Brillouin Scattering Property in Highly Nonlinear Photonic Crystal Fiber with Hybrid-Core Structure

Weiwen Zou, Zuyuan He, and Kazuo Hotate
Department of Electrical Engineering and Information Systems, The University of Tokyo, Tokyo 113-8656, Japan
Tel: +81 5841 6779, Fax: +81 5841 6025, E-mail: {zou, ka, hotate}@sagnac.t.u-tokyo.ac.jp

Abstract: Brillouin scattering property of a highly nonlinear photonic crystal fiber with hybrid-core structure is studied. It is shown that there exist five Brillouin resonance peaks in two groups. These peaks have similarly linear dispersion characteristics and their effective acoustic velocities increase monotonically by the order of the peaks. The acousto-optic overlapping efficiency in the fiber is experimentally measured to be ~50-%. Temperature and strain dependences of the first resonance peak are also investigated.

OCIS codes: (290.5900) Scattering, stimulated Brillouin; (060.2270) Fiber characterization; (060.5295) Photonic crystal fibers

The confinement of optical and acoustic waves in an air-silica photonic crystal fiber (PCF) [1-3] is different from that in an all-silica optical fiber [4,5], which can result in different Brillouin scattering property in PCFs. It was reported that the threshold of stimulated Brillouin scattering (SBS) in a small-core PCF can be fivefold enhanced with multiple discrete resonance peaks in the Brillouin gain spectrum (BGS) [1], although multiple-peak BGS was also observed in small-core all-silica optical fibers [4,5]. McElhenny *et al.* reported that the acoustic dispersion characteristics of the resonance peaks in small-core PCFs are dependent to the order of the peaks [2], while Zhang *et al.* reported that the dispersion characteristics are not linear [3]. These results are quite unique as compared to those in all-silica optical fibers [6], and were attributed to that the longitudinal acoustic modes are coupled with the shear acoustic modes in the PCFs' core region due to the air-silica microstructure [2,3]. In this paper, we present our experimental investigation on the SBS property in a highly nonlinear photonic crystal fiber (HNL-PCF) with hybrid-core structure. We observed five Brillouin resonance peaks in two groups. All the resonance peaks show the similarly linear dispersion characteristics and have monotonically increasing effective acoustic velocities by the order of the peaks. These results are far different from the previous observations [2,3]. Additionally, we measured the acousto-optic overlapping efficiency in the HNL-PCF, and investigated the temperature- and strain-dependence of the first resonance peak in the HNL-PCF.

Shown in the inset of Fig. 1, the cross section of the hybrid-core structured HNL-PCF (Crystal Fiber A/S, NL-1550-NEG-1) comprises of a highly GeO_2-doped core (n_1 = ~1.487) surrounded by a triangularly-arranged F-doped buffer (n_2 = ~1.440) [7]. The triangular hybrid-core diameter is ~2.1 μm and the mode field diameter is ~2.8 μm. The effective refractive index (n_{eff} = 1.457) and the effective area (A_{eff} = 6.2 μm^2) are estimated approximately. The HNL-PCF (~9 m) was spliced to standard SMF pigtails (~15 cm at each end) through ~5-cm high-delta fibers for mode-field matching. The entire loss including the splicing loss and the transmission loss (~ 9 dB/km for the HNL-PCF) is ~4 dB. The experimental setup to measure the SBS is based on the pump-probe scheme as shown in Ref. [6]. The lightwave from a tunable laser source (1532~1565 nm) is divided into two via a 50/50 coupler. One is used as the pump wave that is chopped for lock-in detection and amplified to ~21 dBm by a high-power EDFA. The other is for probe wave which frequency is down-shifted to around the Brillouin frequency shift by a single-sideband modulator (SSBM) and is amplified to ~7 dBm via another EDFA.

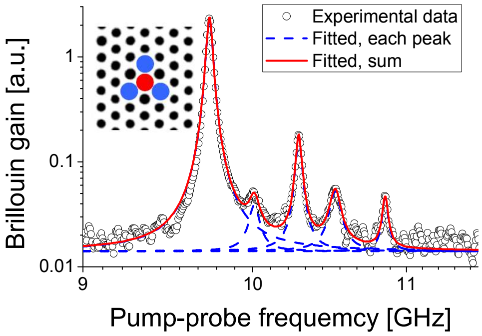

Fig. 1 The BGS of the HNL-PCF measured at 1550 nm. The inset shows the fiber's cross section.

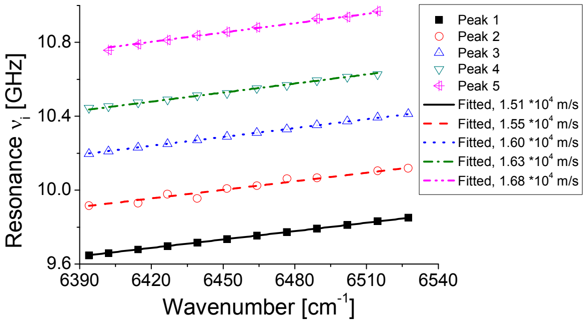

Fig. 2 Acoustic dispersion characteristics of the Brillouin resonance peaks in the HNL-PCF.

The BGS measured at 1550 nm is illustrated in Fig. 1 that exhibits five discrete resonance peaks. The five peaks can be classified into two groups due to the existence of two kinds of acoustic waveguides in the HNL-PCF. The first-kind acoustic waveguide is formed between the GeO_2-doped core and the F-doped buffer plus the air-silica microstructure, and the second-kind is formed between the buffer and the microstructure. By tuning the laser wavelength λ, we repeat the BGS measurement and evaluate each resonance frequency ($\nu_i = 2n_{eff}V_a^{\,i}/\lambda$ with $V_a^{\,i}$ the effective acoustic velocity) via five-peak Lorentz fitting (see an example in Fig. 1). Figure 2 summarizes the dispersion characteristics of all five resonance peaks, i.e. ν_i as a function of optical wave number λ^{-1}. All the peaks show good linear-dependence, which is different from the results reported in [2,3]. The dependence slopes ($k_i = 2n_{eff}V_a^{\,i}$) are obtained by the least-squares linear fitting and the effective acoustic velocities ($V_a^{\,i}$) are deduced as summarized in Table 1. It shows that five resonance peaks have monotonically increasing effective acoustic velocities by the order of the peaks. By evaluating the acoustic velocities in Ge- or F-doped regions, we can ascertain that the first and second resonance peaks are due to the first-kind acoustic waveguide, while the third, fourth, and fifth resonance peaks come from the second-kind acoustic waveguide. All these SBS property are similar to those in all-silica optical fibers [4-6].

Table 1 Summary of measured and deduced parameters of all SBS resonance peaks at 1550nm in the HNL-PCF

	Peak 1	**Peak 2**	**Peak 3**	**Peak 4**	**Peak 5**
ν_i (GHz)	**9.735**	**10.009**	**10.290**	**10.524**	**10.856**
$\Delta\nu_i$(MHz)	**38**	**71**	**40**	**77**	**40**
g_i/g_1 (dB)	**0**	**-22**	**-12**	**-17**	**-21**
$k_i * 10^4$ m/s	**1.51**	**1.55**	**1.60**	**1.63**	**1.68**
$V_a^{\,i}$ (m/s)	**5181**	**5318**	**5490**	**5593**	**5765**

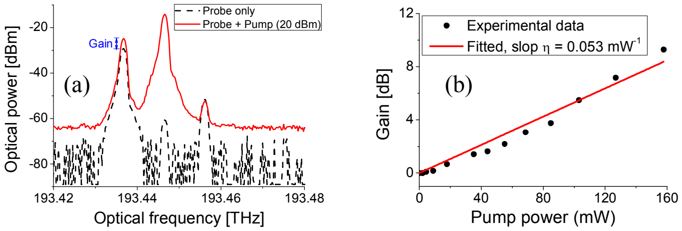

Fig. 3 (a) Example of measured optical spectra with pump wave on (solid) and off (dashed). (b) Brillouin gain of the first peak as a function of pump power.

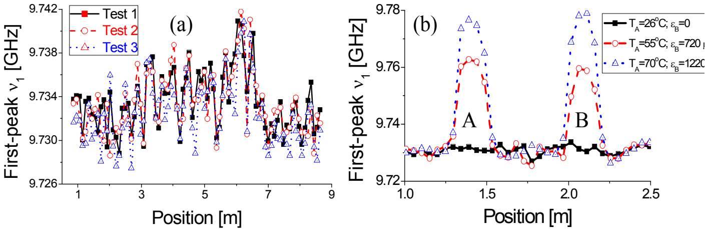

Fig. 4 (a) The ν_1 distribution of the first-peak SBS along the ~9-m HNL-PCF. (b) The ν_1 distribution around the heated and strained fiber segments.

We used an optical spectrum analyzer to measure the spectra of the probe wave at 1550 nm when the pump wave is turned off or on. An example is plotted in Fig. 3(a). The SSBM is driven at 9.735 GHz of the first-peak ν_1 and the probe power is -30 dBm. The Brillouin gain (G, in dB) is evaluated between on/off states of different pump power (P_p), which is summarized in Fig. 3(b). The Brillouin amplification rate (in mW^{-1}) is defined by $\eta = \delta G/\delta P_p = \kappa \cdot g_0 \cdot L_{eff}/A_{eff}^{ao}$ [6] where $g_0 = 1.7\times10^{-11}$ m/W is the Brillouin gain coefficient, $L_{eff} = 8.9$ m the effective length, $\kappa = 10\log10(e)$, and A_{eff}^{ao} the effective acousto-optic area. We evaluate $\eta = 0.053$ mW^{-1} by the linear fitting and deduce $A_{eff}^{ao} = 12.4$ μm^2, which means that the SBS acousto-optic overlapping efficiency is $A_{eff}/A_{eff}^{ao} = \sim 50\%$. Compared to the characterization of the SBS threshold by simply measuring the reflection power [1], our method provides higher accuracy since the influence of the reflected pump wave to the gain (G) is eliminated [see Fig. 3(a)].

Additionally, a distributed feedback laser diode under a sinusoidal frequency modulation is employed as the laser source instead to study the distributed SBS along the HNL-PCF based on Brillouin optical correlation domain analysis (BOCDA) technique [8]. The spatial resolution is ~15 cm. The measured distribution of the ν_1 of the first-peak SBS is plotted in Fig. 4(a). It is confirmed that the ν_1 fluctuation along the HNL-PCF length is less than 15 MHz. We applied several temperature changes to a ~25-cm-length segment (A) at ~1.4 m, and several static strains to a ~20-cm-length segment (B) at ~2.1 m. The distributed SBS around the two segments were repeatedly measured and the measured examples are illustrated in Fig. 4(b). The temperature and strain coefficients are estimated to be 0.99 MHz/°C and 0.038 MHz/με, which are close to those in all-silica optical fibers [6].

In conclusion, we have investigated the SBS property in the HNL-PCF. Due to the F-doped buffer in the hybrid-core structure, the BGS exhibits five resonance peaks in two groups. All five resonance peaks have similar linear dispersion characteristics, and have monotonically increasing effective acoustic velocities by peak's order. The SBS acousto-optic overlapping efficiency is ~50 %. The temperature and strain dependences of the first-peak ν_1 are 0.99 MHz/°C and 0.038 MHz/με.

[1] P. Dainese et al., *Nat. Phys.* **2**, 388-392 (2006).

[2] J. E. McElhenny et al., *J. Opt. Soc. Am. B* **25**, 582-593 (2008).

[3] W. Zhang et al., *Opt. Lett.* **32**, 2303-2305 (2007).

[4] A. Yeniay et al., *J. Lightwave Technol.* **20**, 1425–1432 (2002).

[5] W. Zou et al., *Opt. Express* **16**, 10006-10017 (2008).

[6] W. Zou et al., *Opt. Express* **16**, 18804-18812 (2008).

[7] K. Hansen, *Opt. Express* **11**, 1503-1509 (2003).

[8] K. Y. Song et al., *Opt. Lett.* **31**, 2526-2528 (2006)