SBS Threshold Dependence on Pulse Duration in a 2053 nm Single-Mode Fiber Amplifier

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***Abstract*—Stimulated Brillouin scattering (SBS) is the first nonlinear effect that limits power scaling of narrow linewidth fiber lasers. Nonlinearities typically have a reduced impact when operating at longer wavelengths. However, the SBS gain is considered wavelength independent. To investigate this further, a pulsed 2053 nm source with MHz-linewidth is amplified to >100 W peak powers in single-mode, thulium-doped fiber. The SBS thresholds were measured while varying the pulse duration. Analyzing the SBS threshold measurements suggests that the peak Brillouin gain coefficient is ∼12.2 pm/W with a spontaneous Brillouin bandwidth of ∼17.5 MHz in the passive single-mode fiber at 2053 nm. While the peak Brillouin gain coefficient is comparable to those reported at shorter wavelengths, the spontaneous Brillouin bandwidth is significantly narrower. This indicates that long wavelength sources can inhibit the onset of SBS more readily than short wavelength sources.**

***Index Terms*—2 μm, fiber laser, nanosecond pulsed fiber laser, narrow linewidth, nonlinear optics, stimulated Brillouin scattering, thulium-doped fiber amplifier.**

I. Introduction

HIGH brightness, high power 2 μm fiber lasers are valuable for applications in directed energy, remote sensing, telecommunication, and generating mid-IR light via nonlinear processes. Many of these applications require high peak power and narrow spectral linewidth. However, nonlinearities significantly limit the amplification of narrow linewidth fiber lasers to high peak powers. For laser linewidths on the order of the Brillouin bandwidth (∼10–100 MHz [1]–[4]), stimulated Brillouin scattering (SBS) is the first nonlinearity that limits power scaling. Whereas self-phase modulation (SPM) and stimulated Raman scattering (SRS) have reduced impact at longer wavelengths [4]–[7], SBS is taken to have no wavelength dependence [4].

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Utilizing large mode area fiber amplifiers has enabled MHz-linewidth 2 μm fiber lasers with average powers >100 W [8]–[10] and peak powers >500 W [11], [12]. Peak powers could be further increased to 1 kW by suppressing SBS via broadening the laser's spectral width [11] or applying a strain distribution along the fiber [12]. However, there are relatively few studies of SBS thresholds at 2 μm. This work characterizes SBS thresholds of a 2053 nm, single-mode fiber laser with MHz-linewidth [13]. The pulse duration is varied from 34 ns to CW, and the measured SBS thresholds are compared to a SBS threshold equation for square pulses. The analysis estimates a peak Brillouin gain coefficient of 12.2 ± 0.9 pm/W and spontaneous Brillouin bandwidth of 17.5 ± 0.8 MHz. The spontaneous Brillouin bandwidth is narrower at longer wavelengths, which leads to a reduced effective Brillouin gain. This is a beneficial feature for power scaling narrow linewidth, 2 μm fiber lasers, in which the resulting long coherence length is especially attractive for coherent beam combining.

II. Narrow Linewidth, Variable Pulse Duration 2053 nm Laser

The seed source was a diode laser with 2053 nm center wavelength, measured linewidth of 599 ± 10 kHz, and spectral contrast of 46 dB. The 2 mW average output power was boosted to 5 W through two fiber amplifiers. A fiber-coupled acousto-optic modulator (AOM) shaped the laser signal to form nanosecond pulses with user-defined shape. A preamplifier further increases the average power, while a second AOM reduced the repetition rate. This pulsed signal was then launched into the final amplifier as depicted in Fig. 1.

High spectral purity is important for monitoring SBS, as well as for mitigating any further nonlinear effects such as four-wave mixing (FWM) and SPM. Therefore, the preamplifier output was first incident on a diffraction grating, which acts as a free-space spectral filter. This improves the spectral contrast from 46 dB to 67 dB as shown in Fig. 1.

A wedge was used to monitor backward propagating light from the final amplifier for evidence of SBS. One surface of the wedge was directed to an optical spectrum analyzer (OSA) and the other was incident on a power meter.

The final amplifier consisted of a 2.7 m length of polarization maintaining (PM), thulium-doped fiber (Tm:fiber) (Nufern PM-TDF-10P/130-HE), which was counter-pumped by up to 70 W at 793 nm. The pump combiner's input and output passive fibers

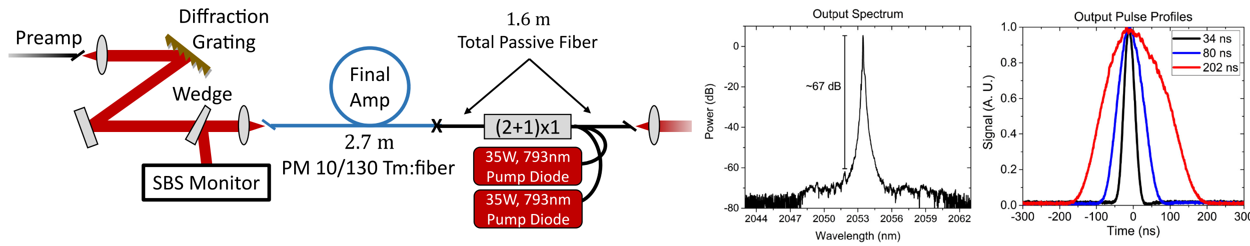

Fig. 1. Left: Layout of the final PM Tm:fiber amplifier. The preamp output is a variable pulse duration (34 ns to CW) source with 100 mW average power at 100 kHz repetition rate. A wedge monitors backward propagating light, which is indicative of SBS occurring in the 1.6 m output passive fiber. Middle: The diffraction grating improves the spectral contrast of the source to > 67 dB. Right: Typical temporal profiles for different pulse durations.

are identical, providing a combined length of 1.6 m (Nufern PM-GDF-10/130-2000-M).

The overall input parameters for the final amplifier were: 100 mW average power, 100 kHz repetition rate, polarization extinction ratio (PER) > 16 dB, and spectral contrast > 67 dB. The pulse duration was varied from 34 ns to CW with Gaussian-like profiles.

III. Stimulated Brillouin Scattering Thresholds

Output peak powers in the final amplifier were limited by SBS. No evidence of SRS, SPM, or FWM was observed when amplifying the pulses. Fig. 2 shows measured spectra of the backward propagating light (sampled off the wedge) for CW and pulsed amplification. There was no evidence of SBS when amplifying the CW signal up to the maximum tested power of 15.8 W. Conversely, pulse amplification revealed clear emergence of the SBS Stokes signal. The SBS frequency shift scales as λ^{-1}, and the measured ~8.4 GHz agrees with an expected 8.35 GHz shift in pure silica [2].

To measure the SBS thresholds, the output power meter was synchronized with the SBS power meter. The percent of output average power backscattered due to SBS was determined after accounting for Fresnel reflections from fiber facets and free-space optics, as well as the gain when propagating backward through the amplifier. In this work, the SBS threshold was defined as the point when 0.1% of the output average power was backscattered. This definition circumvents the need to consider pump depletion, which becomes necessary when defining SBS thresholds >10% [15].

As shown in Fig. 3, there is a distinct τ_p^{-1} dependence on the SBS threshold for pulse durations below 200 ns. Given a typical single-mode final amplifier with a passive fiber output under 2 meters, SBS thresholds would exceed 1 kW for $\tau_p < 10$ ns. This significant threshold enhancement is due to the pulse duration becoming shorter than the acoustic phonon lifetime (10's ns). In this regime, the dominant nonlinearity switches from SBS to SPM, SRS, and FWM [16], [17]. For pulse durations above 200 ns, the measured SBS threshold levels off at approximately 95 W (which agrees with the $\tau_p = 1\,\mu$s result in 1.4 m fiber [12]). For this fiber amplifier, the maximum peak power attainable is 311 W at 34 ns pulse duration, corresponding to ~1 W average power. For a longer pulse duration of 514 ns, the peak power is limited to ~95 W, corresponding to an average power of ~4.8 W (48 μJ pulse energy).

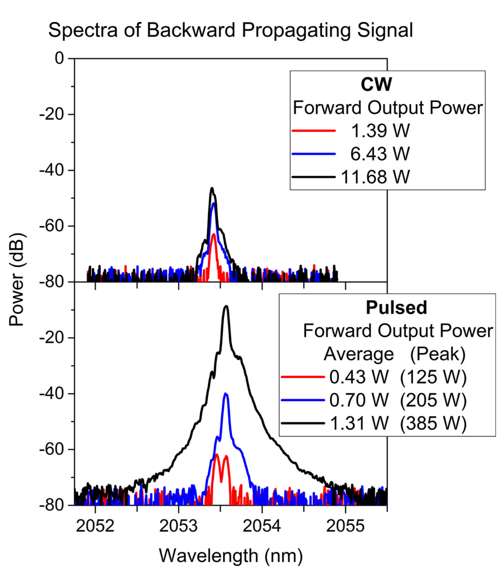

Fig. 2. Backward propagating spectra sampled off the wedge for increasing powers when CW (top) and 34 ns pulses (bottom). SBS Stokes light is evident for the pulsed amplification while absent for CW.

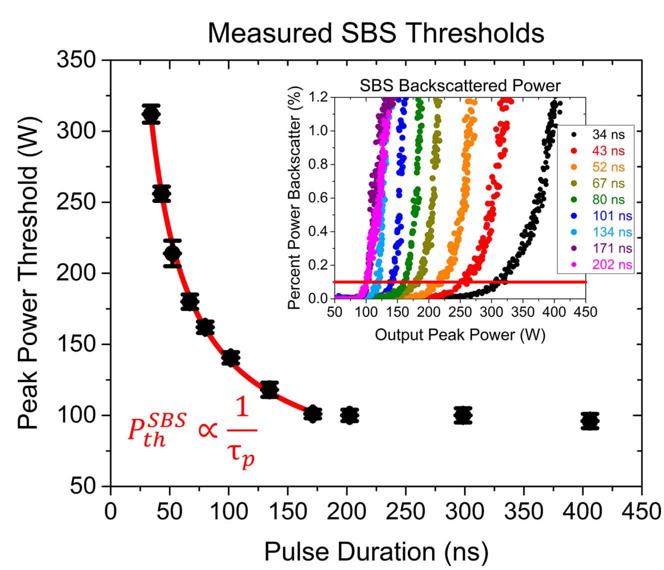

Fig. 3. The SBS threshold is inversely related to the pulse duration. For long pulse durations, the SBS threshold plateaus at 95 W. Inset: The SBS threshold is defined as the output peak power when 0.1% of the output average power is backscattered.

IV. SBS Threshold Analysis

When considering SBS thresholds in the final amplifier, the SBS Stokes shift in the Tm:fiber is offset from the Stokes shift in the passive fiber because of the different core composition [8]. Thus, they can be treated as independent SBS processes. But first, the effective nonlinear length of the Tm:fiber is reduced because of the counter-pumping architecture while seeding far below the saturation energy. This leads to exponential growth of the signal, which allows the Tm:fiber's effective length to be approximated using

$$L_{\mathrm{eff}} \approx \frac{1 - e^{-gL}}{g} \tag{1}$$

where g is the gain (or loss, α, for passive fibers) and L is the fiber length [14]. For the Tm:fiber, L_{eff} never exceeds 1.03 m when the SBS thresholds are reached in these experiments. In contrast, the output passive fiber's effective length is longer at 1.59 m ($\alpha \approx 0.0106\,\mathrm{m}^{-1}$). Secondly, the thermal gradient in the Tm:fiber reduces its peak SBS gain [8]. As a result, because the Tm:fiber and passive fiber have independent SBS thresholds, it is determined that the SBS observed is due to high peak power propagation through the longer effective length output passive fiber (as was similarly observed in [8]).

Analytical derivations for SBS thresholds have been presented throughout literature, but are typically concerned with CW operation [15], [18]. Employing the CW SBS threshold equations for pulsed sources is subject to errors, especially when the pulse duration is on the order of the fiber roundtrip time or smaller (~16 ns for the 1.6 m passive fiber). This is due to the limited interaction of the pump and Stokes wave in the time domain as they propagate in opposite directions. For pulses shorter than ~100 ns, the phonon lifetime itself leads to further constraints when considering transient Brillouin scattering. Nevertheless, an expression for the SBS threshold of square pulses in a short optical fiber was presented by Keaton *et al.* in [19, (38)]. It is not reproduced here due to its length, but is encouraged for the reader.

As the pulse duration approaches infinity for the derivation from [19], the SBS threshold simplifies to

$$P_{\mathrm{th}}^{SBS} = \frac{\Theta \cdot A_{\mathrm{eff}}}{g_B^{\mathrm{peak}} \cdot L_{\mathrm{eff}}} \tag{2}$$

where g_B^{peak} is the peak Brillouin gain coefficient, L_{eff} is the effective fiber length (1.59 m), and A_{eff} is the optical mode area (101 $\mu\mathrm{m}^2$). The unit-less threshold parameter, Θ, is defined in [19] and calculated to be ~18–21 for these experimental conditions. This is in close agreement with Smith's parameter of 21 [18] and Keaton's parameter of 22 [19]. Using the measured 95 W SBS threshold for long pulses (CW-like regime) leads to $g_B^{\mathrm{peak}} = 12.2 \pm 0.9$ pm/W. This is comparable to typical reported values in silica fiber over many wavelengths (12.0 – 26.0 pm/W) [12], [20]–[22]. With this peak Brillouin gain coefficient, [19, (38)] was fit to the SBS threshold measurements allowing the phonon lifetime, τ_{B}, to vary. The phonon lifetime is related to the spontaneous Brillouin bandwidth (FWHM) by $\Delta\nu_B = (2\pi\tau_B)^{-1}$. Fig. 4 plots the data similar to Keaton *et al.* [19], along with the best-fit theoretical SBS thresholds. This occurs for $\tau_{\mathrm{B}} = 9.1 \pm 0.4$ ns, or equivalently $\Delta\nu_B = 17.5 \pm 0.8$ MHz.

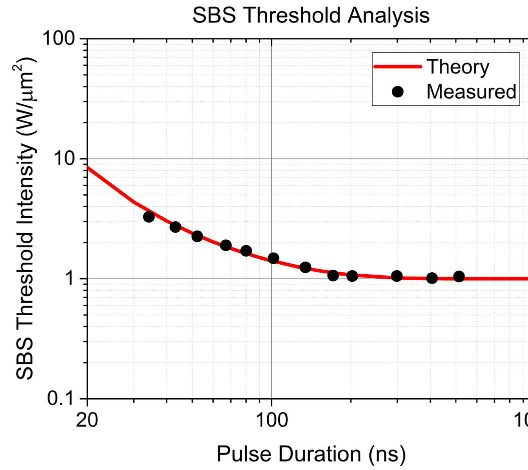

Fig. 4. The SBS threshold intensities as a function of pulse duration. Fitting the data to the SBS threshold derivation from [19] estimates $\Delta\nu_{\mathrm{B}} = 17.5 \pm 0.8$ MHz and $g_B^{\mathrm{peak}} = 12.2 \pm 0.9$ pm/W.

It is important to note that the SBS threshold derivation in [19] was for square temporal pulses, while this experiment studied Gaussian pulses. The square pulse derivation allows the rising/trailing edges to be neglected when solving the differential equation for the Brillouin wave. While it is expected that the effect would be minimal, it is unknown how keeping this term would impact the results. Deriving a full solution is out of this work's scope.

Nonetheless, the calculated spontaneous Brillouin bandwidth at 2053 nm is narrower than those reported at shorter wavelengths [1], [2], [21], [23]–[28]. It is known that the spontaneous Brillouin bandwidth decreases with wavelength, following an anticipated λ^{-2} dependence [2]. Table I lists published spontaneous Brillouin bandwidths in similar fibers over several wavelengths, and the extrapolated bandwidth at 2053 nm assuming a λ^{-2} dependence. These values show close agreement to the bandwidth estimated when fitting to the SBS threshold of square pulses equation. The large standard deviation for the

TABLE I
Comparison to Published Spontaneous Brillouin Bandwidths

Pump λ (nm)	Measured $\Delta\nu_B$ (MHz)	Extrapolated $\Delta\nu_B$ at 2053nm using λ^{-2} dependence (MHz)	Reference
515	140	8.8	[23]
828	90	14.6	[24]
1064	72	19.3	[25]
1064	58	15.6	[26]
1320	35.8	14.8	[21]
1552	29	16.6	[27]
1552	86	49.1	[28]
Average of the extrapolated values		19.8 ± 12.3	[21, 23-28]
Calculated $\Delta\nu_B$ at 2053nm from this work		17.5 ± 0.8	Figure 4 [19] (Eq. 38)

averaged value is due to outliers [23] and [28], neglecting them would give an average of $\Delta\nu_B = 16.2 \pm 1.7$ MHz at 2053 nm.

The fact that the spontaneous Brillouin bandwidth decreases with wavelength is advantageous for narrow linewidth 2 μm lasers. For CW lasers, this implies that for a given spectral width, the SBS threshold is higher at 2 μm than 1 μm because of the reduced spectral overlap. However, as the laser linewidth becomes comparable to the Brillouin bandwidth, this benefit greatly diminishes. Nonetheless, one would expect GHz-linewidth 2 μm fiber lasers to have $\sim$4x higher SBS threshold than a 1 μm counterpart, given all other parameters are constant.

V. Conclusion

SBS thresholds were measured when power scaling a MHz-linewidth, pulsed 2053 nm fiber laser. The SBS peak power thresholds follow a well-defined τ_{p}^{-1} dependence for $\tau_{\mathrm{p}} <$ 200 ns, and plateaus at 95 W for long pulse durations in 1.6 m output passive fiber. The peak power is limited to 311 W in this system, which occurs at the shortest pulse duration of 34 ns. The results are analyzed using a numerical SBS threshold derivation for square pulses in a short optical fiber [19]. From this, the peak Brillouin gain coefficient is estimated to be 12.2 ± 0.9 pm/W with a spontaneous Brillouin bandwidth of 17.5 ± 0.8 MHz in the output passive fiber.

While the peak Brillouin gain coefficient does not show any change with respect to shorter wavelengths, the spontaneous Brillouin bandwidth is distinctly narrower. A narrower Brillouin bandwidth leads to smaller effective Brillouin gain because of the reduced spectral overlap. Therefore, this implies that long wavelength sources require less spectral broadening to alleviate SBS as compared to short wavelength sources. In the pulsed regime, this means that long wavelength sources can suppress SBS more effectively than short wavelength sources, given the same pulse duration. This benefit makes 2 μm attractive for high power, narrow linewidth, fiber lasers. These sources are useful for applications in coherent beam combining, LIDAR, and nonlinear frequency conversion.

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