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Enhancement of Brillouin Scattering Signal in Optical Fibers by Use of Pulsed Pump Light

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We propose a new method of enhancing the Brillouin scattering signal with a relatively low-cost low-power erbium-doped fiber amplifier by using pulsed pump light. When a pulsed pump light with an average optical power of 20 mW, a duty ratio of 20%, and a pulse period of 2 µs was injected into a 1-km-long silica single-mode fiber, the Brillouin signal was enhanced by 25 dB relative to that with a continuous-wave pump light having the same average power. We believe that this method can also be used to enhance the weak Brillouin scattering signal in polymer optical fibers for its detailed characterization. © 2012 The Japan Society of Applied Physics

Brillouin scattering in optical fibers[1,2] is one of the most significant nonlinear effects, and has been extensively studied. It has many useful applications, such as lasing,[3] microwave signal processing,[4] slow light generation,[5] phase conjugation,[6] tunable delay,[7] core alignment,[8] optical storage,[9] and strain/temperature sensing.[10–15] Up to now, Brillouin scattering has been studied not only for glass optical fibers (GOFs) but also for polymer optical fibers (POFs), including poly(methyl methacrylate) (PMMA)-based POFs[16] and perfluorinated graded-index (PFGI-) POFs.[17–20] Brillouin scattering in PFGI-POFs was experimentally observed at 1.55 µm,[17] but the signal was quite small due to their large core diameter and high propagation loss compared with those of GOFs. In order to enhance the Brillouin signal in POFs for more accurate characterization, a high-power pump light needs to be employed. However, commercially available high-power optical fiber amplifiers such as erbium-doped fiber amplifiers (EDFAs) are expensive.

In this paper, we propose a new method of enhancing the Brillouin scattering signal only with a relatively low-cost low-power EDFA by use of a pulsed pump light, and demonstrate its effectiveness using silica single-mode fibers (SMFs). [Note that, in Brillouin optical time-domain reflectometry (BOTDR),[10,11] the pulsed pump light has already been used to spatially resolve the measurement spot, but no detailed study on its signal enhancement effect for accurate Brillouin characterization has been reported.] We show both theoretically and experimentally that, even when the pulsed pump light has low average power, if its peak power is higher than the Brillouin threshold power, the temporally averaged Brillouin scattering signal can be enhanced. When a pulsed pump light with an average optical power of 20 mW, a duty ratio of 20%, and a pulse period of 2 µs was used, the Brillouin signal was enhanced by 25 dB relative to that with continuous-wave (CW) pump light having the same average power.

The dependence of Brillouin Stokes power on CW pump power is known to be nonlinear;[2] the Stokes power begins to grow exponentially when the pump power is higher than the Brillouin threshold power P_{th}, and then reaches saturation. This behavior indicates the transition from spontaneous to stimulated Brillouin scattering (SBS). P_{th} of an SMF is given by[2]

$$P_{\mathrm{th}} = \frac{21 A_{\mathrm{eff}}}{K g_{\mathrm{B}} L_{\mathrm{eff}}}, \tag{1}$$

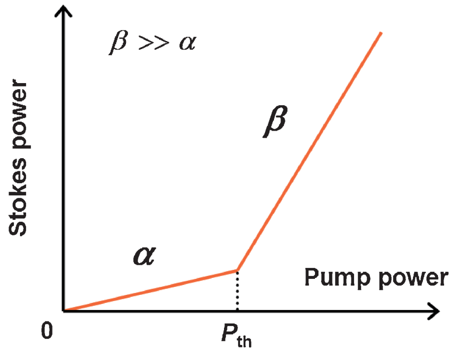

Fig. 1. Two-state model of the Stokes power dependence on pump power. Both axes are in linear scale.

where A_{eff} is the effective cross-sectional area, g_{B} is the Brillouin gain coefficient, and L_{eff} is the effective length defined as

$$L_{\mathrm{eff}} = \frac{1 - \exp(-\alpha L)}{\alpha}, \tag{2}$$

where α is the propagation loss and L the fiber length. K is a polarization-dependent constant, which is 0.667 when the polarization is not maintained.

When a pulsed pump light with its peak power higher than P_{th} is employed, the temporally averaged Stokes power can be enhanced compared with that with a CW pump light having the same average power. Such pulsed pump light with a high peak power can be generated with a low-power EDFA, which typically has a small-signal gain of about 20 to 40 dB and a saturation output power of about 10 to 20 dBm. In the pulsed regime, as long as the average output power does not exceed the saturation output power, the input pulsed light even with several mW peak power experiences the small-signal gain. This condition can be satisfied by sufficiently decreasing the pulse duty ratio, and thus, pulsed pump light with (sub-)watt-range peak power can be obtained.

Prior to experiments, we theoretically analyzed the effectiveness of this method. The Stokes power dependence on pump power was approximated using a simple two-state model as shown in Fig. 1, where α and β represent the slopes of the lines ($\beta \gg \alpha$). The average input power P_{in}, corresponding to the output power of a low-power EDFA, was assumed to be lower than the Brillouin threshold power P_{th}.

When the pump light is CW, the Stokes power is given by

$$P_{\mathrm{Stokes}} = \alpha \cdot P_{\mathrm{in}}. \tag{3}$$

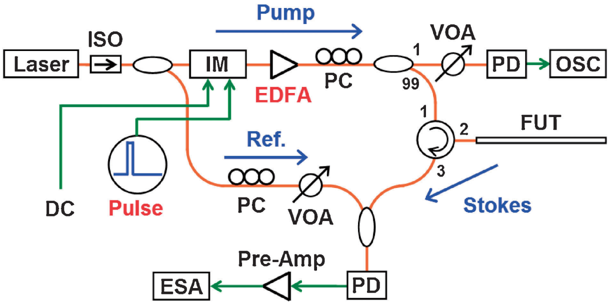

Fig. 2. Experimental setup. DC, direct current; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FUT, fiber under test; IM, intensity modulator; ISO, isolator; OSC, oscilloscope; PC, polarization controller; PD, photodiode; VOA, variable optical attenuator.

When the pump light is ideally pulsed, its peak power is given by

$$P_{\text{peak}} = P_{\text{in}} \cdot \frac{100}{x}, \tag{4}$$

where x is the duty ratio (in %). When P_{peak} is lower than or the same as P_{th}, the temporally averaged Stokes power is given by

$$P_{\text{Stokes}} = \alpha \cdot P_{\text{peak}} \cdot \frac{x}{100} = \alpha \cdot P_{\text{in}}, \tag{5}$$

which is the same as eq. (3). In contrast, when P_{peak} is higher than P_{th}, the Stokes power is given by

$$\begin{aligned} P_{\text{Stokes}} &= [\alpha \cdot P_{\text{th}} + \beta \cdot (P_{\text{peak}} - P_{\text{th}})] \cdot \frac{x}{100} \\ &= \beta \cdot P_{\text{in}} - (\beta - \alpha) \cdot P_{\text{th}} \cdot \frac{x}{100}. \end{aligned} \tag{6}$$

Here, the pulse width dependence of P_{th}[21] is not considered for simplicity. Using $\beta \gg \alpha$, eq. (6) can be further simplified as

$$P_{\text{Stokes}} = \beta \cdot \left(P_{\text{in}} - P_{\text{th}} \cdot \frac{x}{100}\right), \tag{7}$$

which indicates that, as the duty ratio decreases, the Stokes power increases, finally reaching βP_{in}. Thus, it was theoretically shown that, when P_{in} is lower than P_{th}, the Stokes signal can be enhanced by reducing the duty ratio of the pulsed pump light so that its peak power is higher than P_{th}.

The experimental setup is depicted in Fig. 2. In order to measure the Brillouin gain spectrum (BGS) with high resolution, self-heterodyne detection[17] was used. All the optical paths were composed of silica SMFs. A distributed-feedback laser diode (DFB-LD) at 1547 nm was used as a light source, and its output was divided into two light beams with a coupler. One of the beams was directly used as the reference light of heterodyne detection, after passing a polarization controller (PC) and a variable optical attenuator (VOA). The other beam was converted to optical pulses with a LiNbO_3 intensity modulator (IM) having an extinction ratio of over 20 dB, amplified with a low-power EDFA having a small-signal gain of 35 dB, and injected into a fiber under test (FUT) as pump light. Part of the pump light was directly guided to a photodiode (PD) after passing a VOA, and its waveform was monitored with an oscilloscope (OSC) to optimize the input voltages to the IM. Then, the optical beat signal between the Stokes light and the reference light was converted to an electrical signal with a PD. Finally, the signal was amplified by 23 dB with an electrical preamplifier, and monitored with an electrical spectrum analyzer (ESA).

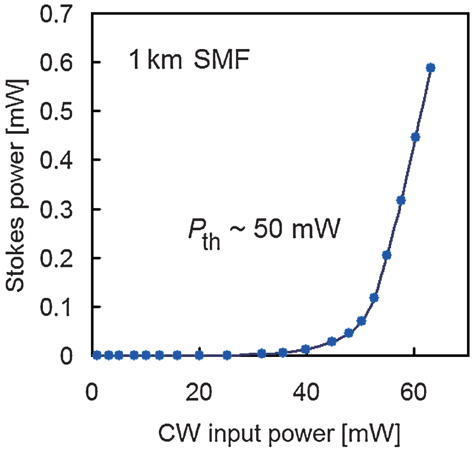

Fig. 3. Measured Stokes power dependence on CW pump power.

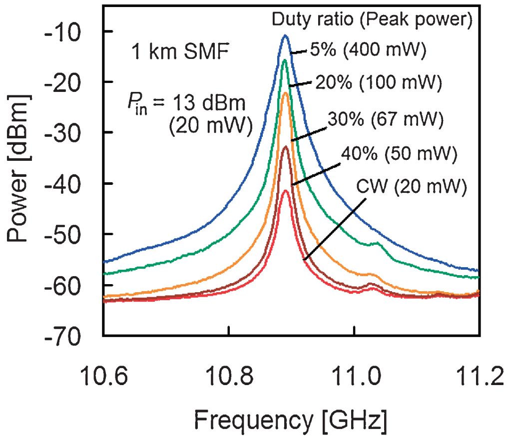

Fig. 4. Measured BGS with the duty ratio varied from 100 (CW) to 5%.

First, a 1-km-long silica SMF was used as an FUT. The Brillouin threshold P_{th} of this FUT was approximately 50 mW, as shown in Fig. 3. This is in good agreement with the theoretical value of 53 mW, which was obtained by substituting in eqs. (1) and (2) the following typical values for silica SMFs:[2] $A_{\text{eff}} = 50\,\mu\text{m}^2$, $g_{\text{B}} = 3 \times 10^{-11}$ m/W, and $\alpha = 0.2$ dB/km.

Figure 4 shows the measured BGS when the output power of the EDFA, i.e., the average power of the pump light, was set to 13 dBm (= 20 mW $<$ P_{th}). The pulse period was fixed at 2 µs, and the duty ratio was varied from 100 (CW) to 5%. When the duty ratio was 40%, the calculated peak power was almost the same as P_{th}. As the duty ratio decreased, the Stokes power was enhanced.

Figure 5 is the Stokes power dependence on the duty ratio. When the duty ratio became lower than 40 mW (i.e., when the peak power became lower than P_{th}), the Stokes power began to grow drastically, and it gradually reached saturation at approximately −10 dBm. The former behavior

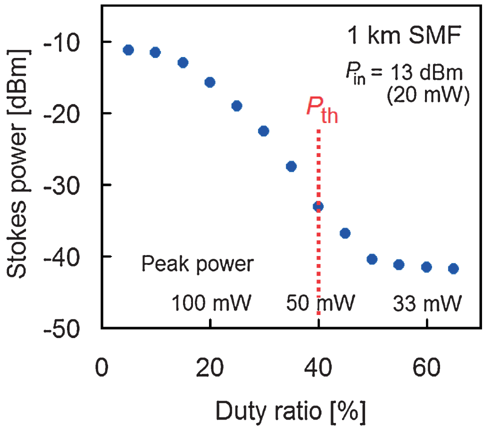

Fig. 5. Measured Stokes power dependence on duty ratio.

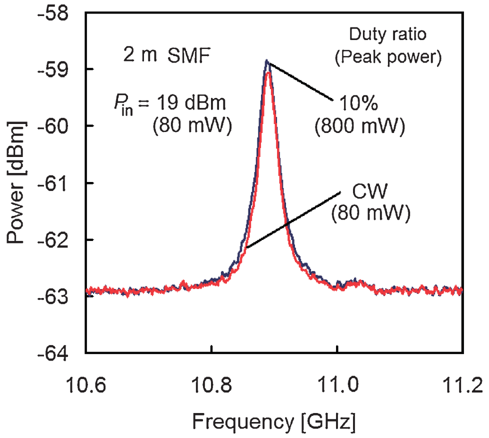

Fig. 6. Measured BGS when the pump light was CW (red) and pulsed (blue) with 10% duty ratio.

can be well explained by eq. (7), while the latter behavior can be understood by the saturation of exponential growth in Stokes power with the increasing pump power.[2] Thus, drastic enhancement (>25 dB) of the Stokes power was achieved when the duty ratio was lower than 20%.

Then, a 2-m-long silica SMF was also used as an FUT, the theoretical $P_{\rm th}$ of which was 26.2 W. Figure 6 shows the measured BGS with CW pump light and with pulsed pump light with 10% duty ratio. The average power of the pump light was set to 19 dBm (= 80 mW), and the calculated peak power of the pulsed pump light was 800 mW. Although this is much lower than $P_{\rm th}$, with the pulsed pump light, the Stokes power was slightly enhanced relative to that with CW. This probably originates from the nonlinearity of the Stokes power dependence on CW pump power even within the range below $P_{\rm th}$.

In conclusion, a new scheme for enhancing Brillouin Stokes power was developed, which exploits pulsed pump light and a low-power EDFA. First, it was theoretically shown that, even when the pulsed pump light has low average power, the temporally averaged Stokes power can be enhanced if its peak power is higher than the Brillouin threshold power. Then, in the experiment, when a pulsed pump light with an average power of 20 mW, a duty ratio of 20%, and a pulse period of 2 μs was injected into a silica SMF, the Stokes power was enhanced by 25 dB relative to that with CW pump light having the same average power. We believe that this method will provide a useful and cost-effective way of characterizing the Brillouin scattering properties in POFs, such as Brillouin frequency shift (BFS) and its dependence on strain, temperature, moisture, and core materials.

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