enable signal amplification along the whole length of a SPhC waveguide.

With the initial and final intensities given by (10), the optimal length of the SRA can be explicitly found from (5a) while the optimal input intensity of the pump is simply given by $I_{p0} = Q_0/S_p$.

It is important to note that the optimal values of Q_0 and Q_L do not depend on the parameter S_p . Assuming that the signal exhibits a net gain, we conclude from (6) that the maximum signal gain corresponds to the lowest possible value of S_p , that is, to $S_p = 1$. According to (4a), this value results in the slowest attenuation of the pump along the amplifier.

Hence, the optimal values of three parameters that maximize the signal gain for this optimization scheme are given by

$$I_{p0} = Q_0, \quad S_p = 1, \quad (11a)$$

$$L = \frac{1}{2\alpha_p} \left[\ln\left(\frac{Q_0^2}{Q_L^2} \frac{\alpha_p + \beta_p Q_L + \xi_p Q_L^2}{\alpha_p + \beta_p Q_0 + \xi_p Q_0^2}\right) - \beta_p Q_0 L_{\text{eff}} \right], \quad (11b)$$

where Q_0 and Q_L are given by (10).

3.2. Optimal L and S_p for a Fixed I_{p0} . If we keep the input pump power constant, then (8a) yields the optimal value for Q_L given in (10), where the minus before the radical is chosen to provide the maximal signal gain. With this value, the critical value of $Q_0 > Q_L$ is found by simultaneously solving (5a), (5b), (6), and (8c). It should be noted that Q_0

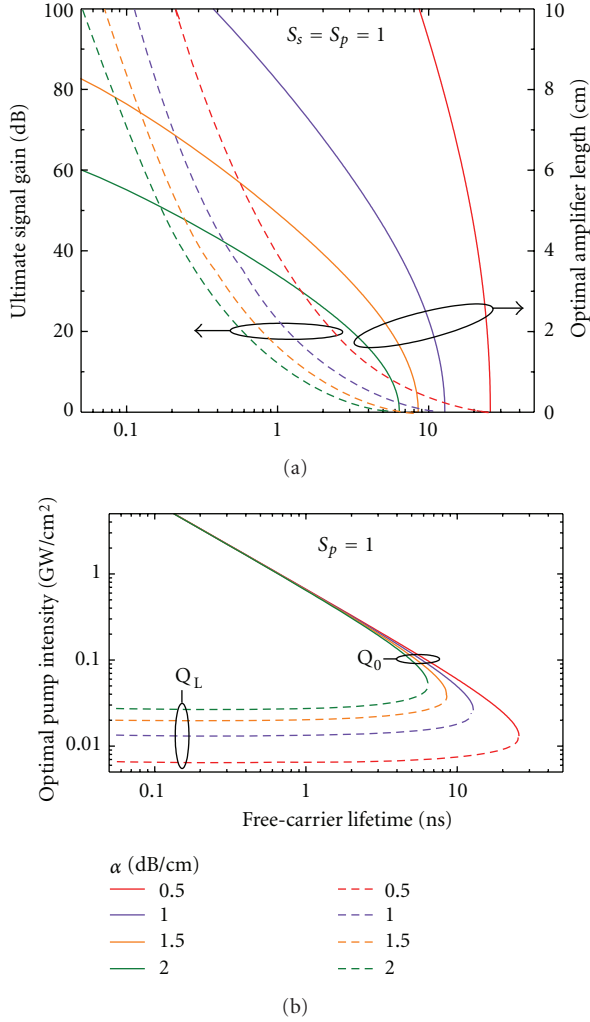


FIGURE 1: (a) Ultimate signal gain (dashed curves) and optimal amplifier length (solid curves) plotted as functions of τ_c for an SRA operating in the undepleted-pump regime when $S_s = S_p = 1$; different colors correspond to different values of $\alpha_s = \alpha_p \equiv \alpha$. (b) Input and output pump intensities calculated as a function of τ_c using (10) with $S_p = 1$. Refer to text for other parameters.

obtained in this way does not generally coincide with that in (10).

Once the optimal quantities Q_0 and Q_L are known, the optimal slow-down factor S_p is given by $S_p = Q_0/I_{p0}$ and the optimal length of the SRA is calculated from (5a).

On substitution of (8a) into (8c), the signal gain may be written as

$$\ln G_s = \frac{\gamma_s - \xi_s(Q_0 + Q_L)}{\alpha_p + \beta_p Q_0 + \xi_p Q_0^2} \left(\frac{Q_0}{Q_L} - 1 \right) S_s I_{p0}. \quad (12)$$

This expression shows that the peak net gain grows in proportion to the input pump power. Since the maximum pump power is equal to Q_0 when $S_p = 1$, we again arrive at the set of optimal parameters given in (11a) and (11b).

3.3. Optimal I_{p0} and S_p for a Fixed L . Consider finally the situation in which the length of an SRA is preset. As we

have seen above, in this case (8b) and (8c) are inconsistent. Therefore, one may either find the optimal input pump power, $I_{p0}(S_p, L)$, for given values of S_p and L by solving (5a), (5b), and (8b) or the optimal slow-down factor of the pump, $S_p(I_{p0}, L)$, for given values of I_{p0} and L by solving (5a), (5b), and (8c). Of course, if after that we also optimize the length of the amplifier, we arrive at the results obtained for the previous two optimization schemes.

Since the values of Q_0 obtained with different optimization schemes are different, the optimal amplifier length and input pump power in (11a) and (11b) are also different. From physical considerations it is, however, clear that the optimal values of Q_0 and Q_L providing the ultimate signal gain are those given in (10).

In Figure 1, we plot the maximum signal gain as a function of free-carrier lifetime that can be achieved in the undepleted-pump regime with a “fast” signal mode ($S_s = 1$). The same figure shows the optimal SRA length and the optimal pump intensity required for the maximum gain. The material parameters are chosen to be $\lambda_s = 1.55 \mu\text{m}$, $\lambda_p = 1.434 \mu\text{m}$, $\alpha_s = \alpha_p = 0.5\text{--}2 \text{ dB}/\text{cm}$, $\beta_s = \beta_p = 0.5 \text{ GW}/\text{cm}^2$, and $g_R = 20 \text{ GW}/\text{cm}^2$. It is seen that the signal gains of $>20 \text{ dB}$ can be realized with pump powers below $1 \text{ GW}/\text{cm}^2$ if $\tau_c \lesssim 1 \text{ ns}$ and linear losses do not exceed $1 \text{ dB}/\text{cm}$. These gains can be increased further by a factor of S_s , which can be more than an order of magnitude, provided the signal beam is sufficiently slowed down by dispersion engineering. Unfortunately, such strong amplification requires relatively long SPhC waveguides (longer than 8 cm in the above example).

Equations (6) and (11b) show that the length of a SRA can be reduced to a few micrometers without noticeably affecting the gain, by simultaneously increasing linear losses and reducing free-carrier absorption in such a manner that the product $\alpha_s \tau_c$ remains constant (so that the values of Q_0 and Q_L do not change). For instance, gains in excess of 20 dB (for $S_s = 1$) can be achieved in a 1.5 mm long SRA with $\tau_c = 0.02 \text{ ns}$ and $\alpha_s = 50 \text{ dB}/\text{cm}$. The optimum length of a SRA also becomes shorter when the amplifier operates in the regime of considerable pump depletion, which we analyze in the next section.

4. Numerical Solution: General Case

As we saw in the previous section, in the undepleted-pump regime, the signal mode should be slowed down as much as possible, while the pump mode should travel with the highest speed. This is not the case when the intensity of input signal, I_{s0} , approaches the ratio $Q_L/(S_s G_s)$ and the pump’s depletion can no longer be ignored [36]. The examples below illustrate the peculiarities of SRA optimization in the regime of heavy pump depletion, in which signal gain is calculated numerically from (1).

Figure 2 shows the contour plots of the net signal gain in an 8 mm long SRA for $I_{p0} = 30 \text{ MW}/\text{cm}^2$ and $I_{s0} = 0.1 \text{ MW}/\text{cm}^2$; the depletion [37] of the pump beam at the amplifier output equals 76% . It is seen that the maximum gain of approximately 17.7 dB is achieved for the slow-down factors $S_s \approx 7.8$ and $S_p \approx 3.4$. More importantly, this gain

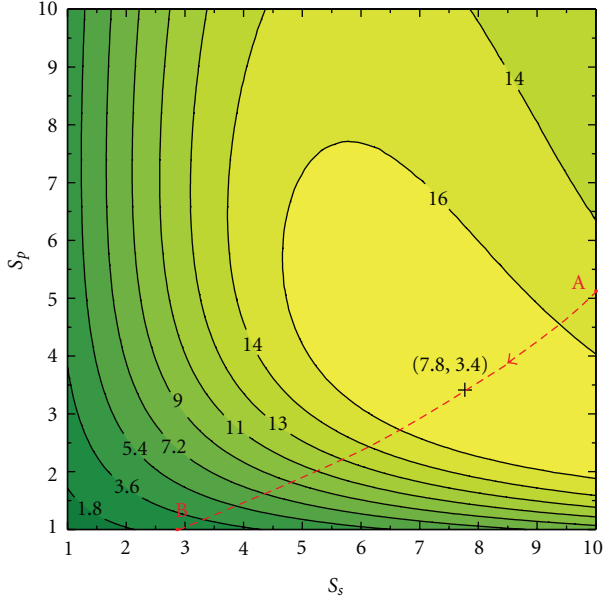


FIGURE 2: Contour plots of signal gain (in dB) for an 8 mm long SRA in the plane formed by the factors S_s and S_p varying in the range 1 to 10. The location marked by + corresponds to the peak gain of 17.7 dB. Here, $I_{p0} = 30 \text{ MW/cm}^2$, $I_{s0} = 0.1 \text{ MW/cm}^2$, $\alpha = 1 \text{ dB/cm}$, and $\tau_c = 0.2 \text{ ns}$. Other parameters are the same as in Figure 1. The red curve shows how the gain peak's position drifts as I_{p0} changes from 15 MW/cm^2 at point A (10, 5.13) to 300 MW/cm^2 at point B (2.9, 1).

value exceeds the maximum gain of 0.85 dB that occurs in the absence of the slow-light effects ($S_s = S_p = 1$) by more than a factor of 20. It should also be noted that, owing to a relatively flat gain peak, the range of tolerable slow-down parameters is rather broad, a feature that facilitates the design of SRAs.

The gain corresponding to the optimal slow-down factors can be increased by optimizing the input pump power. Red curves in Figures 2 and 3 show how the peak gain and the optimal factors S_s and S_p vary with I_{p0} for the same SRA of 8 mm length. One can see that the maximum peak gain of 31.7 dB is reached for $I_{p0} \approx 3.5 \text{ GW/cm}^2$, $S_s \approx 1.6$, and $S_p = 1$. Although the obtained values of I_{p0} and S_p coincide with those in the undepleted-pump regime, the maximum gain and the optimal amplifier length differ from the predictions in Figure 1 (114 dB and 11 cm, resp.). This is a consequence of strong pump depletion (about 84% in the present case).

A further enhancement of gain is generally possible by adjusting the length of the SPhC waveguide. Figure 3 shows this possibility by varying the amplifier length in the range of 2 to 12 mm. However, as the gain profiles corresponding to 2, 4, and 12 mm long SRAs suggest, $L \approx 8 \text{ mm}$ is the optimal length of the amplifier for this specific set of material parameters. For a typical effective mode area of $0.35 \mu\text{m}^2$, pump power of 10 W is required at the input of the optimized SRA. Since it is very difficult to get such high input power levels in a CW regime, the actual maximum gain will be lower than 31.7 dB and will be set by the available pump power.

Comparison of different curves in Figure 3 leads to several conclusions that are important for designing SRAs with optimum performance. First, the optimum slow-down

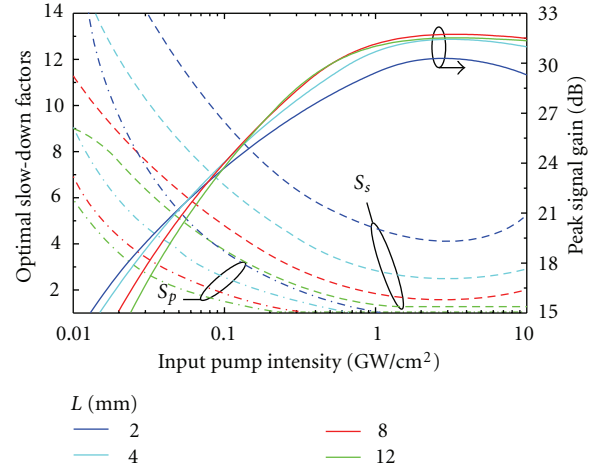


FIGURE 3: Optimal peak signal gain (solid curves) and slow-down factors, S_s (dashed curves) and S_p (dash-dotted curves), as functions of input pump intensity in a 2, 4, 8, and 12 mm long SRAs. Other parameters are the same as in Figure 2.

factors for pump and signal can be reduced by increasing amplifier's length, because SRS is more efficient in longer waveguides. Second, as long as the ultimate signal gain is not achieved, larger pump intensities can compensate for operating with faster pump and signal modes. This is possible, since the reduction in time that light spends inside the amplifier is canceled by its stronger interaction with silicon. Third, strong FCA occurring at high intensities reduces pump depletion and, as a result, requires the use of a slowed signal mode (see the blue dashed curve). This regime is to be avoided in practice because the same peak gain can be achieved with a smaller pump intensity.

As a concluding remark, it is worth noting that our results are valid not only for SPhC waveguides, but also for any other types of slow-light silicon waveguides, regardless of the relative group delay that occurs upon light propagation through them.

5. Conclusions

We have theoretically analyzed the problem of gain maximization in silicon Raman amplifiers operating with slow-light pump and signal modes. Using the undepleted-pump approximation, we derived expressions for the maximum signal gain, optimal input pump power, and optimal length of the amplifier with a fixed cross-section. We also showed that the signal gain is maximized when the pump beam moves at its maximum speed. The signal gain grows indefinitely and can exceed 100 dB, provided the signal beam travels more than 10 times slower than its speed in a bulk silicon. In the regime of substantial pump depletion, the parameters of an amplifier were optimized numerically and a relatively large CW gain of 31.7 dB was predicted for an 8 mm long waveguide pumped at an intensity of 3.5 GW/cm^2 . This result suggests that optimization of slow-light silicon photonic crystal waveguides is a promising approach to the

realization of highly efficient Raman amplifiers built using the SOI platform.

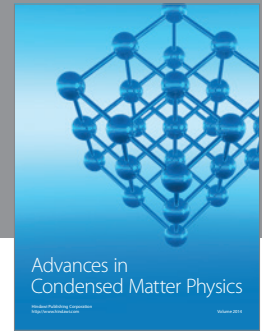
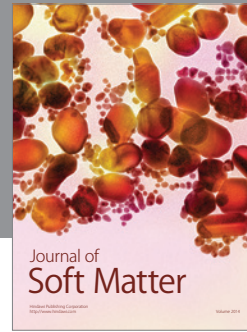
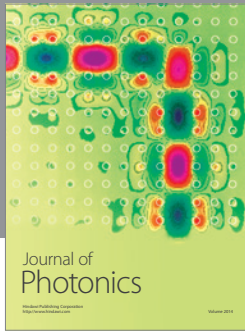
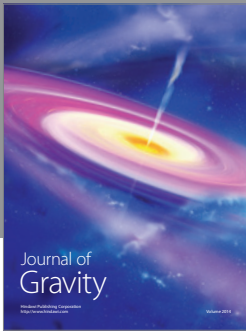
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