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Cavity enhanced stimulated Brillouin scattering in an optical chip for multiorder Stokes generation

Abstract

We report the first demonstration of on-chip cascaded stimulated Brillouin scattering (SBS). Cascaded SBS is characterized in a 4 cm long chalcogenide (As₂S₃) rib waveguide where the end facet reflections provide a monolithic Fabry–Perot (FP) resonator. The presence of the FP cavity reduces the Brillouin gain threshold, which enables observation of cascaded SBS at reduced pump powers. We observe up to three orders of Stokes waves in the backscattered signal at a coupled peak power of 1.34 W. Anti-Stokes waves due to four-wave mixing between the pump and the Stokes wave were observed in the forward spectrum.

Keywords

stimulated, brillouin, cavity, scattering, enhanced, optical, chip, multiorder, stokes, generation

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Cavity enhanced stimulated Brillouin scattering in an optical chip for multiorder Stokes generation

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We report the first demonstration of on-chip cascaded stimulated Brillouin scattering (SBS). Cascaded SBS is characterized in a 4 cm long chalcogenide (As_2S_3) rib waveguide where the end facet reflections provide a monolithic Fabry-Perot (FP) resonator. The presence of the FP cavity reduces the Brillouin gain threshold, which enables observation of cascaded SBS at reduced pump powers. We observe up to three orders of Stokes waves in the backscattered signal at a coupled peak power of 1.34 W. Anti-Stokes waves due to four-wave mixing between the pump and the Stokes wave were observed in the forward spectrum. © 2011 Optical Society of America
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Stimulated Brillouin scattering (SBS) is an inelastic scattering process where the interaction between an optical pump (ω_p) and an acoustic wave (Ω_B) generates a back-scattered signal, called the Stokes signal, at frequency $\omega_s = \omega_p - \Omega_B$ [1]. SBS has been exploited in optical fibers for applications ranging from tunable delay, microwave (MW) generation to multiwavelength Brillouin lasers [2–8]. Realization of multiwavelength Brillouin lasers and MW sources requires multiorder Stokes generation via the cascaded SBS process.

Cascaded SBS occurs when the power in the backscattered first-order Stokes (S1) wave reaches the Brillouin threshold. The Stokes signal S1 then acts as a pump and generates a forward propagating second-order Stokes (S2) wave. For a given pump power, if the power in the N th order Stokes wave reaches the Brillouin threshold, the cascaded SBS process generates Stokes waves up to order $N + 1$. Anti-Stokes (AS) waves are generated due to four-wave mixing (FWM) between the pump and S1.

One way to excite the cascaded SBS process is to use the SBS gain inside a Fabry-Perot (FP) cavity [6,7], where the presence of the cavity reduces the SBS gain threshold [9], enabling cascaded SBS at reduced pump powers. Previous demonstrations of cascaded SBS used FP and ring cavities and Sagnac loop [5–8].

In this Letter, we present the first investigation of multiorder Stokes generation via the cascaded SBS process in an optical chip. SBS was excited in a rib waveguide built on a chalcogenide (As_2S_3) platform using $2\ \mu\text{s}$ pump pulses. Reflection from the front and rear facet of the chip give rise to a FP cavity, which reduces the SBS gain threshold, enabling multi-Stokes generation at reduced pump powers. We observed up to three Stokes orders in the backscattered spectrum at an estimated coupled peak power of 1.34 W. AS waves due to the FWM between the pump and Stokes wave were observed in the forward-scattered spectrum.

Figure 1 shows the concept of on-chip cascaded SBS process in a rib waveguide built on chalcogenide glass,

which offers both large Kerr nonlinearity and SBS gain [4,10]. The backscattered signal shows both S1 and back reflected pump. For large pump powers, S1 reaches SBS threshold and it pumps the generation of the forward propagating S2. FWM between the pump and S1 generate AS waves in the forward direction.

Figure 2 explains the SBS enhancement due to the presence of the FP cavity when the Brillouin gain spectrum is centered at one of the FP resonances. Inside the cavity, light experiences multiple reflections from mirrors with amplitude reflectivity r . At the FP resonance, the round trip phase-shift is an integer multiple of 2π , allowing the reflections to add up constructively. Therefore, the Stokes beams generated by the pump, launched at $z = 0$, adds up constructively, which enhances the Stokes signal. The intensity of the Stokes beam is further enhanced due to the gain from the forward and backward pump. This enhancement of S1 in the presence of a cavity reduces the value of the Brillouin gain threshold

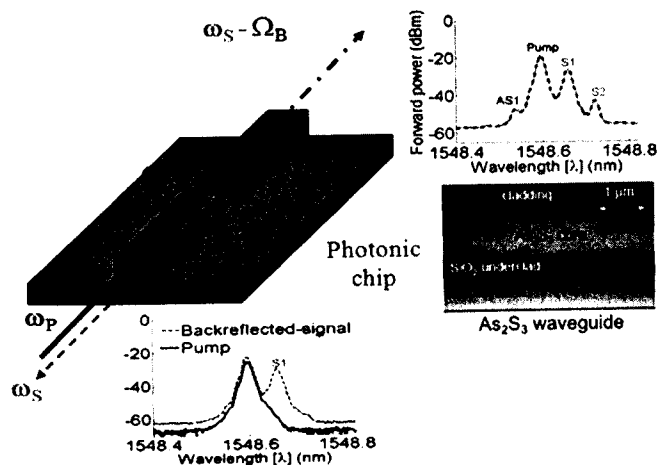


Fig. 1. (Color online) Schematic showing the principle of the on-chip cascaded SBS process where the back- and forward-scattered spectrum (see inset) shows the generation of first- and second-order Stokes due to the cascaded SBS process.

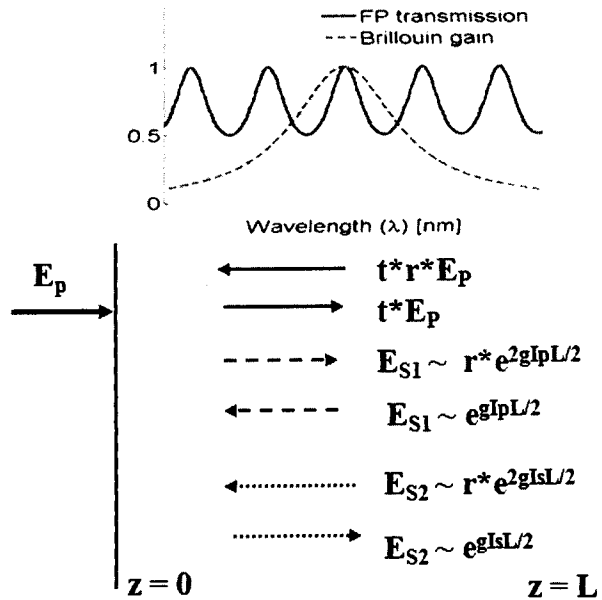


Fig. 2. (Color online) FP cavity enhanced cascaded SBS principle: the pump field E_p (solid) experiences multiple reflections and generates back- and forward propagating S1 wave E_{S1} (-). The S1 waves then undergo multiple reflections and gain and pump the generation of E_{S2} .

$G_{th} = g_0 I_p L_{eff}$, where g_0 is the Brillouin gain coefficient, I_p is the pump intensity, and L_{eff} is the effective length. The modified Brillouin threshold gain (G_{th}^{eff}) in the presence of a FP cavity has a value given by [9]

$$G_{th}^{eff} = [4\alpha L - 2\ln(r_1 r_2)] \left\{ 1 + \left[\frac{\phi}{\Gamma T_l - 2\alpha L + \ln(r_1 r_2)} \right]^2 \right\}, \quad (1)$$

where α is the linear loss parameter; Γ is the phonon decay rate; ϕ is the detuning of the longitudinal mode of the cavity from the peak of the Brillouin gain spectrum; T_l is the transit time inside the medium; L is the device length; and r_1 and r_2 are the amplitude reflectivity of the front and rear facets. This threshold reduction allows cascaded SBS process at reduced pump powers.

Figure 3 shows the experimental set up for characterizing the cascaded SBS process in our chip. Light from a tunable external cavity laser (ECL) was modulated using a Mach-Zehnder modulator (MZM), which was driven by a function generator (FG), to generate $2\mu s$ pump pulses at a repetition rate of 5 KHz. The polarization of the light going into the modulator was controlled using the fiber polarization controller one (FPC1). The pump pulses were then amplified and 99/1 coupler was used to monitor the input pump power. The pump was coupled to the optical chip via circulator (C1) and its polarization was adjusted via FPC2 to maximize the Stokes intensity. While not explicitly monitored, this likely means that the TE mode of the waveguide was excited as this was previously measured to be the lower loss waveguide mode. Back- and forward-scattered signals were collected at port three and port two of circulators C1 and C2, respectively. Port two of C2 was coupled to a 99/1 coupler where the 1% port was used to measure the total output power. The back- and forward-scattered signals were coupled to a 50/50 coupler via VOA1 and VOA2, respectively, to allow selection of either forward or backward

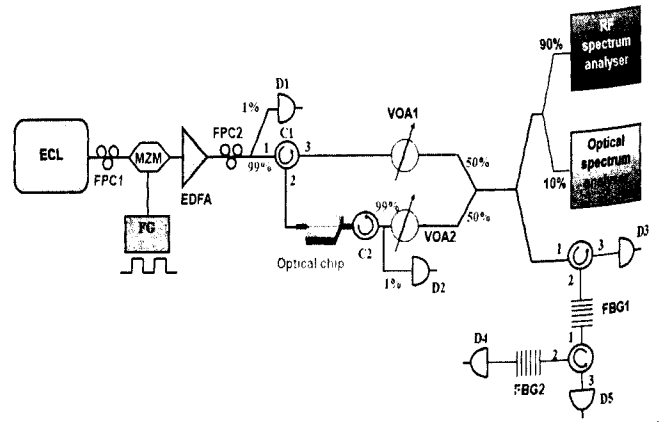


Fig. 3. (Color online) Experimental setup for characterizing on-chip cascaded SBS process.

signal for simultaneous analysis via the RF and optical spectrum analyzers. The other output port of the 50/50 coupler was connected to a fiber Bragg grating (FBG) set up to selectively filter and individually detect the pump and Stokes S1 and S2 signals. The total insertion loss was ~ 8.8 dB, which includes 4 dB of coupling loss at each facet. The waveguide was 4 cm long and has a cross-sectional area of $4\mu m \times 850$ nm.

Figure 4 shows the resultant forward-scattered spectra, obtained by turning off VOA1, at different coupled peak powers. From Fig. 4, it is evident that the power in the S1 signal increases with input pump power. For the coupled peak power of 0.98 W, two Stokes lines became visible in the forward-scattered spectrum as a result of the cascaded SBS process. At the same pump power, the forward-scattered signal shows an anti-Stokes line which arises due to the FWM between the pump and S1. Back-scattered spectra for different coupled peak powers were also measured and showed up to three Stokes orders at a coupled peak power of 1.34 W (see inset Fig. 4).

Figure 5 plots the power in the forward-scattered filtered pump [5(a)] and Stokes signals S1 [5(b)] and S2 [5(c)] as the input pump power was varied. From the measured Stokes power and spectra, the S1 power started to

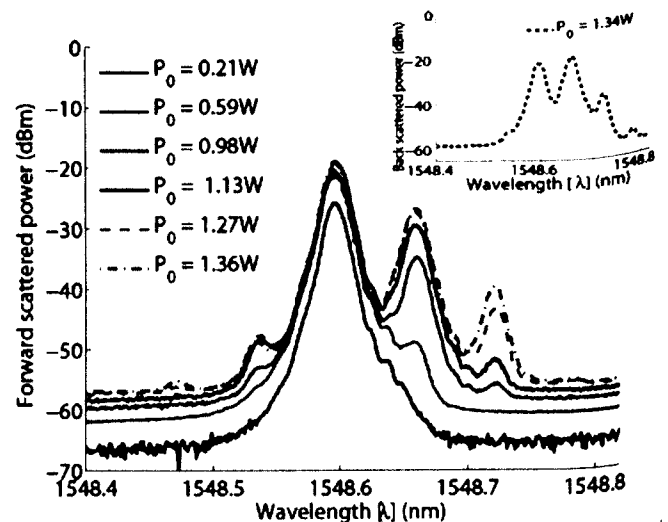


Fig. 4. (Color online) Forward-scattered spectra, at different coupled peak pump powers, showing the generation of multi-order Stokes resulting from cascaded SBS and anti-Stokes arising from FWM between the pump and Stokes.

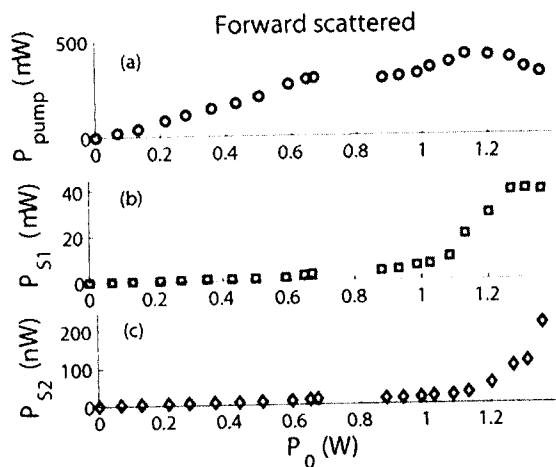


Fig. 5. (Color online) Measured powers in the forward-scattered filtered pump, S1, and S2 signals as the pump power is varied.

increase at a threshold peak power $P_{th} \approx 0.5$ W. From the measured threshold pump power $P_{th} \approx 0.5$ W, we calculate the threshold gain parameter $G_{th} = g_0 P_{th} L_{eff} / A_{eff}$ of 5.6 where we used the Brillouin gain coefficient $g_0 = 0.715 \times 10^{-9}$ m/W [11], $A_{eff} = 2.3 \mu\text{m}^2$, and $L_{eff} = 3.6$ cm. The calculated G_{th} is nearly four times smaller than the typical value of 21 for single-pass SBS. The G_{th} reduction is attributed to the SBS enhancement due to the FP cavity. The FP cavity has a measured free-spectral range (FSR) ~ 0.013 nm, which is measured using the ECL with 1 pm resolution and is consistent with the calculated FSR ($\lambda^2/2nL$) of 0.0126 nm.

As the pump power is further increased, Fig. 5(c) shows that the S2 power increases dramatically above 1.2 W while the S1 power saturates, which is also evident from Fig. 4. In the presence of feedback, the Stokes power fluctuates near the Brillouin threshold, which has been previously reported [9] and therefore it is difficult to measure the pump and S1, S2 powers near the threshold.

To compare the measured G_{th} with the G_{th}^{eff} , Eq. (1) with $\phi = 0$ (i. e. when the FP resonance and Brillouin gain peak are aligned) was used. Figure 6 plots G_{th}^{eff} as a function of reflectance R where both the mirrors were assumed to have the same R and propagation loss is 0.8 dB. Rigorous calculations for the facet reflectance based on a plane wave decomposition method, give $R = 0.24$ for the TE mode, which predicts $G_{th}^{eff} \approx 3.6$. Note that this G_{th}^{eff} value is the ideal case where the facets are identical, perfectly smooth, perpendicular, and the waveguide itself exhibits no mode coupling or polarization mixing. In practice, these conditions are hard to realize in hand cleaved rib waveguides and the FP finesse is consequently degraded. These factors and slight misalignment of the FP modes to the Brillouin gain peak position are the ones thought to have increased the measured G_{th}^{eff} . A future refinement would be to utilize on-chip gratings as the mirrors and ensure single mode operation of the waveguide which would yield a cavity much closer to the predicted one.

In order to confirm the frequencies of S1 and S2, the RF spectrum was measured and is shown in the inset of Fig. 6.

From the measured spectrum, the frequency of S2 (15.34 GHz) is twice the measured S1 frequency

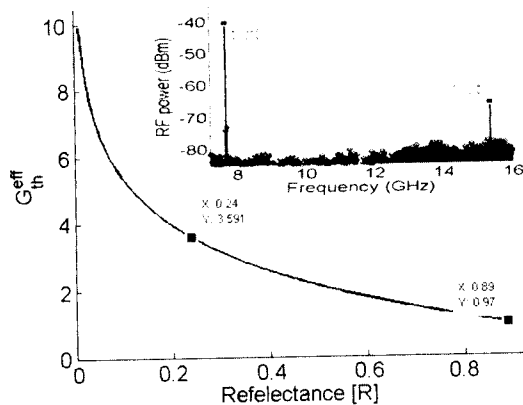


Fig. 6. (Color online) Plot of modified Brillouin threshold as a function of R when $\phi = 0$. The inset shows the measured RF spectrum demonstrating that the shift for S2 is twice the shift for S1.

(7.67 GHz) as would be expected. Finally, the behavior of the S1 generation was investigated for pump pulse widths of 400 ns, 667 ns and 1 μ s. The G_{th} was found to be essentially independent of the pulse duration in this range. The 1 W erbium-doped fiber amplifier used did not allow the coupled CW power to exceed 0.5 W due to insertion losses in the components and therefore SBS could not be excited with a CW pump. However, from Fig. 6, at $R \approx 0.9$, G_{th}^{eff} is close to one, which implies that CW pump power ~ 100 mW would be sufficient to exceed threshold. Exciting SBS in an optical chip with a high finesse FP cavity at reduced pump powers will enable low power, on-chip Brillouin lasers, and MW devices.

In conclusion, we have presented the first demonstration of FP cavity enhanced on-chip SBS for multi-Stokes generation. Up to three orders of Stokes wave are observed in the backscattered spectra at the pump power of 1.34 W. Two AS lines due to FWM between the pump and Stokes are observed in the forward-scattered spectra.

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