Analysis of Optical Isolation Based on Nonreciprocal Raman Scattering in Photonic-Crystal Silicon Waveguides

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It has been shown both theoretically and experimentally that stimulated Raman scattering (SRS) in silicon photonic wires exhibits nonreciprocal behavior: the gain seen by a signal counterpropagating with respect to the pump wave can be much larger than the gain in copropagation at the same pump power. Counter/co gain ratios of up to 340 have been predicted, depending on the waveguide orientation on the substrate [1, 2]. Thus SRS lends itself to the realization of optical isolators [3].

In photonic-crystal waveguides (PhCWGs), SRS is expected to be enhanced due to the slow-light effect. Preliminary investigations indeed predict much potential for the improvement of silicon Raman amplifiers [4–7]. However, an investigation of the SRS *nonreciprocity* in PhCWGs is lacking so far. It is the focus of this paper.

We illustrate the principle using the 2D PhCWG from [8]. We scale it such that the operating wavelength range is in the mid-IR where the usual models reduce to the consideration of only two effects: SRS and linear modal attenuation α. A fictitious waveguide thickness of $0.5\,\mu$m is assumed along the invariant structural dimension for the purpose of defining tangible optical powers.

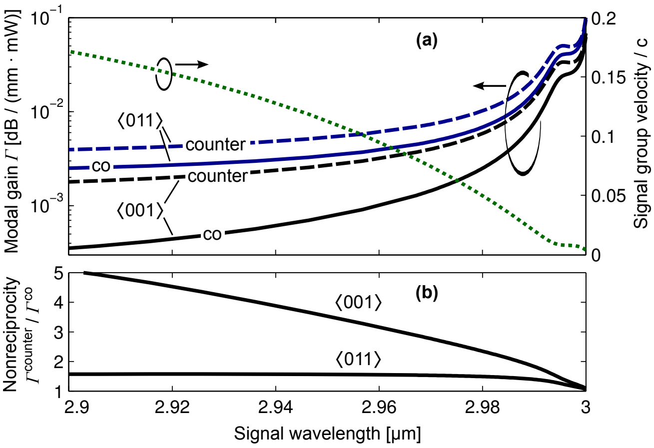

Fig. 1. *(a)* Signal group velocity and Raman gain in dB per mm distance and mW local pump power, vs. signal wavelength (pump implicitly offset by 15.6 THz). *(b)* Raman nonreciprocity (counter/co gain ratio).

The dotted curve in Fig. 1a shows the group velocity of the signal in the PhCWG vs. wavelength. The solid and dashed curves represent the modal Raman-gain coefficients Γ for co- and counter-propagation, respectively (a bulk Raman-gain constant of 10 cm/GW was assumed). There are two pairs of curves, corresponding to two different orientations of the waveguide with respect to the crystallographic axes. In either case, a strong increase of the modal gain towards larger wavelengths is clearly visible, corresponding to the slow-light region of the PhCWG [8]. Most importantly, the co- and counter-gains differ significantly; their ratio is shown in Fig. 1b. This nonreciprocity reaches values of 1.6 for the $\langle 011\rangle$ waveguide orientation (comparable to the nonreciprocity in photonic wires [3]), and even up to 5.1 for the $\langle 001\rangle$ orientation.

We now model the performance of an MZI-based optical isolator [3], now based on the PhCWGs just analyzed. A schematic is shown in Fig. 2. Fig. 3 shows optimization results for the $\langle 011\rangle$ waveguide orientation. The thick curves correspond to a simple model where the linear modal attenuation α is assumed wavelength-independent (1.0 dB/cm), and the modal co- and counter-propagating gains scale according to Fig. 1a. Pump powers P_A and P_B are needed for the two MZI arms; to realize an "ideal" isolator with complete backward isolation and a forward transmission of 0 dB, the powers must be chosen as shown in Fig. 3 (solid and dashed). In the slow-light region, they are on the order of merely 10 mW, while the required PhCWG lengths (dotted) approach 10 cm.

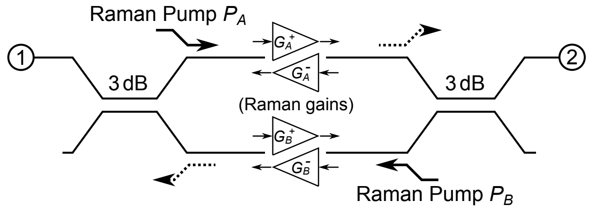

Fig. 2. Mach-Zehnder-based Raman-pumped optical isolator [3].

The picture changes when we assume that the modal attenuation α increases linearly with the slowdown factor [9]. In that case the thin curves in Fig. 3 apply. The required pump powers no longer decrease as strongly in the slow-light region, instead the PhCWGs may be made much shorter, less than 20 mm now.

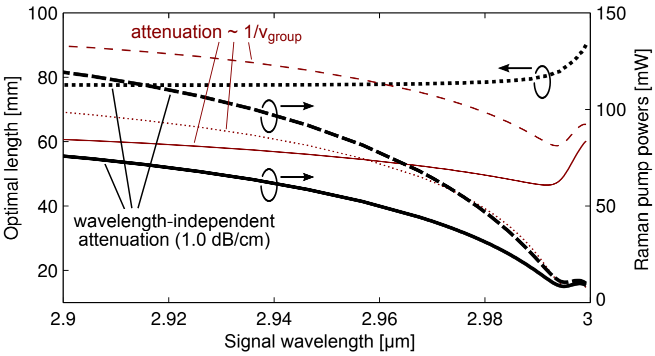

Fig. 3. *Thick:* optimized isolators for wavelength-independent α. Solid (P_A) and dashed (P_B) are pump powers required for forward IL = 0 dB; dotted are corresponding MZI lengths. *Thin:* corresponding result for group-velocity-dependent α.

In conclusion, we have found that the use of PhCWGs instead of photonic wires in Raman-based optical isolators has the advantage of either reduced pump powers or shorter lengths, depending on the attenuation behavior.

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