

Optimization of Raman Lasing in Silicon-on-Insulator Optical Waveguides

Hassan Kaatuzian and Mohammadreza Khorasaninejad

Photonics Research Laboratory, Electrical Engineering Department, Amirkabir University of Technology
424 Hafez Avenue, Tehran-15914, Iran

Phone: +98-21-66466009, E-mail: hsnkato@aut.ac.ir and reza_khorasani@aut.ac.ir

1. Introduction

Over the past several decades, there has been a continuous effort to realize optical lasing in silicon but we have not witness a reliable approach to fulfill this desire. This unsuccessful quest emanates from the fact that silicon has a long radiative recombination lifetime but a relatively short nonradiative lifetime, so the efficiency of light emission in silicon is very small, about 10^{-6} [1]. Recently, Stimulated Raman Scattering (SRS) provides a solution to obviate this challenging barrier [1]. Although, it becomes applicable to achieve optical lasing in Silicon-on-Insulator (SOI) waveguide by SRS, the presence of nonlinear losses comprising Two-Photon Absorption (TPA) and Free-Carrier Absorption (FCA) introduces large excess loss that limits efficiency of lasing.

2. Influence of Stokes and Pump Reflectivities

In a silicon Raman laser the lasing threshold is reached when the optical Raman gain of the laser medium is exactly balanced by the sum of all the losses experienced by pump power in the laser cavity including TPA, FCA and intrinsic cavity loss. Optical power dissipation of TPA can be ignored but FCA generated mainly by TPA allocates the major part of total loss to itself [1]. The excess loss from TPA-generated free carriers in the silicon waveguide may be estimated by quantifying the number of carriers generated from the incident pump power and effective recombination lifetime of them, τ_{eff} . Especially, in Continuous Wave (CW) silicon Raman lasers, FCA not only decreases efficiency of lasers but also increases the threshold pump power of them. Due to the high pump powers required for lasing operation in CW pumped silicon Raman lasers, their performance are restricted remarkably, in particular for low power applications.

In order to construct a silicon laser cavity, dielectric reflection mirrors are deposited directly onto either facet of it. Therefore, the left facet exhibits a reflectivity of $R_{s,l}$ for Stokes waves and $R_{p,l}$ for pump powers; similarly, the right facet has a reflectivity of $R_{s,r}$ for Stokes waves and $R_{p,r}$ for pump powers. At the beginning, we study a silicon laser with reflectivities of $R_{p,l} = R_{p,r} = R_{s,r} = 30\%$ and $R_{s,l} = 100\%$, the same as [2] (we refer this laser as conventional laser later on). We focus on a conventional laser as a starting point due to compare our simulation results with it. In our simulations, we assume parameters as reported in [2]. Fig. 1 illustrates output powers as a function of waveguide length. The conventional laser has a maximum output power of $P_{out} = 4.3\text{ mW}$ at $L = 45.6\text{ mm}$

(see the curve marked with squares) which has been already obtained in [2]. This figure also shows the corresponding curves for the case which Stokes and pump reflectivities of right facet are changed properly. As a consequence, the laser with $R_{s,r} = 35\%$ and $R_{p,r} = 40\%$ has the output power of 11.6 mW at $L = 45.6\text{ mm}$ (see the curve marked with crosses). Similarly, the output power of the laser increases to 16.6 mW by choosing $R_{s,r} = 40\%$ and $R_{p,r} = 60\%$ for the same waveguide length (see the curve marked with triangles), meaning a considerable throughput improvement is provided by assigning suitable values for $R_{s,r}$ and $R_{p,r}$.

Besides, it can be seen from the curve marked with squares that allowable lengths of laser are limited to a range of 35 to 60 mm. In contrast, for curves marked with crosses and triangles lasing is possible for laser lengths between 28 and 70 mm and between 26 to 78 mm, respectively. In other words, the laser length can be chosen more freely in compare with the conventional laser, which presents another beneficial effect of our approach.

Due to determine optimal values of these reflectivities we simulate the Raman laser whereas $R_{s,r}$ and $R_{p,r}$ vary from 0% to 100% at input power of $P_{in} = 4\text{ W}$. Result of this simulation is plotted in Fig. 2 indicating that optimum reflectivities for Stokes and pump are $R_{s,r} = 55\%$ and $R_{p,r} = 100\%$, respectively. By using optimal reflectivities the output power of the Raman laser increases to 21.2 mW which is five times greater than 4.3 mW .

3. Bidirectional Pumping

We know that the FCA loss term is proportional to the square of pump power [1]. Therefore, due to adjust its negative effect we bisect the input power and pump the laser from both ends instead of only one end. By this trick, the peak power of pump inside the laser cavity decreases, which leads to reduce density of generated free carriers, the most important obstacle to acquire high lasing efficiency. Like single-side pumped laser, we simulate this Raman laser again at input power of $P_{in} = 4\text{ W}$ to specify its optimum reflectivities. As seen in Fig. 3, optimum reflectivities of the right facet of the waveguide for Stokes and pump are 50% and 0%, respectively. In this study, we assume a reasonable and feasible range of reflectivity between 30% and 100%. Thus, by imposing this limitation we choose $R_{p,r} = 30\%$ instead of 0%. By exploiting bidirectional pumping method and optimal reflectivities concurrently the output power increases to 31.1 mW meaning an output power improvement by a factor of more than seven.

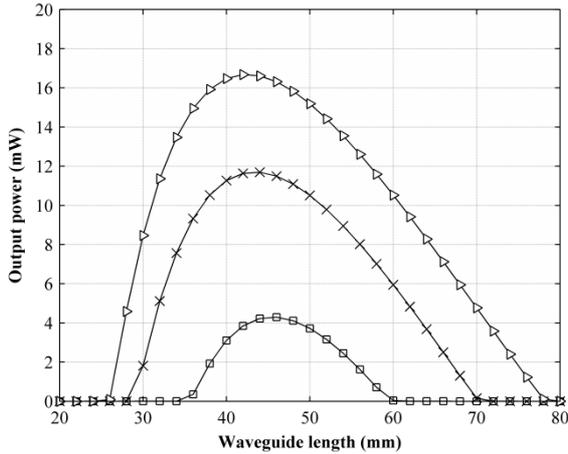


Fig. 1 Output powers of the laser versus waveguide length L for $R_{s,r}=R_{p,r}=30\%$ (marked with squares), $R_{s,r}=35\%$ & $R_{p,r}=40\%$ (marked with crosses) and $R_{s,r}=40\%$ & $R_{p,r}=60\%$ (marked with triangles).

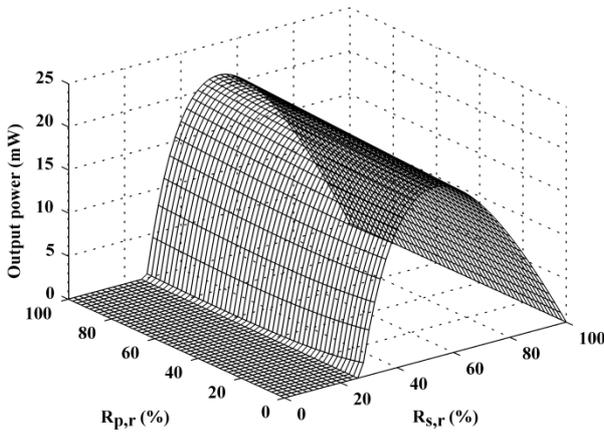


Fig. 2 Single-side pumped Raman laser output power versus $R_{s,r}$ and $R_{p,r}$ at $L=45.6$ mm.

4. Input-Output Characteristics

Now, we look at input-output characteristics of lasers discussed in previous sections. As shown in Fig. 4, the conventional laser has a lasing threshold of $P_{th} = 2.8$ W (see the curve marked with squares). Above threshold, the output power enhances approximately linearly with increase of input power. However, further increase of input power intensifies damaging effect of FCA which not only leads to saturation and reduction of the output power but also ceases lasing operation when the input power becomes larger than a shutdown threshold. Next, we simulate this laser while its reflectivities are optimal reflectivities obtained from Fig. 2. The input-output characteristic of this laser is also plotted in Fig. 4 (see the curve marked with circles). Using optimal reflectivities causes a significant improvement of output power at all input power levels larger than threshold. In addition, the lasing threshold reduces to 1.75 W which is 37% lower than that for the conventional laser and also the shutdown threshold ascends considerably. In an effort toward additional improvement of laser output power we suggested pumping the Raman laser bidirectionally and then we found optimal reflectivi-

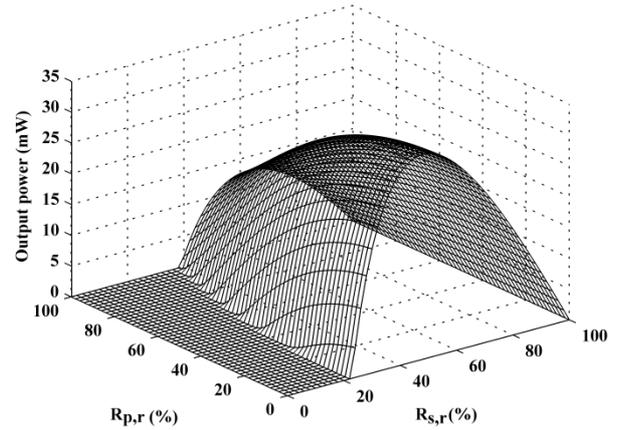


Fig. 3 Bidirectionally pumped Raman laser output power versus $R_{s,r}$ and $R_{p,r}$ at $L=45.6$ mm.

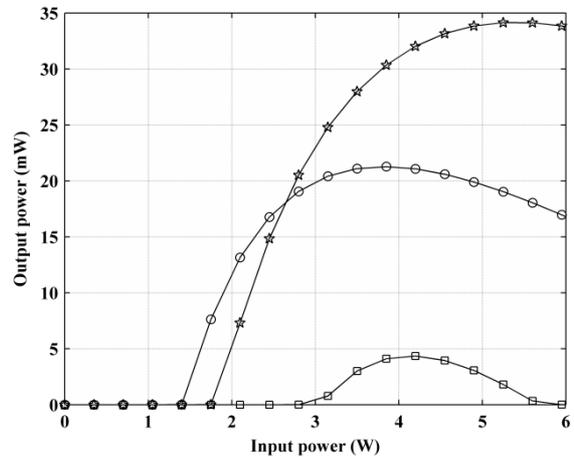


Fig. 4 Input-output characteristics of the laser for $R_{s,r}=R_{p,r}=30\%$ (marked with squares), $R_{s,r}=55\%$ & $R_{p,r}=100\%$, optimal reflectivities, (marked with circles), and $R_{s,r}=50\%$ & $R_{p,r}=30\%$, bidirectional pumping and optimal reflectivities, (marked with asterisks).

ties for this laser in previous section. Fig. 4 shows output power of this laser as a function of input power (see the curve marked with asterisks). The laser exhibits threshold reduction and its output power improves especially at high input powers in compare with two later described lasers.

5. Conclusions

We showed that reflectivity coefficients play an important role to improve the Raman laser efficiency. Thus, due to circumvent the detrimental effect of FCA and enhance performance of the laser, we suggested pumping the laser from both ends instead of only one. Finally, by combining these two approaches we improved the efficiency of laser by a factor of more than seven.

References

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- [2] M. Krause, H. Renner and E. Brinkmeyer, Spectroscopy **21**(1), 26-32, 2006.