Brillouin gain spectrum dependences on temperature and strain in erbium-doped optical fibers with different erbium concentrations

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Brillouin Stokes power in erbium-doped optical fibers (EDFs) can be potentially controlled by pumping, but no report has been provided on its detailed characterization. In this study, as the first step toward this goal, the Brillouin gain spectra in EDFs with three different erbium concentrations (0.72, 1.20, and 2.28 wtppt) are measured at 1.55 μm without pumping, and the Brillouin frequency shifts (BFSs) and their dependences on strain, temperature, and erbium concentration are fully investigated. In the EDF with 0.72-wtppt concentration, the BFS was 11.42 GHz, and its temperature and strain coefficients were 0.87 MHz/K and 479 MHz/%, respectively. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4806986]

Brillouin scattering is one of the most significant nonlinear phenomena in optical fibers,[1,2] and, by exploiting the dependences on Brillouin frequency shift (BFS) on temperature and strain,[3,4] it has been applied to distributed fiber-optic temperature/strain sensing for smart materials and structures. There are many parameters for evaluating the sensor performance, including spatial resolution, measurement range, measurement speed, and signal-to-noise ratio (SNR), which can be, in some cases, improved by enhancing the Brillouin signal power. For example, in the time-domain techniques,[5,6] the measurement range is limited by the optical attenuation, so it has been elongated by using Raman amplification and/or inserting optical fiber amplifiers.[7] With enhanced signal, the measurement time, which is closely related to the time of signal integration, can also be shortened. As for the correlation-domain techniques,[8–10] in Brillouin optical correlation-domain reflectometry (BOCDR),[9,10] the spatial resolution was partially limited to ~13 mm by the weak Brillouin signal,[10] and was enhanced to ~6 mm by employing a tellurite glass fiber with a high Brillouin gain coefficient, i.e., with strong Brillouin signal.[11] Thus, Brillouin signal amplification is extremely important to improve the performance of distributed sensing systems.

Another approach to enhance the Brillouin signal is to use pumped optical fibers doped with rare-earth ions, such as neodymium, thulium, samarium, holmium, ytterbium, and erbium ions. With their optical amplification capability, Brillouin signal is expected not only to be enhanced but also to be controlled at high speed by adjusting the pump light, which will be of great interest in other Brillouin application fields. Although fundamental Brillouin properties in neodymium- and thulium-doped fibers have already been investigated,[12] those in erbium-doped fibers (EDFs), which are most commonly used as key components of optical amplifiers of all the rare-earth-doped fibers,[13,14] have not been reported yet.

In this work, we measure the Brillouin gain spectra (BGS) in ~19-m-long EDFs with three different erbium concentrations (0.72, 1.20, and 2.28 wtppt) at 1.55 μm without pumping, and investigate the BFSs and their dependences not only on temperature and strain but also on erbium concentration. The BFS and its temperature and strain coefficients in the EDF with 0.72-wtppt erbium concentration were 11.42 GHz, 0.87 MHz/K, and 479 MHz/%, which decreased, increased, and decreased with increasing erbium concentration, respectively.

A light beam injected into an optical fiber interacts with acoustic phonons and generates a backscattered light beam called Stokes light.[1,2] This phenomenon is called Brillouin scattering, and the Stokes light spectrum is called BGS. The center frequency of the BGS is lower than that of the incident light by the amount called BFS. In optical fibers, the BFS ν_B is given as[2]

$$\nu_B = \frac{2 n v_A}{\lambda}, \tag{1}$$

where n is the refractive index, v_A is the acoustic velocity in the fiber, and λ is the wavelength of the incident light. The BFS is, together with v_A, known to largely change depending on temperature and strain applied to the fiber,[3,4] and has been exploited in sensors. Since the BFS and its temperature and strain dependences drastically differ according to the fiber materials and structures, they have been investigated in various kinds of special fibers to improve the sensor performance, which are well summarized in Ref. 12.

The physical properties of the three EDFs that were used in the experiment as fibers under test (FUTs) are provided in Table I. They had different erbium concentrations of 0.72, 1.20, and 2.28 wtppt, and the same cladding

TABLE I. Physical properties of EDF samples.

EDF sample No.	1	2	3
Length (m)	17.6	19	19
Erbium concentration (wtppt)	0.72 "low"	1.20 "moderate"	2.28 "high"
Mode-field diameter (μm)	7.2	7.5	7.4
Refractive index difference (%)	0.7	0.64	0.66
Peak absorption at 1.53 μm (dB/m)	18	30	57

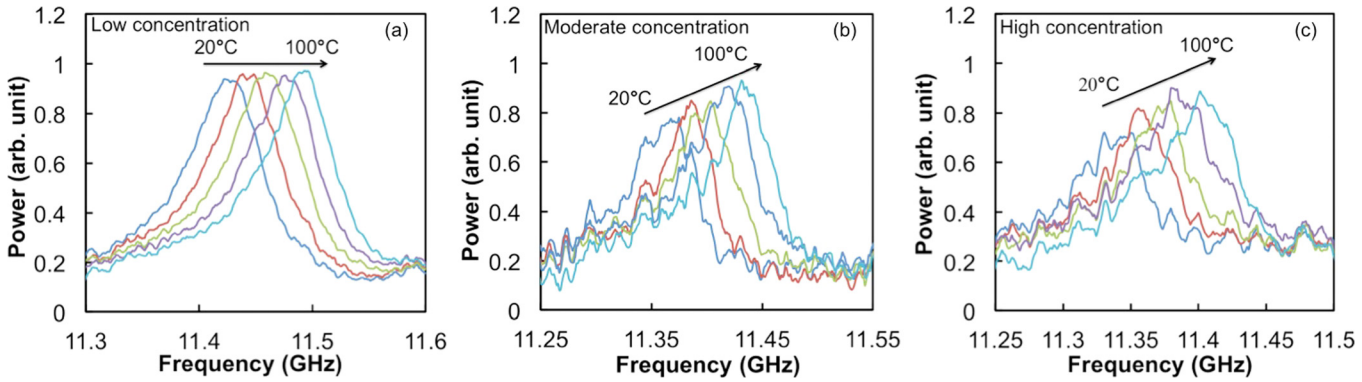

FIG. 1. Measured BGS dependences on temperature in EDFs with erbium concentrations of (a) 0.72 wtppt (low), (b) 1.20 wtppt (moderate), and (c) 2.28 wtppt (high).

refractive indices of ∼1.46. Both ends of each FUT were spliced to 1-m-long silica single-mode fibers (SMFs) with a fusion splicer (FSM-50S, Fujikura). By optimizing the arc duration, the optical loss at the spliced point was suppressed to lower than 0.1 dB. The open end of the 1-m-long SMF was immersed into matching oil ($n = 1.46$) to suppress the Fresnel reflection. The experimental setup for investigating the BGSs in EDFs was almost the same as that reported in Ref. 15 based on self-heterodyne detection. A laser diode (LD) at 1550.4 nm was used as a light source, and the optical power injected into the FUT was set to 20 dBm with an EDF amplifier (EDFA). The polarization states of the incident light and the reference light were optimized with polarization controllers (PCs). Though the Stokes light included the Brillouin signal caused in the 1-m-long SMF between the circulator and the FUT, it had no influence on this measurement, because the BFS in the SMF was ∼500 MHz lower than that in the EDF (see below). Different strains were applied to the whole length of the EDF fixed on a translation stage using epoxy glue, while the temperature along the whole length of the EDF was adjusted with a heater.

The temperature dependence of the BGS in the EDF with low erbium concentration is shown in Fig. 1(a). The temperature was controlled from 20 °C up to 80 °C with a step of 20 °C, and we utilized a Lorentzian fitting to derive the BFS from the BGS. The BFS at 20 °C was 11.42 GHz, which is ∼500 MHz higher than that of standard silica SMFs. With increasing temperature, the BFS shifted toward higher frequency. The same measurements were performed for the EDFs with moderate and high erbium concentrations, as shown in Figs. 1(b) and 1(c), where similar behavior was observed. The optical propagation losses in these EDFs at 1.55 μm (without pumping) are higher than that in the EDF with low erbium concentration, the Stokes power or the SNR was lower. Figure 2 shows the BFS dependence in the EDFs at 20 °C on erbium concentration. The error bars represent the standard errors for the measurements repeated five times. As the erbium concentration was increased, the BFS was decreased. This trend is not consistent with the fact that the BFS in standard silica SMFs (without erbium doping) is ∼10.8 GHz, which is probably caused by alumina co-doped to suppress the clustering effect of erbium ions[16,17] (note that alumina doped to some fibers is known to raise the BFS).[18] Figure 3(a) shows the measured BFS dependences in the three EDFs on temperature, from which each slope, i.e., temperature coefficient can be plotted as a function of erbium concentration, as shown in Fig. 3(b). With increasing erbium concentration, the BFS temperature coefficient was linearly decreased with a slope of −1.0 MHz/K/wtppt. The BFS temperature coefficients of ∼0.8 MHz/K were lower than those of ∼1.18 MHz in silica SMFs.[4] This is probably because the temperature coefficients of the acoustic velocities (especially, Young's moduli) in the EDFs, which dominantly determine the BFS temperature coefficients, are lower than those in silica SMFs owing to the doped erbium and co-doped alumina.

Next, the strain dependence of the BGS in the EDF with low erbium concentration was measured, as shown in Fig. 4(a). As the applied strain was increased, the BGS shifted toward higher frequency. The same measurements were performed for the other EDFs, as shown in Figs. 4(b) and 4(c), where similar behavior was observed. Figure 5(a) shows the measured BFS dependences in the three EDFs on strain, from which the dependence of the BFS strain coefficient on erbium concentration was derived, as shown in Fig. 5(b). With increasing erbium concentration, the strain coefficient was slightly enhanced with a slope of 5.92 MHz/%/wtppt. The BFS strain coefficients of ∼485 MHz/% were lower than those of ∼580 MHz/% in silica SMFs.[3] This also seems to originate from the lower strain coefficients of the Young's modulus in the EDFs than those in silica SMFs.

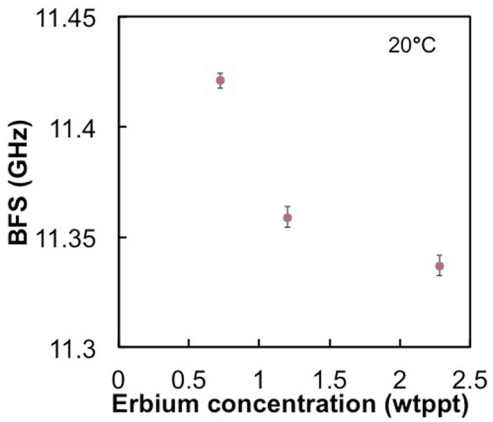

FIG. 2. BFS in EDFs at 20 °C as a function of erbium concentration.

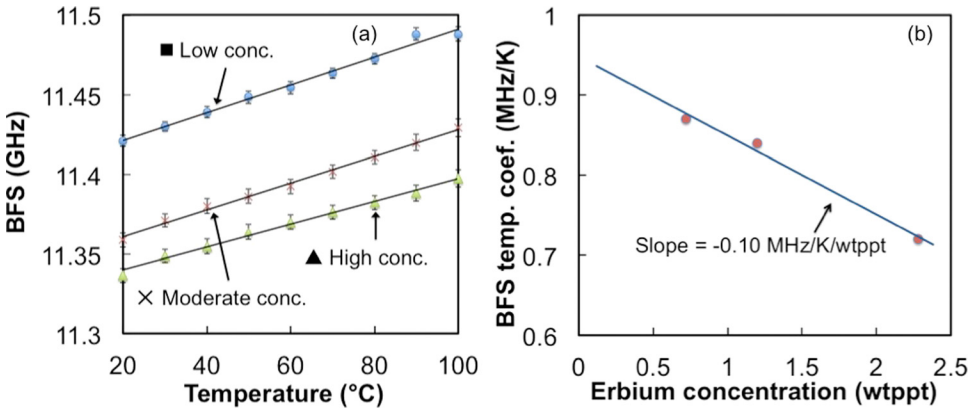

FIG. 3. (a) Temperature dependences of BFS in EDFs with different erbium concentrations. (b) Temperature coefficient of BFS in EDFs as a function of erbium concentration.

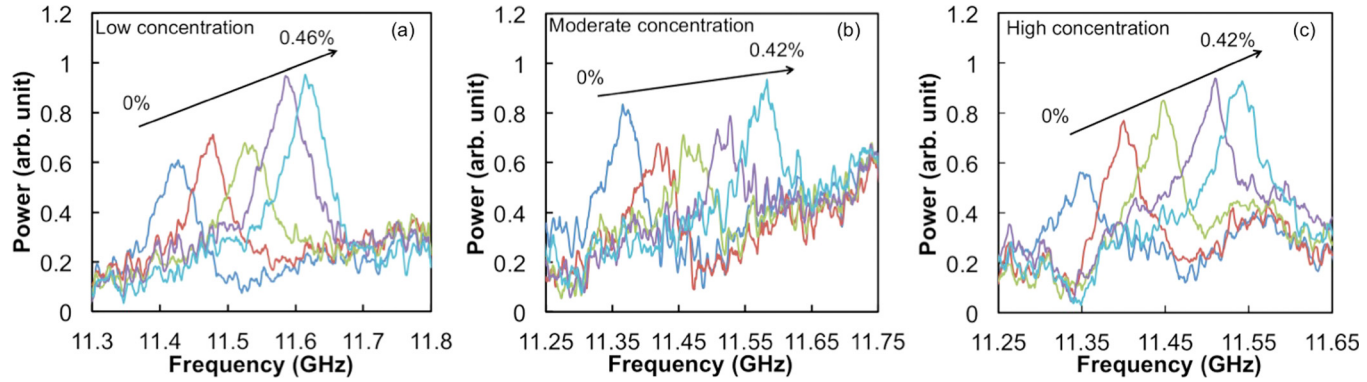

FIG. 4. Measured BGS dependences on strain in EDFs with erbium concentrations of (a) 0.72 wtppt (low), (b) 1.20 wtppt (moderate), and (c) 2.28 wtppt (high).

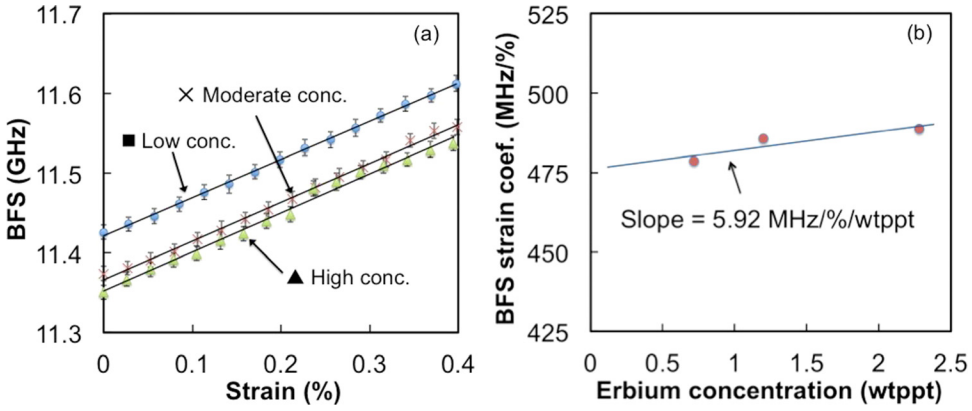

FIG. 5. (a) Measured BFS dependence on strain in EDFs with different erbium concentrations. (b) Strain coefficient of BFS in EDFs as a function of erbium concentration.

In conclusion, we measured the BGSs in EDFs with three different erbium concentrations at 1.55 μm without pumping, and fully investigated the BFSs and their dependences on strain, temperature, and erbium concentration. In the EDF with low erbium concentration (0.72 wtppt), the BFS and its temperature and strain coefficients were 11.42 GHz, 0.87 MHz/K, and 479 MHz/%, which were found to be controlled to some extent by adjusting the erbium concentration. We believe these measurement results will be useful as a fundamental archive in developing pumped-EDF-based Brillouin sensors as well as in controlling the Brillouin properties (at least, the Stokes power) at high speed by adjusting the pump light. To fully clarify the pumping effect on the BGS in EDFs is an urgent necessity.

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[1]E. P. Ippen and R. H. Stolen, Appl. Phys. Lett. **21**, 539 (1972).
[2]G. P. Agrawal, *Nonlinear Fiber Optics* (Academic Press, New York, 1995).
[3]T. Horiguchi, T. Kurashima, and M. Tateda, IEEE Photon. Technol. Lett. **1**, 107 (1989).
[4]T. Kurashima, T. Horiguchi, and M. Tateda, IEEE Photon. Technol. Lett. **2**, 718 (1990).

[5]T. Horiguchi and M. Tateda, J. Lightwave Technol. **7**, 1170 (1989).
[6]T. Kurashima, T. Horiguchi, H. Izumita, S. Furukawa, and Y. Koyamada, IEICE Trans. Commun. **E76–B**, 382 (1993).
[7]X. Jia, Y. Rao, L. Chang, C. Zhang, and Z. Ran, J. Lightwave Technol. **28**, 1624 (2010).
[8]K. Hotate and T. Hasegawa, IEICE Trans. Commun. **E83-C**, 405 (2000).
[9]Y. Mizuno, W. Zou, Z. He, and K. Hotate, Opt. Express **16**, 12148 (2008).
[10]Y. Mizuno, Z. He, and K. Hotate, IEEE Photon. Technol. Lett. **21**, 474 (2009).
[11]Y. Mizuno, Z. He, and K. Hotate, Opt. Commun. **283**, 2438 (2010).
[12]Y. Mizuno, N. Hayashi, and K. Nakamura, J. Appl. Phys. **112**, 043109 (2012).
[13]E. Desurvire, J. R. Simpson, and P. C. Becker, Opt. Lett. **12**, 888 (1987).
[14]R. J. Mears, L. Reekie, I. M. Jauncey, and D. N. Payne, Electron. Lett. **23**, 1026 (1987).
[15]Y. Mizuno and K. Nakamura, Appl. Phys. Lett. **97**, 021103 (2010).
[16]B. J. Ainslie, J. Lightwave Technol. **9**, 220 (1991).
[17]P. Myslinski, D. Nguyen, and J. Chrostowski, J. Lightwave Technol. **15**, 112 (1997).
[18]P. Dragic, T. Hawkins, P. Foy, S. Morris, and J. Ballato, Nat. Photonics **6**, 627 (2012).