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Stimulated Brillouin Scattering Suppression in Fiber Amplifiers via Chirped Diode Lasers

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14. ABSTRACT

We propose to simultaneously suppress stimulated Brillouin scattering (SBS) and enable coherent combination by seeding fiber amplifiers with a linearly-chirped diode laser. The seed spectrum will appear broadband to suppress the SBS, but the well-defined chirp will have sufficient coherence to allow the active phasing of multiple amplifiers. The phasing can be accomplished without strict optical path-length matching by interfering each amplifier's output with a reference, processing the resulting signal with a phase-locked loop, and using the error signal to drive an acousto-optic frequency shifter at the frontend of each fiber amplifier.

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1. Background/Introduction

Stimulated Brillouin scattering (SBS) is a major factor limiting the output power of a fiber laser. If the pump intensity is constant[*], the threshold for SBS is $gIL{\sim}20$, where L is the length of the fiber, and the intensity is $I = P/A$. P is the incident laser power, and A is the mode area. The Brillouin gain is given roughly by $g = g_0 \Delta\ _B/\Delta\ _L$, if the laser bandwidth $\Delta\ _L$ is large compared to the Brillouin bandwidth $\Delta\ _B$. g_0 is the Brillouin gain on line center. Techniques to suppress SBS have included (1) simply increasing A (which leads to multimode operation and a reduction in spatial brightness), (2) increasing $\Delta\ _L$, (3) using large mode area fibers to maintain single-mode operation, and (4) using highly doped fibers to quickly absorb the pump light and minimize L. A combination of (2) and (3) has yielded 10 kW from a single-mode fiber master-oscillator power-amplifier (MOPA)[†]. The disadvantage is that the ~2-THz output bandwidth precludes coherent beam combination.

We propose that such amplifiers could be seeded with a rapidly chirped diode laser so that (a) the spectrum appears broadband in order to suppress the SBS, but (b) the frequency variation is extremely well defined so that multiple fiber lasers can be coherently combined with acousto-optic frequency shifters[‡] (*3*). Coherent combination of 10 single-mode fiber lasers could then yield a robust, efficient, diffraction-limited 100-kW source.

Long-distance fiber telecommunications are also adversely affected by SBS. In this case, the laser cannot be chirped without distorting the information being transmitted. So, another approach is to vary the Stokes shift along the fiber length (*1*). In this experiment, the core diameter of a 14-km single mode fiber was tapered from 8 to 7 µm, which changed the Stokes shift by 49 MHz. This is the equivalent of a chirp of 10^{11} Hz/s in our system. The SBS was suppressed by a factor of 2.3. Unfortunately, this technique is not an option for the large core areas used in high power fiber lasers, because the Stokes shift corresponds to the bulk value, i.e., it no longer depends on core diameter.

Recently, a 1-W and a 1.4-kW ytterbium (Yb) fiber amplifier were actively phase locked to a common oscillator, but the 25-GHz oscillator bandwidth means that the amplifier path lengths have to be *mechanically* matched to ~1 mm (*2*). Extrapolating to the 2-THz bandwidth of the IPG amplifier[†] implies that to coherently combine multiple amplifiers, path lengths will have to

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[*] If the pump intensity is not constant due to gain or loss, *I* can be replaced by an effective intensity or *L* can be replaced by an effective length.

[†] An IPG Photonics model YLS-10000-SM.

[‡] Telaris, Inc., has applied for a patent on the technique; the contribution of the U.S. Army Research Laboratory (ARL) was to quantify the amount of SBS suppression for a given fiber length, chirp, and SBS bandwidth.

be matched to ~0.010 mm. We anticipate that our method will *electronically* compensate for path length differences up to 1 m. This advance will make it much easier to construct the system in the first place, and much easier to replace an amplifier chain in the field.

Two preliminary steps have already been taken. Optical phase-locked loops have been jointly developed by Telaris (*3, 4*) and Caltech to coherently combine six (non-chirped) diode lasers (*5–8*). More recently, the same group has chirped a (single) 40-mW, 1.55-µm diode laser at 10^{14} Hz/s using a phase-locked loop and a fiber-optic Michelson interferometer (*9*). The chirp has now been extended to 5×10^{15} Hz/s. This report describes a proposal to combine chirping and phase locking.

Now, ~10-kW single-mode Yb fiber amplifiers are commercially available. Currently, a high bandwidth seed is needed to suppress SBS in the final amplifier stage. The output phase and frequency vary to such an extent that coherent combination of multiple units is out of the question. This proposal is a first step towards coherently combining 10 of these lasers.

This proposal exploits the recent development at Telaris and Caltech of optical phase-locked loops for coherently combining multiple (non-chirped) diode lasers. By incorporating a fiber interferometer, the technique has been extended to chirp a (single) laser diode at 10^{15} Hz/s in an extremely linear fashion, over a range of 100 GHz. Telaris is developing the optoelectronics to combine both techniques, for delivery to ARL.

The first-year goal will be to phase lock two chirped 10-W erbium (Er) fiber amplifiers to a master oscillator and show SBS suppression by a factor of six via a chirp of 10^{15} Hz/s. We will also show that the feedback system can accommodate initial and transient fiber path length differences of ~1 m. The second-year goal will be to coherently combine at least four chirped 40-W Yb amplifiers and push the SBS suppression to ~60× via a chirp of 10^{16} Hz/s.

2. System Configuration

We envision a system consisting of a rapidly chirped diode laser, a fiber splitter to multiple parallel chains, each with a fiber-coupled acousto-optic frequency shifter (AOFS), a single-mode fiber amplifier, and phase detection optics (figure 1). The waveform to each AOFS is controlled by an optical phase-locked loop (OPLL) so that the amplifier outputs are maintained in phase despite initial and transient variations in fiber length.

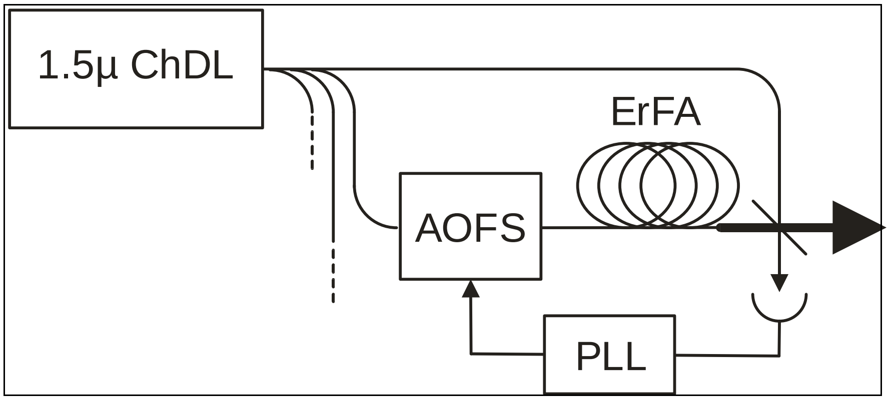

Figure 1. Chirped diode laser seeding one or more Er fiber amplifiers, each preceded by an AOFS driven by a phase-locked loop.

The compensation for amplifiers of different path lengths is achieved electronically through the use of AOFSs. For linearly chirped light, a frequency shift Δν is equivalent to a path length difference of (*9*)

$$L = \frac{c\,\Delta\upsilon}{n\,\alpha} \tag{1}$$

For a given chirp α and a maximum frequency shift of $\Delta\upsilon_{max}$, the maximum path length difference that can be compensated is given by

$$L_{max} = \frac{c\,\Delta\upsilon_{max}}{n\,\alpha} \tag{2}$$

For a diode laser tuning range of χ, the period of the chirp is given by

$$\tau = \frac{\chi}{\alpha} \tag{3}$$

Representative values of the mismatch tolerance, chirp period, and chirp length ($c\tau/n$) are given in table 1 for $\Delta\upsilon_{max}$ = 10 MHz[§] and a diode laser tuning range of χ = 100 GHz. The chirp lengths are much longer than the 15-m final stage of a typical high power fiber amplifier, so a Stokes wave will never be in resonance with the laser more than once.

[§] A Brimrose model AMF-100-20-1550-2FP imposes a shift of 100 ±10 MHz.

Table 1. Mismatch tolerance, chirp period, and chirp length for two values of chirp.

Chirp α (Hz/s)	**Mismatch Tolerance L_{max} (m)**	**Chirp Period τ (μs)**	**Chirp Length (km)**
10^{15} Hz/s	2	100	21
10^{16} Hz/s	0.2	10	2.1

3. SBS Suppression

In the case of homogeneous broadening, the steady-state SBS gain is a Lorentzian with a maximum at the Stokes frequency

$$g(\omega) = \frac{g_0}{1 + \left(\frac{\omega - \omega_L + \Omega}{\Delta\omega_h}\right)^2} \tag{4}$$

where g_0 is the gain on line center, ω_L is the laser frequency, and Ω is the Stokes shift. We can estimate the degree of SBS suppression by considering a laser beam having a chirped frequency $\omega_L(z,t) = \omega_0 + 2\pi\alpha\left(t + \frac{L-z}{\mathrm{v}}\right)$, propagating at +v in a fiber of length L. A Stokes wave that starts on resonance, i.e., at the peak of the Brillouin gain spectrum at $(z,t) = (L,0)$, will experience a gain given by

$$g(z) = \frac{g_0}{1 + \left(\frac{4\pi\alpha}{\Delta\omega_h}\frac{L-z}{\mathrm{v}}\right)^2} \tag{5}$$

This frequency will have the largest gain at $z = L$, and then immediately decrease (dashed line in figure 2). A higher frequency will initially see an increase in gain, until it comes into resonance with the pump, followed by a decrease. The frequency that experiences the largest net gain over the length of the fiber will be offset from resonance by $\delta = \alpha\tau/2$ and have its peak gain at $z = L/2$, where α is the chirp and τ is the transit time of the fiber (solid lines in figure 2).

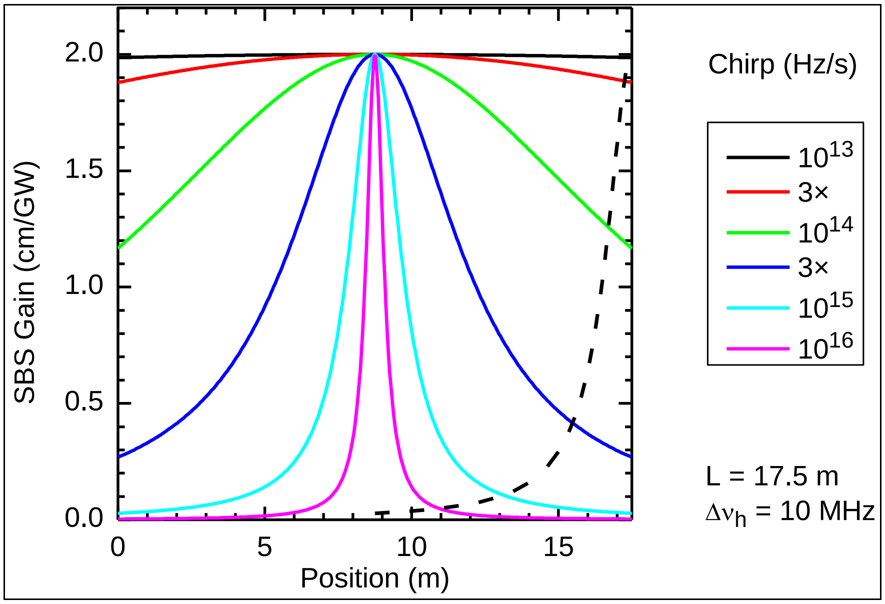

Figure 2. SBS gain vs. position in a Yb fiber amplifier, for various chirps, at the optimum Stokes frequency in each case. The fiber length is 17.5 m. The SBS bandwidth is 10 MHz (half width at half-maximum [HWHM]). The dashed line shows the gain seen by a Stokes wave that starts on resonance at z = L, for a chirp of 10^{15} Hz/s.

The z-integral of the gain vs. chirp shows that at low chirp the offset doesn't matter, but at high chirp, an additional factor of two in chirp is required to achieve a given suppression.

A Stokes wave at the peak of the gain curve, propagating at –v, near threshold, will experience a net gain (per unit laser intensity) of

$$\int_0^L g\,dz = \int_0^L \frac{g_0\,dz}{1+\left(\frac{\omega-\omega_L(z)+\Omega(z)}{\Delta\omega_h}\right)^2} = \int_0^L \frac{g_0\,dz}{1+\left(\frac{2\pi\delta-4\pi\alpha\,(L-z)/\mathrm{v}}{\Delta\omega_h}\right)^2}$$

$$= g_0\frac{\Delta\omega_h\,\mathrm{v}}{4\pi\alpha}\left[\tan^{-1}\frac{2\pi}{\Delta\omega_h}\delta-\tan^{-1}\frac{2\pi}{\Delta\omega_h}\cdot\left(\delta-\frac{2\alpha L}{\mathrm{v}}\right)\right] \tag{6}$$

For $\alpha\to 0$ this reduces to g_0L. For large chirp, this goes as $g_0\,\Delta\omega_h\mathrm{v}/4\alpha$.

For the optimal value of δ, and $g_0 = 2\cdot 10^{-11}$ m/W, calculations of the integrated gain as a function of α have been made for two values of the SBS bandwidth and two values of the fiber length (figure 3). For a bandwidth of $\Delta\omega_h = 2\pi\cdot 10^7$ Hz (HWHM), and $L = 17.5$ m†, this implies a 6× reduction in SBS gain for a chirp of $\alpha = 10^{15}$ Hz/s, and 60× for 10^{16} Hz/s. An important feature of this scheme is that long delivery fibers can be accommodated. As an example, for an SBS bandwidth of 10 MHz and a chirp of 10^{15} Hz/s, the integral over the fiber length (z-integral) of the gain is the same for a 17.5-m fiber and a 35-m fiber. Once the chirp has reduced the gain length to a fraction of the fiber length, further increases in fiber length do not increase the integrated gain.

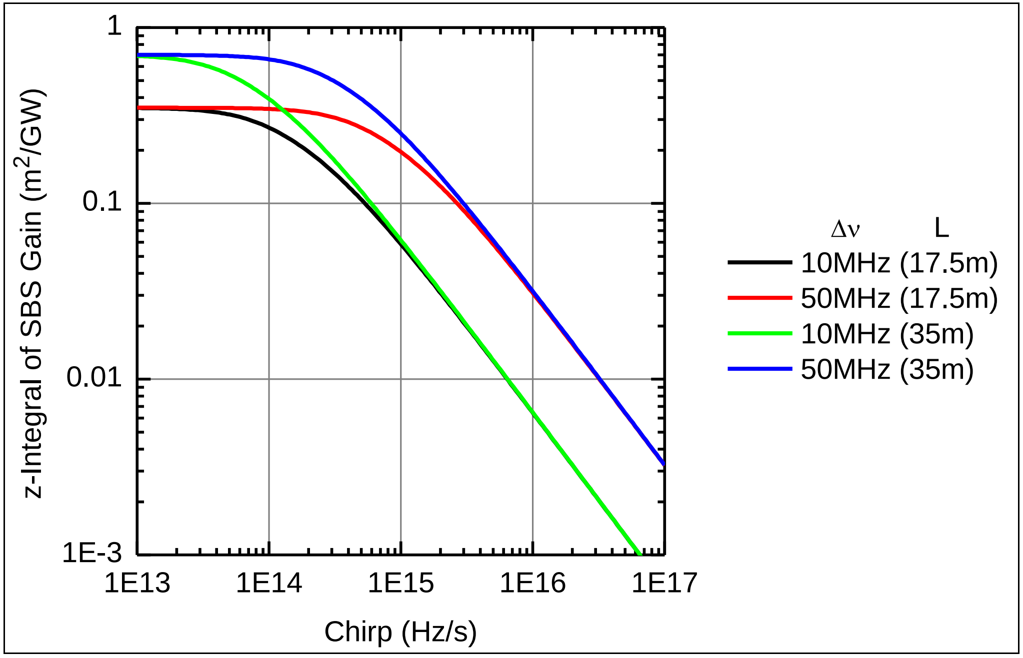

Figure 3. Plot of the z-integral of the SBS gain vs. chirp, for several values of the SBS bandwidth (HWHM) and fiber length.

A plot of the z-integral of the SBS gain versus offset shows that (1) the optimum offset increases with chirp, (2) the gain at the optimum offset decreases with chirp, and (3) the gain bandwidth broadens with chirp (figure 4).

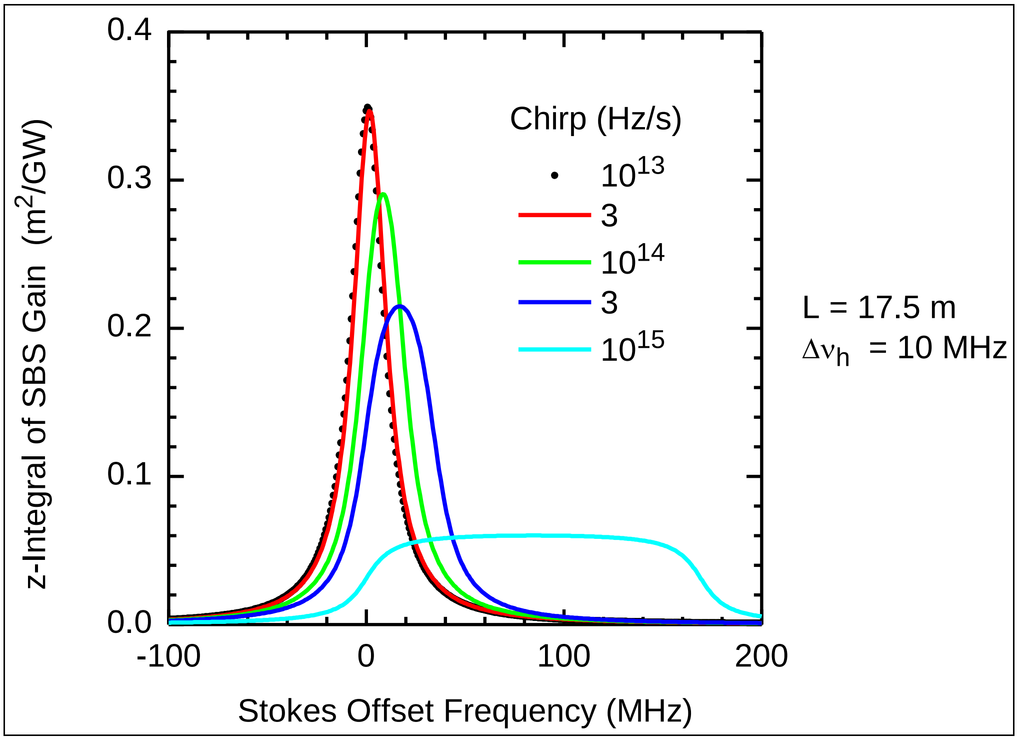

Figure 4. Plot of the z-integral of the SBS gain vs. Stokes offset frequency, for an SBS bandwidth of 10 MHz (HWHM) and a fiber length of 17.5 m.

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4. Discussion

This technique has a qualitative resemblance to chirped pulse amplification (CPA), the most widely used technique for amplifying ultrashort optical pulses. In the case of CPA, the pulse is chirped and stretched by propagation through a pair of gratings, before amplification. The resulting lower intensity helps avoid nonlinear processes in a solid-state amplifier. In our (continuous wave) case, chirping the laser suppresses the nonlinear process of stimulated Brillouin scattering in a fiber amplifier.

A technical risk will be that the SBS gain in 10–20 m fiber amplifiers turns out to be much broader than the 10-MHz value appropriate for bulk silica, due to inhomogeneous broadening. We believe the risk is low because a recent study of a 148-km single-mode fiber revealed a bandwidth of only 30 MHz (*10*). We believe that α can be increased to 10^{16} Hz/s to offset an increase in $\Delta\nu_h$.

Another technical risk is that the transient phase variations intrinsic to the fiber amplifier are too rapid for the phase-locked loop to follow. Published data on the power dependence of the phase noise spectrum (including self-phase modulation) at the output of a 10-W fiber amplifier (*11*) suggest that the 1-MHz bandwidth phase-locked loops already developed at Telaris will be faster than required.

5. Conclusion

Our analysis shows that linearly-chirped diode lasers have the potential to greatly suppress the stimulated Brillouin scattering that is currently limiting the output power of high spatial and spectral brightness fiber amplifiers. Using reasonable values for the fiber length and Brillouin bandwidth, we anticipate a factor of 6× reduction in SBS gain for a chirp of 10^{15} Hz/s and a 60× reduction for a chirp of 10^{16} Hz/s.

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List of Symbols, Abbreviations, and Acronyms

AOFS	acousto-optic frequency shifter
ARL	U.S. Army Research Laboratory
CPA	chirped pulse amplification
Er	erbium
HWHM	half width at half-maximum
MOPA	master-oscillator power-amplifier
OPLL	optical phase-locked loop
SBS	Stimulated Brillouin scattering
Yb	ytterbium

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