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Observation of spontaneous Raman scattering in silicon slow-light photonic crystal waveguides

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We report on the observation of spontaneous Raman scattering in silicon photonic crystal waveguides. Continuous-wave measurements of both forward scattered and backscattered Stokes emissions are reported in single line-defect waveguides in hexagonal lattice photonic crystal silicon membranes. By utilizing the Bragg gap edge dispersion of the TM-like mode for pump enhancement and the TE-like fundamental mode onset for Stokes enhancement, the spontaneous Raman scattering coefficient was observed to increase by up to six times in the region of slow group velocity. The results show explicit nonlinear enhancement in a silicon photonic crystal slow-light waveguide device. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3050457]

The prospect of silicon acting as an active optical material with the possibility of amplification and lasing has been the driving force behind the research of Raman scattering in silicon-on-insulator waveguides. This evolved from the observations of spontaneous Raman scattering in silicon rib waveguides[1] through the observations of amplification[2] and finally to lasing.[3,4] In addition to these achievements in relatively large mode area rib waveguides, the observation of spontaneous scattering[5] and amplification[6] has been made in submicron channel waveguides. In order to reduce the threshold power of Raman lasers, racetrack cavity[7] lasers have been studied experimentally. It has been shown theoretically that the high confinement and unique dispersion properties of photonic crystal cavities[8,9] and waveguides[10] can be utilized to further reduce threshold values and enhance Stokes emission. Spontaneous Raman scattering has been observed in GaAs photonic crystal slab waveguides;[11] however no wavelength dependence of the Stokes emission was reported.

The enhancement of Raman scattering in photonic crystal waveguides (PhCWGs) when compared to the aforementioned rib waveguide structures is due to two mechanisms: higher modal confinement and larger group indices. The waveguides studied here have a modal area of 0.13 μm^2 (averaged over one unit cell in the direction of propagation), which put them close in value to the nanowire waveguide devices studied previously.[5,6] Such small modal areas lead to large optical intensities and increase the probability of Raman scattering. The periodic lattice of the photonic crystal membrane leads to a Bragg-reflection-like lateral confinement (total internal confinement in the vertical direction) for transverse electric (TE) optical mode. This Bragg confinement leads to a flat dispersion curve at the fundamental mode onset, as seen in Fig. 1(a). These slow-light frequencies, which have been observed experimentally,[12] are frequencies where the optical mode experiences large amounts of Bragg reflections from the bulk photonic crystal lattice on the either side of the waveguide. For transverse magnetic (TM) polarized light, no photonic band gap exists;[13] however there is still a periodic modulation of the effective index in the direction of propagation due to the lattice.[14] This modulation creates a one-dimensional photonic crystal, creating a distinctive Bragg stop gap at the Brillouin zone edge. Of course, the corresponding edges of the stop gap exhibit flat dispersion curves, indicative of slow light. For both of these areas of the dispersion curve, the TE mode onset and the TM stop gap edges, slow light offers the possibility of increased light-matter interaction, effectively increasing the probability for Raman scattering to take place. The higher power density within the waveguide due to the increased multiple Bragg reflection at the slow-light region is the phenomenon we are exploiting here. It has been shown theoretically that the scattered Stokes intensity in silicon PhCWGs is inversely proportional to the product of the pump and Stokes group velocities.[10]

In our experiments the pump laser is TM polarized and tuned in the vicinity of the upper edge of the Bragg stop gap.

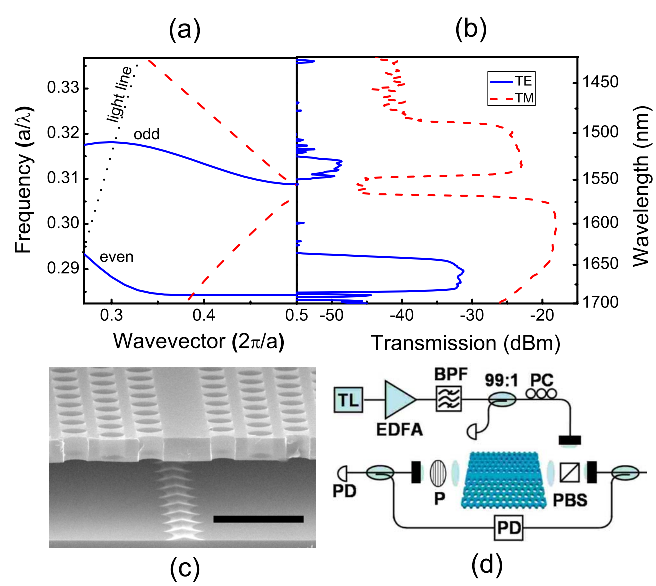

FIG. 1. (Color online) (a) Calculated projected band structure for the W1 PhCWG. (b) Measured transmission of fabricated waveguide. (c) Scanning electron microscope image of PhCWG (scale bar: 1 μm). (d) Experimental setup: TL, tunable laser; EDFA, erbium fiber doped amplifier; BPF, band pass filter; PC, polarization controller; P, polarizer; PBS, polarized beam splitter. and PD, photodetector.

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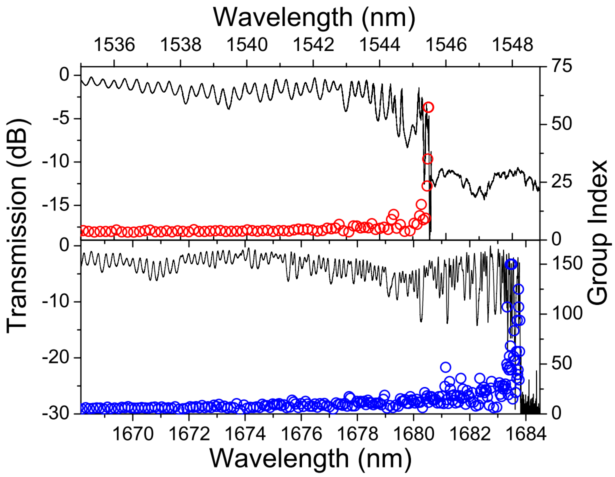

FIG. 2. (Color online) High resolution ($\Delta\lambda = 1$ pm) tunable laser transmission measurements (solid lines) and derived group index (open circles). (Top) TM polarization. (Bottom) TE polarization.

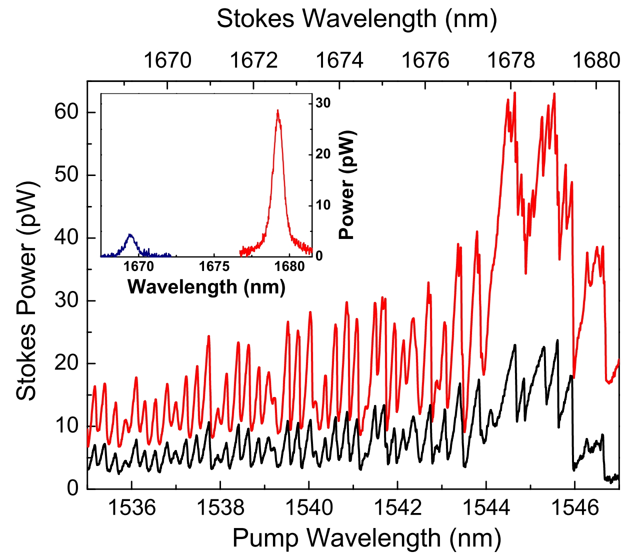

FIG. 3. (Color online) Measured spontaneous emission vs pump wavelength. (Red line) backscattered Stokes. (Black line) forward scattered Stokes. (Inset) Measured forward Stokes spectrum for $\lambda_{pump} = 1535$ nm and $\lambda_{pump} = 1544.24$ nm. Coupled pump power ~ 15 mW.

By careful design of the PhCWG parameters (lattice constant, hole radius, and slab thickness), the resulting Stokes emission is scattered into the fundamental TE mode onset. This results in both the pump and Stokes wavelength operating at wavelengths of high group index.

The waveguides used in our experiment are fabricated utilizing deep-UV photolithography on silicon-on-insulator wafers with a 250 nm thick layer of silicon and a 1 μm layer of SiO_2 on silicon substrate. The holes are etched using a plasma dry-etch process. After the dry etch, a wet etch of hydrofluoric acid is used to remove the underlying SiO_2, creating a suspended silicon membrane [see Fig. 1(c)]. The devices are then cleaved manually. The fabricated photonic crystal has a lattice constant of 480 nm and holes with a radius of 0.34a (163 nm). From cutback measurements the minimum waveguide loss for the TM-like mode was found to be (1.1 ± 0.2) dB/mm and (2.9 ± 1.0) dB/mm for the TE-like mode. In agreement with previous studies[15,16] of PhCWG loss, the loss in our waveguides was seen to increase dramatically when approaching the TE mode onset. The transmission properties of the waveguide were experimentally verified using a supercontinuum source and can be seen in Fig. 1(b).

If any claim of Stokes emission enhancement due to slow group velocity is to be made, the group index of both pump and Stokes modes must be measured. In order to do this, high spectral resolution transmission measurements (wavelength step of 1 pm) were taken off the PhCWG (see Fig. 2). Utilizing the method outlined in Ref. 12, the transmission data of the waveguide were analyzed and the Fabry–Pérot oscillation spacing was used to determine the group index. This method allows us to measure the group index of both Stokes and pump modes *in situ*. The maximum group indices of TM-like and the TE-like modes of the waveguide were measured to be 57 and 149, respectively, similar orders of magnitude to those observed in Refs. 12, 15, and 16. The high resolution transmission data show that there is a 2.2 THz (2.9 nm) difference between the optical phonon frequency spacing (15.6 THz or 135 nm at the pump wavelength of maximum TM group index) and the frequency spacing between the wavelength of maximum TM and TE group indices (17.8 THz or 137.9 nm). This difference reduces the expected maximum Raman enhancement, which is proportional to the product of the Stokes index (n_s) and pump index (n_p) (Ref. 10) since the peak n_s does not occur at the Stokes wavelength that would be generated by the peak n_p wavelength.

To characterize the spontaneous Raman scattering properties of these waveguides the experimental setup shown in Fig. 1(d) is used. A polarization beam splitter is used to ensure that the pump is TM polarized and to allow collection of the backscattered TE Stokes emission. The Stokes output is then measured using an optical spectrum analyzer (resolution at 0.5 nm) or photodetector.

Figure 3 shows the total Stokes power for both forward scattered and backscattered emissions with respect to the pump wavelength. Since the pump wavelength is far from any electronic resonances, there should only be a $(1/\lambda_s)$ (Ref. 4) variation in the Stokes output with respect to the pump wavelength. However, as can be seen in Fig. 3, the Raman emission of the waveguide has a strong pump wavelength dependence. As the pump wavelength approaches the TM stop gap edge, the Raman emission increases. If the Raman emission variation with pump wavelength was solely dependent on loss, one would expect it to drop as it approaches the TM stop gap, as loss in both the TE and TM modes increases as they approach their regions of large group index. The fact that the Raman emission does not decrease as the pump approaches the stop gap edge, but in fact increases, is a sign of group index dependence. In order to characterize the Stokes emission enhancement, we introduce a simple model[5] $dP_s^{\pm}/dz = \mp \alpha_s P_s^{\pm} \pm \kappa P_p^{+}$, where P_s^{+} and P_s^{-} are the forward scattered and backscattered Stokes powers, respectively. κ is the spontaneous Raman scattering coefficient, which has been shown[10] to be inversely dependent on the Stokes and pump group velocities. P_s^{+} is the pump power and is defined as $P_s^{+} = P_0 e^{-\alpha_p z}$. α_s and α_p are the wavelength dependent losses in the Stokes and pump modes, respectively. They are derived by scaling the measured transmission to the minimum measured losses which were determined by cutback measurements on a similar PhCWG. We

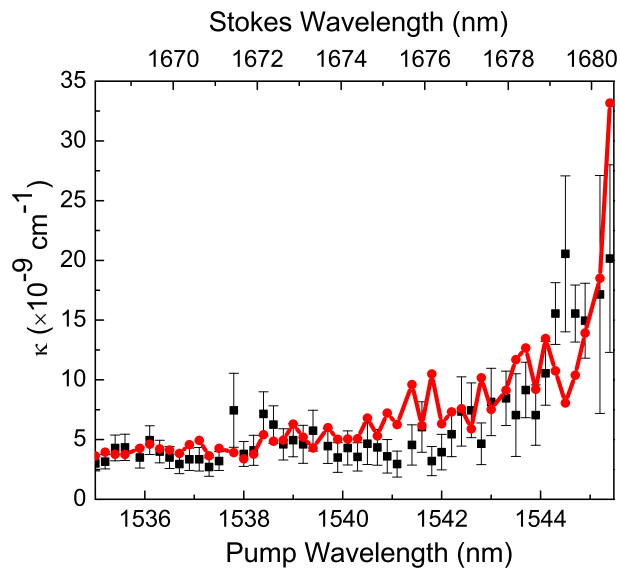

FIG. 4. (Color online) Spontaneous Raman scattering coefficient with respect to pump wavelength. (Black squares) derived Raman scattering coefficient (κ) from model. (Red circles and line) Product of experimentally determined Stokes and pump group velocities (see Fig. 2) multiplied by a fitting constant.

use this model to fit the measured Stokes power in order to derive the pump wavelength dependent value of κ (see Fig. 4). Knowing that κ is directly proportional to the product of the Stokes and pump group indices, we also plot in Fig. 4 the product of the experimentally derived TE and TM mode group indices (utilizing a constant fitting parameter). It can be seen that the fitted κ values follow the experimentally measured product of the Stokes and pump group indices closely and are shown to be enhanced by six times (within the error bars) in the region of high group index in comparison with the region of normal group index away from the TM stop band edge.

This simplified model does not take into account any nonlinear absorption such as two-photon absorption (TPA) or free-carrier absorption. For our experiment this is a valid assumption since the pump power utilized ($P_0=15$ mW) is very low compared to the expected power (30 W),[5] where TPA would become non-negligible for a device with the length and modal area equal to ours. No deviation from a linear relationship between pump power in and pump power out was observed in our measurements. It has been experimentally verified that TPA is group index dependent;[17] however no observations of such an increase in absorption were observed in our measurements due to the low pump powers used in this experiment.

In conclusion, we have made observations of spontaneous Raman scattering in silicon slow-light PhCWGs. The group index of both the pump and Stokes modes was characterized experimentally and it was shown that the spontaneous Raman scattering coefficient exhibited an observable correlation with the product of the measured group indices. The enhancement of the Raman scattering coefficient due to the slow light was measured to be over six times. This enhancement is encouraging and could be exploited to create compact Raman amplifiers and lasers.

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