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Observation of Stimulated Raman Scattering in Silica-Cladded Silicon Photonic Crystal Waveguides with Modified Holes

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Abstract

We measured Raman scattering in a silica-cladded silicon photonic crystal (PhC) waveguide with modified holes. Nonlinear increase of the Stokes signal intensity, which indicates the onset of stimulated Raman scattering, was observed as the pump power increases. This is the first demonstration of stimulated Raman scattering in silica-cladded PhC structures.

1. Introduction

Silicon photonics defines a significant advancement in the development of integration with Complementary metal–oxide–semiconductor (CMOS) electronics on a single silicon substrate, but silicon-based light sources and amplifiers using electronic transitions are difficult to realize due to indirect electronic band-gap of silicon. Large nonlinear optical coefficient of silicon can offer an opportunity to achieve laser oscillation or light amplification by various third-order nonlinear effects. In the past decade, pulsed and continuous-wave (CW) Raman amplifiers [1-2] and Raman lasers [3,4] based on stimulated Raman scattering (SRS) effect have been demonstrated using cm-long silicon waveguides. However, further miniaturization of the device and reduction of the required pump power are still demanded.

Photonic crystal (PhC) is an attractive structure for making the device size small and for improving the efficiency. Recently, ultra compact Raman laser with low threshold power has also been demonstrated using a high-*Q* air-bridge PhC nanocavity [5]. Considering light amplification at multiple wavelengths with high output power, waveguide (WG) structures would be advantageous. Enhanced spontaneous and stimulated Raman scattering in silicon air-bridge PhC WGs due to the slow light effect have been observed [6,7]. On the other hand, there is no study on Raman scattering in silica-cladded PhC WGs, which are also useful structures thanks to their better mechanical and thermal stability.

Here, we report Raman scattering in silica-cladded PhC WGs. We observed stimulated Raman scattering in a PhC WG with modified holes under the CW excitation. To our best knowledge, this is the first demonstration of stimulated Raman scattering in non-air bridge PhC structures.

2. Sample and Experiment Setup

The device in this experiment was fabricated by CMOS-compatible processes. The device was designed as silica cladded Mickey-mouse-like (MML) PhC WGs [8] with x=0.7, lattice constant (a) =462 nm, WG length =200a=92.4 μm, r/a=0.302 as Fig.1 (a). The thickness of the slab (D) is 210 nm. This design was adopted in order to tune both pump and Stokes wavelengths close to the band edge for enhancing the slow light effect on Raman scattering. At both ends of the PhC WG, Si wire waveguides are connected for better light coupling from outside. The scanning electron microscope (SEM) image is shown in Fig.1 (b). Due to over exposure in the fabrication process, the ear holes (as Fig.1 (a)) of MMLWG connect together. However, effect of modified holes on Raman scattering is still expected as discussed below.

We used lens fibers to couple light beam in and out the access from spot size converters to Si wire WGs as Fig.1 (c). The top view and side view of samples could be observed by infrared camera to see the fiber position. In this study, a CW laser source with amplifier was used. Linear transmittance spectrum is measured by using optical spectrum analyzer. The Stokes signals are detected by InGaAs photodiode array through a monochrometer.

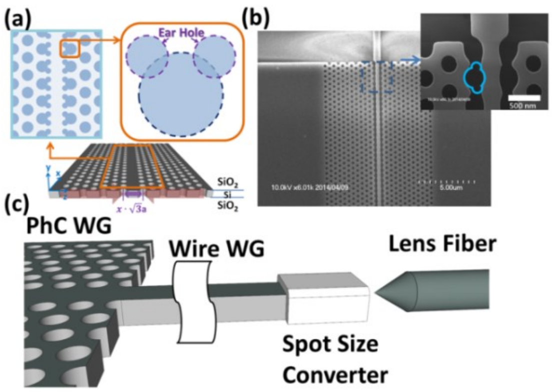

Fig. 1(a) Illustration of designed silica cladding PhC WG and the modified holes. (b)SEM images of the fabricated MML PhC WG. The images were taken after removing the silica clad. (c) Schematic of light coupling configuration. Light beams couple in and out devices by lens fiber. Wire WG and spot size converter are designed at the entrance and exit of PhC WG for improving coupling efficiency.

3. Optical Characterization Results

Figure 2 (a) shows the transmittance spectrum of the device for TE polarization. We redraw outline of MML patterns from SEM images and calculated the corresponding photonic band structure, which is also shown in Fig. 2(a). The measured transmittance is low around wavelength of 1260 nm to 1460 nm due to at the slab-mode region, which area is colored gray in the calculation band structure. The stop-band around 1550 nm in measurement also matches the band-gap in the calculation band structure.

We first measured Raman scattering at a fixed pump power of 10 mW. Figure 2(b) shows Stokes signal intensity as a function of pump wavelength. To understand the effect of slow light, the transmittance spectra for pump (black line) and Stokes (red line) wavelengths are plotted in Fig. 2 (c). Note that the frequency separation of pump and Stokes waves should match $\Delta\omega_R=2\pi\times15.6$ THz (Raman shift of silicon). The strong Stokes signals were obtained around 1475 nm, where both pump and Stokes wavelengths are relatively close to the bandegdes (shadowed region in Fig. 2 (b) and (c)). Therefore, the enhancement of Raman scattering in this range can be attributed to slow light effect. Compared to higher group velocity region of 1510 nm, 10 times enhancement of Raman peak intensity was observed. We measured the Raman intensity in the same spectral range but for different pump polarization (i.e. TM polarization). The maximum Stokes intensity with TM-polarized pump was ~1/8 of that with TE-polarized pump. This can be understood by considering the fact that the group velocity at the pump wavelengths is lower for TE-like mode than for TM-like modes.

Figure 3 shows pump power dependence of Stokes signal at two different pump wavelengths λ_1=1459.87 nm (black circles) and λ_2=1475.60 nm (blue triangles). Stokes signal in the former case increases superlinearly as the pump power increases. This shows a clear evidence for the onset of stimulated Raman scattering. In the latter case, on the other hand, no nonlinear increase of Stokes signal was observed. Detail analyses for this difference are necessary. However, it can be partly understood by considering the difference of group velocity in stokes waves. Two arrows in the transmittance spectrum (see the Inset) indicated the Stokes wavelengths corresponding these two pump wavelengths. Strong interference in the spectrum is caused by the reflections at the interfaces between wire WG and the PhC WG. Sharper peaks with narrower fringe spacing around the Stokes wavelength for the pump at former case λ_1 indicate the smaller group velocity than that for the latter case.

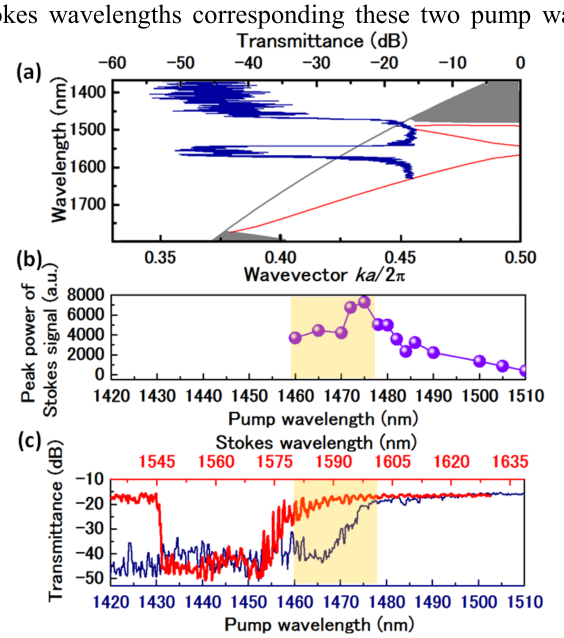

Fig. 2 (a) Transmittance spectrum and the corresponding calculated band structure by the parameters from the SEM images. (b) Raman peak intensity as a function of pump wavelength. (c) Transmittance spectra for TE polarization around pump wavelength range of 1420 nm~1510 nm (blue line) and around Stokes wavelength range of 1533 nm~1650 nm (red line).

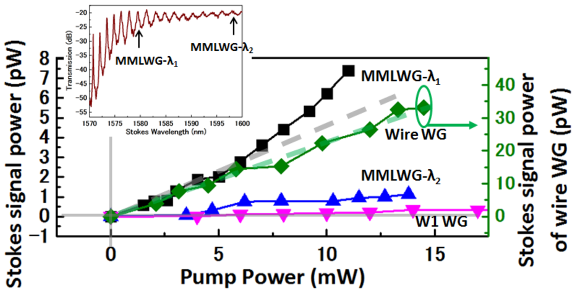

Fig. 3 Power dependence of Raman scattering signals of MML PhC WGs which Stokes wavelengths at λ_1=1459.87 nm and λ_2=1475.60 nm, W1 WG ((a=435 nm, L=87 μm, r/a=0.3, D=210 nm)), and 2-mm long wire WG. Broken lines show linear dependence. Inset: Transmittance spectrum in the wavelength range of 1570nm~1600nm.

We also measured Raman singles in a silica-cladded W1 PhC WG (a=435 nm, L=87 μm, r/a=0.3, D=210 nm) and a 2 mm-long Si wire waveguide. However, only the linear dependence of Stokes signal on pump power was observed at the same pump powers (see also Fig. 3). This indicates that PhC WGs with modified holes are useful for highly efficient Raman amplifier or lasers.

4. Conclusions

We observed enhanced Raman scattering due to the slow light effect in a silica-cladded silicon photonic crystal waveguide with modified holes. The Stokes signal at around the bandgap edge, i.e. the low group velocity region, was ~10 times larger than that at high group velocity wavelengths. The Stokes signal intensity shows nonlinear increase as pump power increasing. This nonlinear increase indicates the onset of stimulated Raman scattering. The device used here is far from the ideal one due to the fabrication imperfection. Further enhancement of performance could be expected by optimizing the device fabrication.

Acknowledgements

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