Dependence of stimulated Brillouin scattering in pulsed fiber amplifier on signal linewidth, pulse duration, and repetition rate

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The dependencies of stimulated Brillouin scattering (SBS) threshold in pulsed fiber amplifiers on spectral linewidth, pulse duration, and repetition rate are measured and discussed. Experimental results show that the SBS threshold is highly related to spectral linewidth and pulse duration. Therefore, the power handling limitation in a pulsed fiber amplifier may be the average power in some cases and the peak power in others.

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High-power pulsed fiber lasers with narrow-linewidth can be employed widely in several applications such as LIDAR, remote sensing, nonlinear frequency generation, coherent beam combining, and others[1−3]. However, the output power of the fiber laser is mainly limited by its nonlinearities such as stimulated Brillouin scattering (SBS)[4,5]. SBS leads to backward-propagated stokes in an optical beam. This is potentially destructive as it can reduce output optical efficiency. SBS has the lowest threshold among nonlinear effects in the fiber amplifier of narrow linewidth systems[5,6]. Thus, this topic has gained research interest due to its importance in fiber amplifiers. The SBS threshold in continuous wave (CW) fiber amplifiers is predictable, because it has been widely researched. The SBS threshold is mainly dependent on the laser signal linewidth, the effective area of the mode, and the length of the fiber, among others[5,7−9]. However, this dependency is more complicated in pulsed fiber amplifiers[1,6,10−13]. It has been proposed that SBS can be prevented by simply reducing pulse duration to below 16 ns[5,6]. This assumption, however, has not been proven experimentally. The dependence of SBS on signal linewidth for a CW-operated fiber laser[14], to our knowledge, has not yet been done for pulsed laser.

Notably, Sjöberg *et al.*[10] studied SBS dependence on pulse using a Q-switched laser with durations ranging from 20 to 60 ns. However, they used passive fiber in that study. Thus, the property of SBS in a gain medium could not be treated as equal. As mentioned above, it is important to study in detail the dependencies of SBS in pulsed fiber amplifier on signal linewidth, pulse duration, and repetition rate.

In this letter, we conducted a detailed experimental study of the SBS threshold in pulsed fiber amplifiers. We obtained pulsed lasers with different pulse durations and repetition rates as well as CW lasers with different linewidths using electro-optic modulator (EOM) and a phase modulator (P-M), respectively. These lasers were amplified in a single-mode fiber (SMF) amplifier, and the SBS thresholds were measured. The dependence of the SBS threshold in pulsed fiber amplifiers on spectral linewidth, pulse duration, and repetition rate were discussed based on the measurements.

The experimental setup for SBS threshold measurements is shown in Fig. 1. In our system, we used a commercial CW seed at 1 064 nm with a linewidth of ∼20 kHz and an output power of ∼50 mW[15]. The $LiNbO_3$ P-M was connected to the CW seed in order to broaden the linewidth of the CW laser[16]. This process enabled more than 20-mW power to be delivered from the P-M because P-M loss was about 3 dB. The narrow linewidth pulsed laser was achieved when the EOM was connected to the CW seed[17]. The EOM had an optical handling power of 100 mW and a high bandwith of >10 GHz. The average power of the pulsed laser after the EOM was 0.3–2 mW due to EOM loss. We used a fiber pre-amplifier (FPA1) to amplify the average power to about 3–15 mW. Both the EOM and P-M were driven by a function generator (FG).

FPA2 was used to amplify the pulsed/CW laser to about 50 mW. A 99/1 coupler (coupler 1) was connected to FPA2. Both pre-amplifiers were based on single-mode Yb-doped fiber (SM YDF: NA=0.11, core diameter is 6 μm) with a length of 1 m. The YDFs were core-pumped by SMF pigtailed at 976-nm laser diodes (LDs) via wavelength division multiplexing (WDM). The pulse shape and linewidth were detected using a photoelectric detector (PD) and Fabry-Perot (F-P) interferometer from

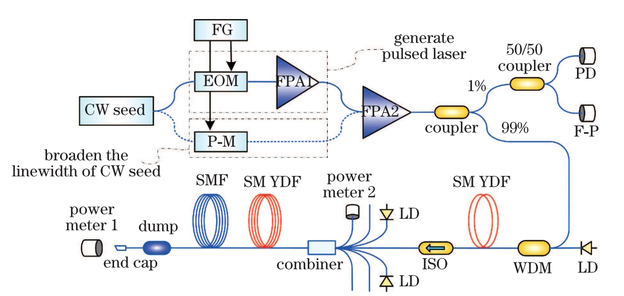

Fig. 1. Experimental setup.

the 1% port of coupler 1. The 99% port of coupler 1 was followed by a two-stage all-fiber cascade amplifier. The first-stage amplifier, which was based on SM YDF (NA = 0.11, core diameter is 6 μm) with a length of 1.2 m, amplified the pulsed/CW laser to about 200 mW of average power. We used the fiber isolator (ISO) in the system to protect the components by preventing backscattering light. The main amplifier was clad-pumped by 2 multimode double-clad fiber pigtailed at 976 nm LDs via a (6+1)×1 signal/pump combiner. The gain fiber was SM YDF with a core diameter of 5 μm, a cladding diameter of 130 μm, and a length of 11 m. A power meter (power meter 1), which was connected to an unused pump port of the combiner, was used to monitor the backward light. The power of the backward light non-linearly increases compared with the output power when the SBS threshold arrives in the main amplifier. A SMF with a length of 20 m was connected to the YDF to decrease the SBS threshold of the system. The unabsorbed pump power was dumped at the end of the SM fiber, and a fiber end cap was arranged at the output port at an angle of ~8 °C to avoid signal feedback and prevent end facet damage. The average power was tested by another power meter (power meter 2).

Connecting the CW seed to the P-M channel facilitates the broadening of the linewidth of the CW laser through phase modulation[18]. The linewidth of the laser sent out from coupler 2 was confirmed using a F-P interferometer. A laser spectrum was generated when the F-P interferometer was scanned over the free spectral range (FSR) of 4 GHz (the resolution limit of this F-P interferometer was ~4 MHz) (Fig. 2). In Fig. 2, CW and 10-MHz/cw represent the power characteristic of the CW laser without modulation and the CW laser phase modulated by sine wave signal with a 10-MHz frequency, respectively. Results show that the seed is a single-frequency laser,

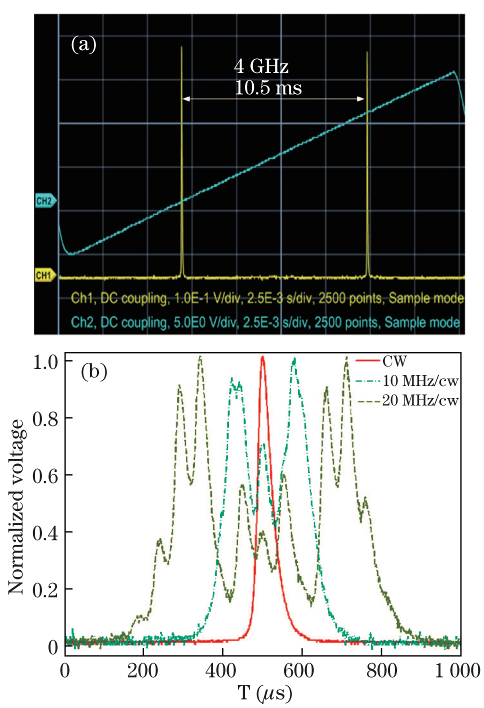

Fig. 2. Spectra of the (a) CW seed and (b) phase-modulated CW laser over a F-P interferometer.

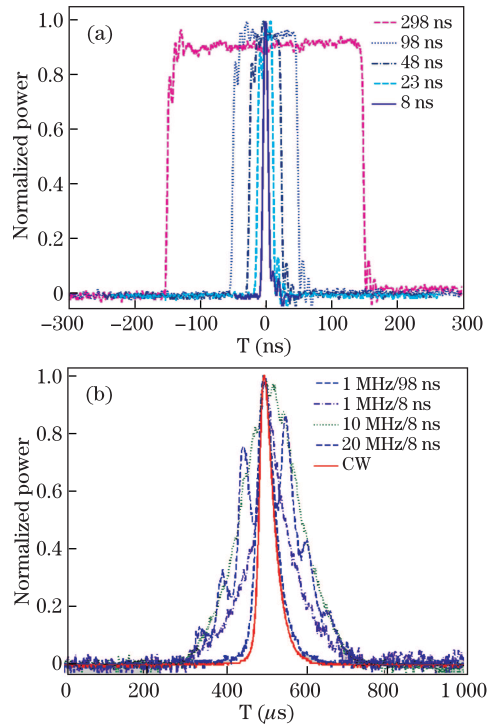

Fig. 3. (a) Pulse shapes and (b) spectra at different pulse durations and repetition rates.

and the linewidth of the CW laser is broader when phase modulated by a sine wave signal with higher frequency.

Pulsed laser was obtained when the CW seed was connected to the EOM channel. Meanwhile, pulse duration and repetition rate were modified by changing the driven signal generated by the FG. The pulse shapes of the pulsed laser with different durations and the typical spectra of the pulsed laser are shown in Fig. 3, where 1-MHz/98 ns represents the intensity-modulated pulsed laser with a duration of 98 ns and a repetition rate of 1 MHz. The spectra of the external modulation pulsed laser is related to repetition rate and pulse duration[19].

The input signal power in optical fibers, at which the Stokes wave increases rapidly and may even be comparable with the forward power, is called the SBS threshold[4]. Here, we mainly observed the SBS threshold by monitoring the backward light. Backward light power nonlinearly increases compared with the output power when the SBS threshold arrives in the main amplifier. We measured the backward and output power of the CW lasers with different linewidths, as well as those of pulsed laser with different durations and repetition rates to study the dependence of the SBS threshold on linewidth, pulse duration, and repetition rate. We repeated these measurements three times. The means of the results are shown in Fig. 4(a). Backward power serving as a function of concluded peak output powers are shown in Fig. 4(b).

The SBS threshold for CW laser is determined by[14]

$$P_{\mathrm{SBS\_ave}} = 21\frac{A_{\mathrm{e}}K}{g_{\mathrm{B}}L_{\mathrm{e}}}\left(1+\frac{\Delta V_{\mathrm{S}}}{\Delta V_{\mathrm{B}}}\right), \quad (1)$$

where $P_{\mathrm{SBS\_ave}}$ is the average SBS threshold, A_{e} is the effective fiber waveguide core area, K is the polarization factor, g_{B} is the peak Brillouin gain coefficient, L_{e} is the

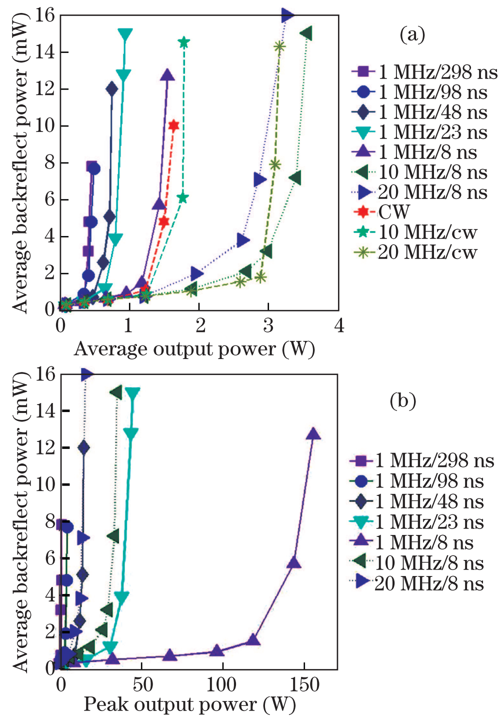

Fig. 4. Backward power as functions of the (a) forward average and (b) peak powers.

effective length, $\Delta V_{\rm S}$ is the linewidth of the laser, and $\Delta V_{\rm B}$ is the spectral width of the Brillouin-Gain spectrum (BGS). The $\Delta V_{\rm B}$, which is related to fiber properties and is always less than 100 MHz, is very small because it is related to the damping time of acoustic waves (~10 ns). The SBS threshold can be increased by broadening the laser linewidth. The SBS thresholds in our experiment were different when the lasers had different linewidths (Fig. 2(b)). This is manifested by the curves of CW, 10 MHz/cw, and 20 MHz/cw in Fig. 4(a). The SBS threshold of pulsed laser is also highly related to the linewidth when we used another CW seed with a linewidth of more than 0.06 nm. Nonlinear increase of backward light is not observed, and pump power is at its maximum when either the CW or pulsed laser are amplified.

The SBS threshold is higher when the pulse duration is shorter. The average power threshold and the peak power threshold both increased when we shortened pulse duration. The curves of 1 MHz/298 ns to 8 ns in Figs. 4(a) and (b), respectively, show that the spatial overlap between the laser pulses and their corresponding counter-propagating stokes pulsed-generated by SBS shortened when the pulse duration of the laser pulses are reduced. This means that the SBS threshold of shorter-pulsed laser increases, because the interaction between the laser pulses and the stoke pulses is weakened. The SBS average threshold of the pulsed laser with 10-MHz repetition rate is also higher than the CW laser phase-modulated by 10-MHz sine wave (Fig. 4(a)). However, the SBS threshold in this case has narrower linewidth (~60 MHz) than the CW laser (~80 MHz), as shown in Figs. 2(b) and 3(b), respectively.

The Brillouin gain is substantially reduced in pump pulses with widths that are shorter than the lifetime of the acoustic phonon[5]. However, if the repetition rate of laser pulses is high enough, the time interval between laser pulses becomes short enough to enable successive pulses to pump the same acoustic wave in a coherent manner. Thus, the SBS threshold may not increase when the pulse duration is shortened. For example, in optical communication systems, the repetition rate of pump pulses is 1 GHz, and the width of each pulse is ~100 ps. The pulse train is not uniform for lightwave signals, such as "1" and "0" bits. Moreover, this pseudorandom pulse train increases the Brillouin threshold by a factor of two or so compared with the CW case[5].

A comparison between the curve of 10 MHz/8 ns with that of 1 MHz/8 ns shows that the 8-ns pulsed laser with 10-MHz repetition rate has a higher SBS average threshold, and the pulsed laser with a 1-MHz repetition rate has a higher SBS peak threshold (Fig. 4). This means that the SBS phenomenon is caused by two factors. First, when the repetition rate of the pulsed laser is relatively low and the laser pulses have very high peak power, stoke pulses are almost completely created by each laser pulse decay before the next laser pulse arrives, and as such, the SBS threshold is limited by the peak power. Second, the interaction of the pulsed laser and the acoustic wave is integrated in the time domain. Therefore, when the average power is high enough due to relative higher repetition rate, the rapidly increasing power of the stokes wave that are comparable with the forward power occurs even when the peak power is not very high. The average power becomes the limitation in this situation.

When the repetition rate is higher (such as over 20 MHz in our experiment), the characteristic of the SBS becomes more complicated because it neither agrees with the quasi-CW case nor the transient regime. The average and peak SBS thresholds both decreased when the repetition rate of 8-ns pulses increased from 10 to 20 MHz. This may be determined by the overlap between the pulsed laser and the acoustic wave.

In conclusion, we report comprehensive experimental measurements of the SBS threshold in a fiber amplifier. Phase and intensity modulation are used to obtain CW lasers with different linewidths and pulsed lasers with different pulse durations and repetition rates. The SBS thresholds of these lasers are measured and discussed carefully. The thresholds of both the CW laser and pulsed laser are highly related to the spectral linewidth. Specifically, the SBS threshold of pulsed laser is higher when the pulse duration is shorter, whereas pulsed lasers with narrower linewidth may have higher average threshold than CW lasers in some cases. Moreover, the power handling limitation in the pulsed fiber amplifier may be the average power in some cases and the peak power in others.

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