Visible Light Stimulated Brillouin Scattering in Small-Core Photonic Crystal Fibers

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Abstract: A reduced stimulated Brillouin scattering threshold power in small-core PCFs is achieved using visible wavelength excitation. We explain this in the context of acousto-optic interactions at length-scales relative to the fiber geometry.

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1. Introduction

Small-core photonic crystal fibers (PCFs) present new opportunities for developing compact and efficient photonic devices because of a significant enhancement to the effective nonlinearity through tighter confinement of the guided optical mode. However, recent studies of Brillouin scattering [1, 2] have shown that small-core PCFs exhibit a two-to-fivefold increase in stimulated Brillouin scattering (SBS) threshold compared to values predicted by accepted guided-wave theory [3]. In addition, multiple peaks are commonly observed in the Stokes spectra for the case of both spontaneous [1] and stimulated [2] Brillouin scattering, in contrast to the typical single-peaked spectrum exhibited by conventional step-index fibers. These phenomena have been explained by the richer acoustic dynamics that influence the Brillouin response in PCFs with a small core. Such observations suggest that PCFs may in fact offer little benefit, although to date, these studies have been restricted to infrared wavelengths. Here, we characterize SBS in small-core PCFs under visible light excitation (532 nm); in addition, we verify previous observations at 1550 nm.

2. Experiment, Results and Discussion

Our setup is shown in Fig. 1a. We characterized two separate fibers: PCF-1 (L=10 m) was endlessly single-moded and exhibited strong birefringence arising from structural asymmetries (Fig. 1b); PCF-2 (L=40 m) had a similar, although more symmetric, microstructure, and thus exhibited only weak birefringence. PCF ends were angle-cleaved to eliminate feedback. Our analysis was supported by numerically computed eigenmodes of Maxwell's equations from a scanning electron microscope (SEM) image of the PCF microstructure [4].

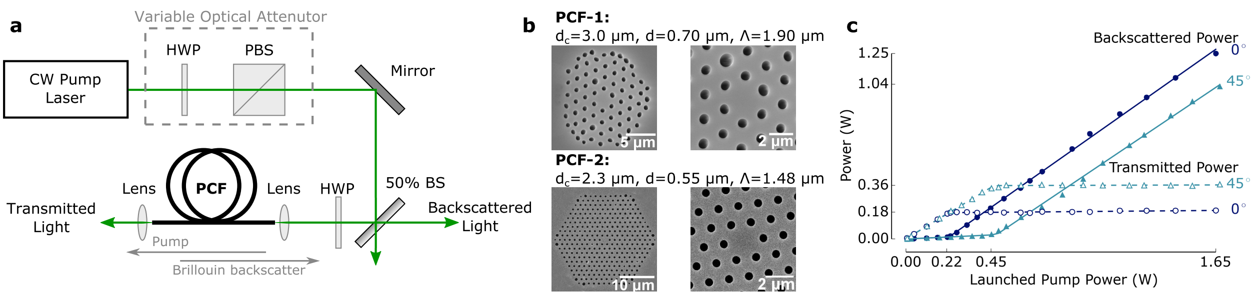

Fig. 1. (a) Setup: Pump laser - 532 nm source (15 MHz linewidth) or 1550 nm source (1 MHz linewidth), HWP - half-wave plate, (P)BS - (polarizing) beam splitter. (b) SEM images of PCF microstructures: d_c - core diameter, d - air-hole diameter, Λ - hole pitch. (c) Backscattered and transmitted powers in PCF-1 (0° and 45° refer to the linear pump polarization angle relative to a fiber principal axis).

In both PCFs, the transmitted power saturated and backscattered power increased sharply at a threshold pump power, P_{th}. This SBS threshold can be calculated from [3]: $P_{th} = 21KA_{eff}/g_B L_{eff}$ where A_{eff} is the optical mode effective area, L_{eff} is the effective fiber length, $L_{eff} = (1-e^{-\alpha L})/\alpha$, to account for loss, α in fiber length L, g_B is the peak Brillouin gain and K is a polarization-dependent factor. For the strongly birefringent PCF-1 under 532 nm excitation, a 220 mW threshold power was recorded for linearly-polarized pump light launched along a fiber principal axis ($K = 1$). When rotating the pump polarization by 45° to lie between the principal axes ($K = 2$), the measured threshold power doubled (Fig. 1c). From this, the peak Brillouin gain was calculated as 4.8×10^{-11} m/W, in agreement with typical gain values for silica fibers. A 33.5 GHz Stokes shift was measured using a scanning Fabry-Pérot interferometer and the stimulated Stokes signal had a resolution-limited width of 50 MHz exhibiting no asymmetry or multi-peak structure.

In PCF-2, threshold values were calculated using a peak Brillouin gain value of 4.8×10^{-11} m/W, $K = 3/2$ for a low birefringence fiber and the parameters shown in Fig. 2a inset. At 532 nm there was strong agreement between the threshold from theory (70 mW) and experiment (69 mW) but at 1550 nm, the experimental value of 1160 mW was $\sim$5 times higher than predicted. Stokes shifts were measured as 33.4 GHz under 532 nm excitation and 11.0 GHz for 1550 nm pump light (Fig. 2a). The stimulated Stokes signal from visible pump light was a symmetric single peak, whereas strong asymmetry was observed for 1550 nm light, suggesting multiple peaks in the spectrum. However, the limited resolution of our interferometer prevented measurement of distinct peaks. These observations support reports in literature of multi-peaked and high-threshold SBS behaviour in small-core PCFs at 1550 nm [1, 2], whereas at a pump wavelength of 532 nm we saw no such irregularity.

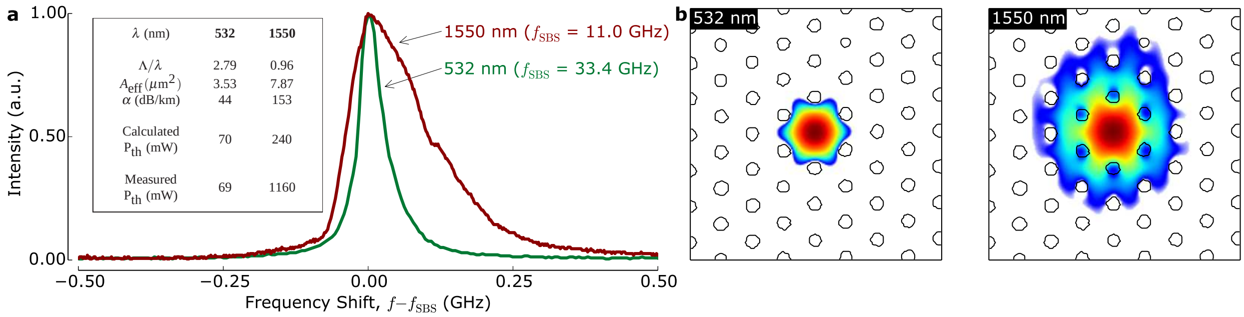

Fig. 2. (a) Brillouin backscattered spectra in PCF-2 (inset shows fiber parameters) for 532 nm and 1550 nm pump light. (b) Computed electric field densities of the fundamental modes. Color scale: -15 0 dB.

We relate our observations to the influence of the small-core ($A_{core} = 4.15$ μm^2) on acousto-optic interactions. Acoustic modes in fiber can consist of both longitudinal (Lo) and transverse (Tr) waves, although only Lo waves contribute significantly to Brillouin scattering [1]. In PCFs, air-glass boundaries result in strong acoustic reflections and coupling between Lo and Tr acoustic waves in the core. For 532 nm light, $A_{eff} < A_{core}$ suggesting tight confinement of the optical mode to the core (verified by the simulated mode profile, Fig. 2b). Acoustic waves are generated in the core by electrostriction with strong longitudinal strains, resulting in intense backscattering. At 1550 nm, the optical field leaks into the cladding as $A_{eff} > A_{core}$ and there is greater radial diffraction of acoustic waves induced in the core by electrostriction, since longer wavelength pump light produces longer acoustic wavelengths [2]. Reflections at the glass-air boundaries couple Lo and Tr waves, forming hybrid acoustic modes, which yield different frequency shifts and produce a multi-peaked Stokes spectrum. Furthermore, the reduced proportion of pump light in the core leads to a reduction in coherent backscattered power since any pump field overlapping the air-holes will experience a different Brillouin response, raising the SBS threshold.

In conclusion, our study shows that the up-to-five-times increase in SBS threshold in small-core PCFs, arising from acoustic interactions in a confined geometry, can be eliminated by choosing a pump wavelength much smaller than the core diameter. The influence of feedback and the temporal dynamics of SBS in small-core PCFs will also be discussed. Our work paves the way to more efficient Brillouin lasers and sensors.

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