Characterization of Brillouin Gain Spectra in Polymer Optical Fibers Fabricated by Different Manufacturers at 1.32 and 1.55 μm

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***Abstract*— We characterize the Brillouin gain spectra (BGS) in perfluorinated graded-index polymer optical fibers (PFGI-POFs) at 1.32 μm and 1.55 μm. Three kinds of PFGI-POFs with the same core diameter, but which are fabricated by different manufacturers, are tested. For all the PFGI-POFs, the Stokes power measured at 1.32 μm is higher than that at 1.55 μm due to the lower propagation loss, but significant differences in Stokes power are observed among the three. Based on the measurement obtained by the optical time-domain reflectometry, we show that the actual propagation loss of the PFGI-POFs plays a crucial role in observing BGS.**

***Index Terms*— Brillouin gain spectrum (BGS), Brillouin scattering, nonlinear optics, polymer optical fiber (POF).**

I. Introduction

BRILLOUIN scattering is one of the most significant nonlinear processes in optical fibers, and has been the focus of many theoretical and experimental investigations for several decades [1], [2]. So far, a number of applications of Brillouin scattering have been reported, such as lasing [2], signal processing [3], slow light generation [4], optical storage [5], core alignment [6], and strain/temperature sensing [7]–[10]. In order to improve their performance, not only Brillouin scattering in silica single-mode fibers (SMFs) but also that in various kinds of specialty fibers has been extensively studied. They include silica multimode fibers [11], tellurite glass fibers [12], chalcogenide glass fibers [13], bismuth-oxide glass fibers [14], and photonic crystal fibers [15]. Recently, we successfully observed Brillouin scattering at 1.55 μm in polymer optical fibers (POFs) [16], which offer extremely high flexibility, low-cost and easy connection, and high safety compared to other glass fibers. The POFs used in the experiment were perfluorinated graded-index (PFGI-) POFs based on cyclic transparent optical polymer (CYTOP). Their Brillouin gain coefficient was estimated to be approximately 3.09×10^{-11} m/W, which was almost the same as that of silica SMFs. We also investigated the dependences of the Brillouin frequency shift (BFS) on strain and temperature in a PFGI-POF at 1.55 μm, and found that Brillouin scattering in PFGI-POFs can be potentially utilized to develop high-accuracy temperature sensors with reduced strain sensitivity [17].

In general, Brillouin scattering properties vary depending on the structure especially of the fiber core, including materials, diameter, and fabrication method. Up to now, BFS in polymethyl methacrylate (PMMA)-based POFs and its strain and temperature dependences have been estimated and compared with those of PFGI-POFs [18], [19], which partially revealed the effect of employing different core materials. The influence of the core diameter on BGS in PFGI-POFs has also been investigated [20]. However, no study has been reported on how BGS in PFGI-POFs is influenced by their fabrication method, which is of great importance in selecting optimal POFs for future Brillouin applications.

In this letter, the BGS in PFGI-POFs fabricated with different methods is investigated. Three kinds of PFGI-POFs with the same core diameter provided by different manufacturers are tested at 1.32 and 1.55 μm. For all the PFGI-POFs, the Stokes power measured at 1.32 μm is higher than that at 1.55 μm, but large difference in Stokes power is observed among the three PFGI-POFs. Based on the measurement by optical time-domain reflectometry (OTDR), we conclude that the actual propagation loss of the PFGI-POFs plays a vital role in BGS observation.

II. Principle

Spontaneous Brillouin scattering (SpBS) occurs when pump light is Bragg-reflected by the refractive-index modulations generated by acoustic phonons. The backscattered Stokes light suffers a Doppler shift called BFS, ν_B, which is given by [2]

$$\nu_B = \frac{2\, n_{\text{eff}}\, v_A}{\lambda_p} \tag{1}$$

where n_{eff} is the effective core refractive index, v_A is the acoustic velocity, and λ_p is the wavelength of the pump light.

When the power of the pump light is higher than Brillouin threshold power P_{th}, stimulated Brillouin scattering (SBS) is induced, leading to the drastic enhancement in Stokes power. The lower P_{th} is, the higher the Stokes power at the same

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TABLE I
PHYSICAL PROPERTIES OF THE PFGI-POFs. L, FIBER LENGTH; d, CORE DIAMETER; n_{eff}, EFFECTIVE CORE REFRACTIVE INDEX; NA, NUMERICAL APERTURE; α, NOMINAL PROPAGATION LOSS DEDUCED FROM ATTENUATION SPECTRUM; L_{eff}, CALCULATED EFFECTIVE FIBER LENGTH

Fiber	A	B	C
Manufacturer	Asahi glass	Sekisui chemical	Chromis fiberoptics
L (m)	103	200	200
d (μm)	62.5	62.5	62.5
n_{eff}	~1.35	~1.35	~1.35
NA	0.185	0.185	0.185
α (dB/m)gt 1.32 μm	0.025	0.025	0.025
α (dB/m)gt 1.55 μm	0.25	0.25	0.25
L_{eff} (m)gt 1.32 μm	77.76	118.94	118.94
L_{eff} (m)gt 1.55 μm	17.82	17.87	17.87

pump power is, and so P_{th} can be used as an indicator for roughly evaluating the Stokes power. P_{th} is given by [2]

$$P_{\mathrm{th}} = \frac{21\, b\, A_{\mathrm{eff}}}{K\, g_B\, L_{\mathrm{eff}}} \qquad (2)$$

where b is the correction factor for multimode fibers [21], A_{eff} the effective cross-sectional area, K the polarization coefficient, g_{B} the Brillouin gain coefficient, and L_{eff} the effective fiber length defined as $L_{\mathrm{eff}} = [1-\exp(-\alpha L)]/\alpha$ (α, propagation loss; L, fiber length) [2]. In evaluating the Stokes power of the fibers having the same numerical aperture (NA) and core diameter, if we neglect the wavelength dependence on g_{B}, L_{eff} is the most dominant in Eq. (2), because b and A_{eff} are basically functions only of NA [21] and of core diameter [22], respectively.

III. EXPERIMENTAL SETUP

Three kinds of PFGI-POFs, denoted by A, B, and C, were used as the fibers under test (FUTs). Their physical properties are summarized in Table I. Although they were fabricated by different manufacturers, they had almost the same core diameter d, effective core refractive index n_{eff}, NA, and propagation loss α both at 1.32 μm and at 1.55 μm (Note that α was not actual loss but nominal loss deduced from the attenuation spectrum of CYTOP [23]). Due to the difference in fiber length L, the effective lengths L_{eff} were also different.

The experimental setup is depicted in Fig. 1. As a light source, either a neodymium: yttrium aluminum garnet (Nd: YAG) laser at 1320 nm or a distributed-feedback (DFB) laser at 1547 nm was employed. The output of the laser was divided into two: pump light and reference light. The pump light was injected into the FUT, one end of which was polished and optically butt-coupled to the silica SMF. The power of the pump light was adjusted to 20 dBm using, if necessary, an erbium-doped fiber amplifier (EDFA). The Stokes light was mixed with the reference light, the power of which was controlled with a variable optical attenuator (VOA). The optical beat signal was converted to an electrical signal

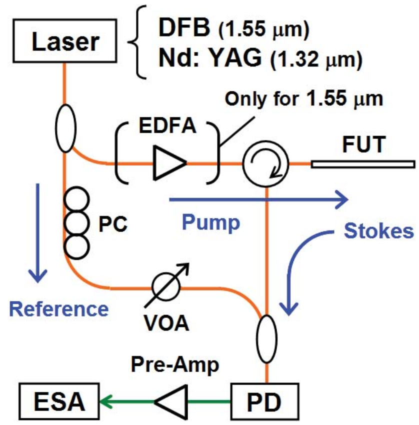

Fig. 1. Experimental setup. DFB: distributed-feedback. EDFA: erbium-doped fiber amplifier. ESA: electrical spectrum analyzer. FUT: fiber under test. Nd:YAG: neodymium:yttrium aluminum garnet. PC: polarization controller. PD: photo-detector. VOA: variable optical attenuator.

with a photo-detector (PD), and amplified by 23 dB with an electrical pre-amplifier. Finally, it was detected with an electrical spectrum analyzer (ESA); and thus, the BGS can be observed with high resolution.

IV. EXPERIMENTS

Figure 2 shows the measured BGS of the three FUTs at 1.32 and 1.55 μm. The pump power was 20 dBm, and the polarization state was optimized for each measurement. At 1.55 μm, nearly identical BGS was observed for A and B, but no BGS was obtained for C. The center frequency of the BGS, i.e., the BFS, was ~2.8 GHz, which agrees well with the previous reports at 1.55 μm [16], [17]. In contrast, at 1.32 μm, the obtained Stokes power was much higher than that at 1.55 μm for all the three FUTs. Even for C, small but clear BGS was observed. The BFS of ~3.3 GHz is in good agreement with the theoretical value of 3.28 GHz, which was calculated using Eq. (1) under the assumption that n_{eff} and υ_A are independent of λ_p. The Stokes power enhancement for all the FUTs was mainly caused by the wavelength dependence of their propagation loss [23], so we predict that, if pump light at 1.10 or 1.20 μm (α ~0.01 dB/m) is used, the Stokes power will be further enhanced.

Another important feature in Fig. 2 is that, both at 1.32 μm and at 1.55 μm, the measured Stokes power for A, B, and C was not consistent with L_{eff} shown in Table I, which was calculated using nominal loss α. For instance, though L_{eff} is almost the same for all the three FUTs at 1.55 μm, BGS was not observed for C. Also, though L_{eff} of A at 1.32 μm is smaller than that of B, the measured Stokes power of A at 1.32 μm was a little higher than that of B. This inconsistency seems to originate from the fact that the nominal loss α used to calculate L_{eff} does not necessarily agree with the actual loss in the FUTs.

In order to clarify this point, Rayleigh-based photon-counting OTDR measurement was performed at 1.31 μm for the three FUTs: A, B, and C. Measurement time was <3 minutes for each FUT. Figure 3 shows the results, which confirm that the actual propagation loss, i.e., the slope of the

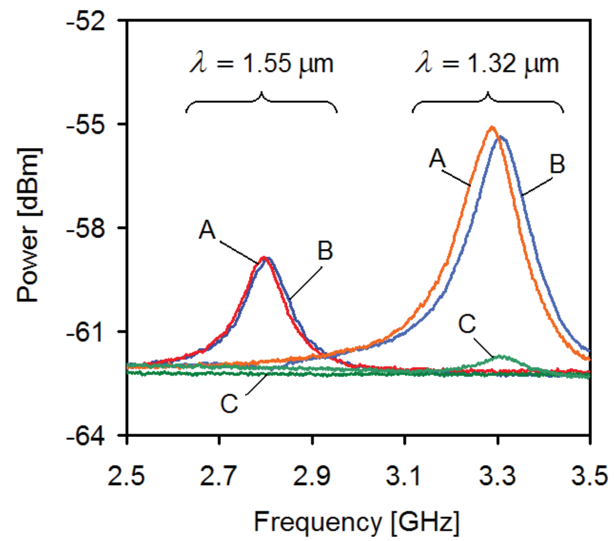

Fig. 2. Measured BGS for the FUT A, B, and C at 1.32 μm and 1.55 μm.

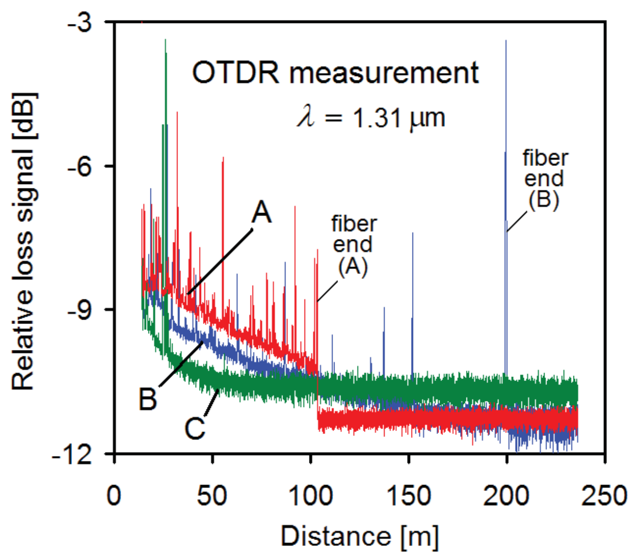

Fig. 3. OTDR measurement results for the FUT A, B, and C at 1.31 μm.

curve, of C is over 3 times higher than those of A and B. The actual loss seems to be nearly the same ($\sim\alpha$) for A and B, but B has a damaged point at ~25-m position. These results explain the inconsistency of the BGS measurement, showing that undamaged PFGI-POFs with low actual propagation loss (leading to low P_{th}) should be employed to obtain as high Stokes power as possible.

V. Conclusion

We investigated the BGS in three PFGI-POFs fabricated by different manufacturers at 1.32 and 1.55 μm. For all the PFGI-POFs, the Stokes power measured at 1.32 μm was higher than that at 1.55 μm due to the lower propagation loss, but striking difference in Stokes power was observed among the three. Then we performed OTDR measurement to clarify the reason for the difference, and showed that the actual propagation loss of the PFGI-POFs plays an extremely important role in BGS observation. We believe these results will be of great use in selecting POFs suitable for Brillouin applications in future.

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