Efficiency of silicon Raman lasers in sub-micron strip waveguides: unidirectional ring lasing versus Fabry-Perot cavities

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Due to its spectral flexibility, Raman lasing in silicon waveguides is an attractive means for the generation of wavelengths that are otherwise difficult to achieve, such as the mid-IR wavelength region [1]. Several CW silicon Raman lasers (SRLs) have already been demonstrated [1, 2, 3, 4], where thresholds as low as 20 mW and power-conversion efficiencies of 16% at pump powers of 300 mW could be achieved [4]. All of these SRLs have been based on comparatively large rib waveguides. By using much smaller strip waveguides, it is expected that the overall power levels can be scaled down even further due to their smaller effective mode areas [2].

However, another consequence of the scaling-down of waveguide dimensions is that the Raman gain becomes significantly direction-dependent. We have previously shown that a Stokes wave propagating in a direction opposite to the pump wave can experience a local gain that is up to 50% larger than the gain experienced by a co-propagating Stokes wave [5]. In a ring-resonator (RR) SRL based on small strip waveguides, this non-reciprocity could be strong enough to force the laser to operate unidirectionally, i. e., the laser light would circulate predominantly in the direction opposite to its pump. This is in contrast to RR-SRLs based on the larger rib waveguides, where lasing has been reported to be bidirectional [3]. Unidirectional lasing has the advantage that the entire output power exits the laser at only one port. Furthermore, as we show here, it makes RR-SRLs significantly more efficient than Fabry-Perot (FP) SRLs, since in the latter designs the laser light always (at least during one half of the round-trip) experiences the less efficient co-directional amplification.

In order to optimize various non-cascaded and cascaded RR- and FP-SRLs, we use a model similar to [6], taking into account linear waveguide losses α, two-photon absorption, free-carrier absorption (characterized by a free-carrier lifetime τ_{eff}) and Raman scattering among the pump and various lasing wavelengths. We use the fundamental TE mode of a silica-clad silicon strip waveguide ($W = 500\,\text{nm}$, $H = 220\,\text{nm}$) with a strong Raman non-reciprocity [5], and we assume resonant coupling of the pump laser at $\lambda_p = 1455\,\text{nm}$ into the SRL, thereby allowing for resonant pump-power enhancement [1, 2, 3, 4]. In RR-SRLs, we assume unidirectional propagation of each Stokes order in accordance with the discussion above. Because the contradirectional Raman gain is larger, this means that successive Stokes orders propagate in alternating directions. Finally, during the optimization we varied the cavity-coupling ratios for the pump and output wavelengths, the cavity length, and the pump power (in the range $0 \ldots 100\,\text{mW}$) to find the maximum possible laser output power.

Fig. 1a shows the characteristics of the optimized non-cascaded SRLs. The FP-SRL (thick dotted curve) emits up to 17 mW, while the RR-SRL is, in accordance with our expectations, significantly more efficient, emitting up to 24 mW (thick solid curve). This larger efficiency can be traced back to the fact that the RR-SRL has been assumed to operate only in the more efficient way, namely contradirectional to its pump, while in the FP-SRL also the less efficient copropagating direction is inavoidably involved. This is illustrated by the numerical experiment of deliberately assuming a reciprocal waveguide where the Raman gain is equally efficient in both directions. We then obtain the two thin curves in Fig. 1a (one of which coincides with the thick dotted curve). The difference between the optimized FP- and RR-SRLs is indeed much smaller here. The remaining Figs. 1b and c correspond to first- and second-order cascaded SRLs and show an even clearer superiority of the RR-SRL.

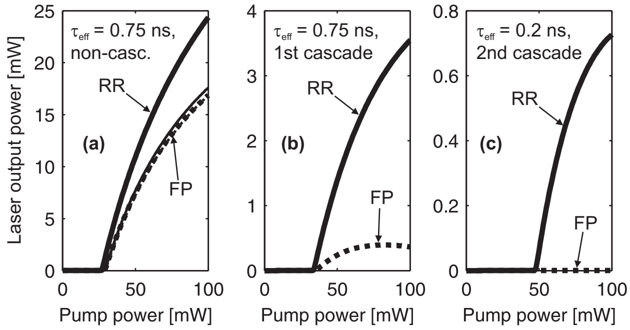

Fig. 1. Characteristics of optimized SRLs for $\alpha = 1.0\,\text{dB/cm}$.

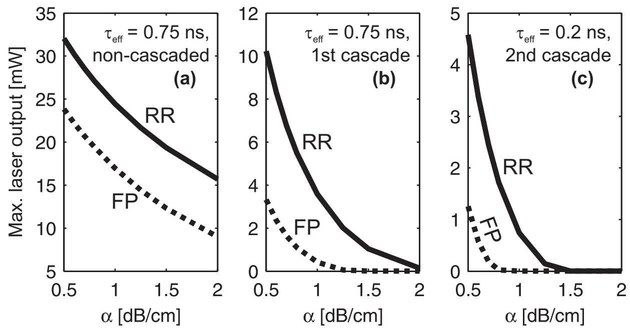

Fig. 2. Optimized output power of SRLs vs. linear losses α.

Finally, Fig. 2 shows the optimized laser output power as a function of the linear waveguide losses. The ring-resonator SRLs (solid curves) consistently perform better than the Fabry-Perot SRLs (dotted curves) due to the non-reciprocity of the Raman gain in the sub-micron strip waveguides.

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