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EXPERIMENTAL STUDY OF SBS SUPPRESSION VIA WHITE NOISE PHASE MODULATION (POSTPRINT)

Brian Anderson, et al.

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Technical Paper

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AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
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KIRTLAND AIR FORCE BASE, NM 87117-5776

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//Angel Flores//
ANGEL FLORES
Program Manager

//Kenton Wood//
KENTON WOOD
Chief, Laser Division

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14. ABSTRACT

Power scaling of single-frequency high power optical fiber lasers is limited due to the stimulated-Brillouin scattering (SBS). Towards that end, line broadening through white noise phase modulation can be used to suppress SBS. Theoretical models predict the SBS threshold enhancement factor as a function of linewidth and fiber length, but have yet to be experimentally verified. A radio frequency (RF) white noise source (WNS), in conjunction with RF low pass filters, is used to randomly modulate an optical signal through an electro-optic modulator (EOM). The optical signal is broadened, with optical bandwidth controlled through RF filtering. Subsequently, this modulated signal is used in a cutback experiment with a passive fiber. Studies describing enhancement factors as a function of linewidth and fiber length are investigated. Results indicate a reduction in the SBS threshold enhancement factor at shorter fiber lengths, which is in reasonable agreement with the theoretical predictions. Finally, we compare these results with cutback experiments conducted using phase modulation through pseudo random bit sequence (PRBS).

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Experimental study of SBS suppression via white noise phase modulation

Brian Anderson[1,*], Craig Robin[2], Angel Flores[2], Iyad Dajani[2]
[1]CREOL, University of Central Florida, 4000 Central Florida Blvd, Orlando, FL 32816
[2] Air Force Research Laboratory, 3550 Aberdeen Ave SE, Kirtland AFB, NM, USA 87117-0001
*bmanders@knights.ucf.edu

Abstract: Power scaling of single-frequency high power optical fiber lasers is limited due to the stimulated-Brillouin scattering (SBS). Towards that end, line broadening through white noise phase modulation can be used to suppress SBS. Theoretical models predict the SBS threshold enhancement factor as a function of linewidth and fiber length, but have yet to be experimentally verified. A radio frequency (RF) white noise source (WNS), in conjunction with RF low pass filters, is used to randomly modulate an optical signal through an electro-optic modulator (EOM). The optical signal is broadened, with optical bandwidth controlled through RF filtering. Subsequently, this modulated signal is used in a cutback experiment with a passive fiber. Studies describing enhancement factors as a function of linewidth and fiber length are investigated. Results indicate a reduction in the SBS threshold enhancement factor at shorter fiber lengths, which is in reasonable agreement with the theoretical predictions. Finally, we compare these results with cutback experiments conducted using phase modulation through pseudo random bit sequence (PRBS).

1. INTRODUCTION

High power fiber laser amplifiers suitable for beam combining are currently limited by nonlinear effects such as stimulated Brillouin scattering (SBS). The design of such amplifiers requires the output to have narrow linewidth and high beam quality in order to maximize combining efficiency and the intensity of the beam in the far field. SBS is the process by which high intensity light generates a backward traveling Stokes wave; thus limiting the forward traveling power. In an active fiber, this process is particularly worrisome as the backwards traveling wave can cause pulsations; leading to the destruction of components in the fiber amplifier.

The SBS threshold is dependent on several factors [1], thereby allowing flexibility in the design of higher power fiber amplifiers. In particular, early theoretical models have shown a relationship between the SBS threshold and the effective area of the fiber (A_e), the Brillouin gain coefficient in the fiber (g_b), the effective length of the fiber (L_e), the spectral width of the seed laser (ν_p), and the Brillouin gain bandwidth (ν_b).

$$\boldsymbol{P_{th} = \frac{21A_e}{g_b L_e}\left(1 + \frac{\nu_p}{\nu_b}\right)} \tag{1}$$

However, not all of these parameters are unconstrained. For example, the area of the fiber can only be increased to some maximum value while still maintaining near diffraction-limited beam quality. The most accessible parameter is the seed laser bandwidth. In principle, the seed bandwidth can be made very broad, but for laser beam combining applications linewidths less than 10 GHz are desired [2]. Broader linewidths may hinder efficient beam combining, due to added path length complexities in coherent beam combining and beam quality degradation in spectral beam combining.

With these requirements, it is of interest to find and characterize efficient methods of spectral broadening a single frequency seed laser such that the final bandwidth remains within the range suitable for beam combining. The most common methods are phase modulation techniques such as sinusoidal, pseudo-random bit sequence (PRBS), and white noise source (WNS). Of these, sinusoidal and PRBS phase modulation have been studied both theoretically and experimentally [3, 4]. In contrast, several theoretical models of WNS have been reported [5,6], but few experimental results exist to confirm these models. Those results which do exist are more suited for the design of parametric amplifiers [7, 8], as the experiments focus on the SBS enhancement factor for long fibers. It is of particular interest to test the effects of WNS phase modulation for shorter fiber lengths, as these fiber lengths are the most likely to be used for the design of high power fiber amplifiers and are also the point at which theoretical models predict a deviation from the enhancement factor derived analytically for long fibers. Although WNS phase modulation is widely used in industry for the design of kilowatt level fiber amplifiers [9], limited experimental quantitative data has been reported. To that end, we present studies of WNS modulation in fiber amplifiers. Quantitative analysis describing SBS enhancement factors as a function of linewidth and fiber length are presented. In addition, experimental results are compared to the theoretical predictions. Furthermore, comparison is made to cutback experiments conducted using phase modulation through PRBS.

2. THEORETICAL BACKGROUND

Theoretical modeling on the effect of WNS phase modulation has been reported based on the numerical integration of the coupled wave equations [5]. Simulations were generated for two different cases: one with a power spectral density (PSD) containing a Lorentzian distribution and another using a sinc-squared distribution. For these different distributions, the SBS threshold was computed, allowing the enhancement factor to be calculated as a function of the linewidth normalized to the Brillouin bandwidth of the fiber. For any given fiber length, the enhancement factor is defined as the ratio of the SBS threshold obtained with phase modulation applied to the signal to the SBS threshold obtained for the same length of fiber without the application of phase modulation (i.e. single-frequency).

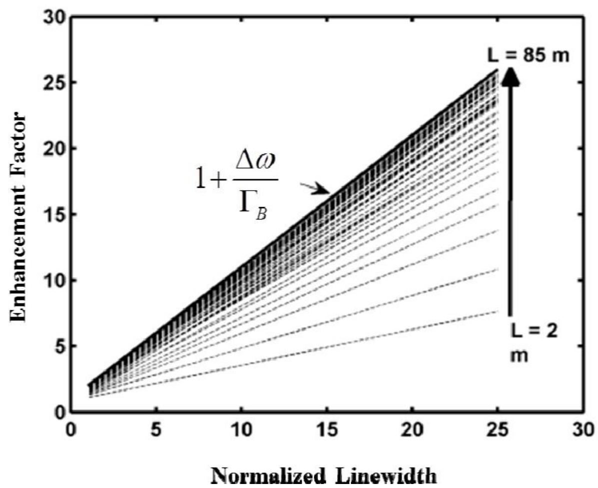

Figure 1: Enhancement factor as a function of normalized linewidth for a Lorentzian PSD for various fiber lengths [5].

The simulations indicate that at long fiber lengths (for a Lorentzian optical signal), the enhancement factor approaches that predicted by Eq. 1 (Figure 1). At shorter fiber lengths, this enhancement factor is no longer expected to follow Eq. (1).

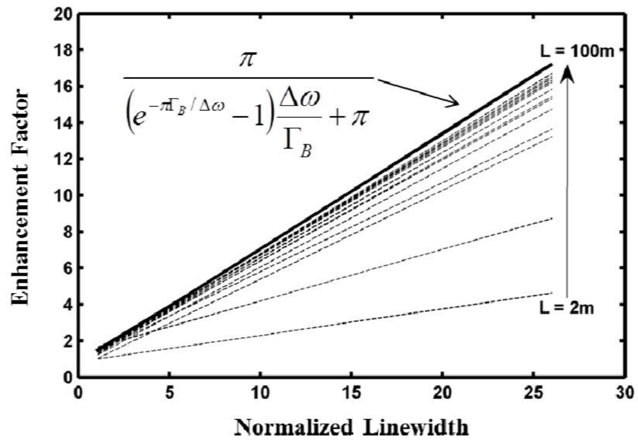

Figure 2: Enhancement factor as a function of normalized linewidth for a sinc-squared PSD for various fiber lengths [5].

The simulations in [5] also shows that the enhancement factor depends on the shape of the linewidth (Figure 2), as indicated from simulations with the sinc-squared PSD. Although this lineshape dependence does not change the overall trend, it does suppress the enhancement factor. For the sinc-squared distribution the enhancement factor is suppressed by a factor of 0.64. The theoretical work of [6] confirms this length dependence and attributes the reduction in the enhancement factor at shorter lengths to the stochastic nature of noise requiring a modified interpretation of the spectral width. At shorter lengths, the traverse time of the Stokes light is relatively short and consequently the benefit from the random nature of the WNS is not fully realized. The work in [6] indicates that the enhancement factor follows the equation:

$$\boldsymbol{EF} = \frac{\nu_B}{\nu_B + \frac{c}{n_{fiber}L}} \boldsymbol{EF_{Ideal}} \quad (2)$$

This equation should hold true for any lineshape, and the general trend should be a seen in a cutback experiment. For a fiber with a refractive index of 1.45, and a Brillouin bandwidth of 52 MHz, the enhancement factor for a fiber of length 10 m as provided by Eq. (2) is 72% of the ideal enhancement as compared to a fiber length of 75 m which would have an enhancement factor 95% of the ideal value.

3. EXPERIMENTAL SETUP

To produce the WNS phase modulated optical signal, we use an RF WNS to generate a uniformly random distribution of voltage fluctuations over a range of frequencies from 100Hz to 1.5GHz with a flatness of 2 dB. This RF signal is amplified and filtered with low-pass filters before being applied to an electro-optic phase modulator (EOM) (Fig 3a), where the optical signal of a seed laser is modulated (Fig. 3b), and broadens the bandwidth of the seed laser (Fig. 3c). We amplify this modulated signal up to 90 W using an ytterbium-doped fiber amplifier with a core diameter of 10 µm and a cladding diameter of 125 µm, where the output is then used to study the SBS process in a PM 10/125 passive fiber.

The appropriate voltage at which to drive the EOM depends on the particular experimental setup. It was decided to select the modulation voltage based on the produced spectral shape. For a given range of input frequencies, it was found that below a certain applied voltage, a sharp peak would be seen on the output spectrum corresponding to a portion of the optical signal remaining unmodulated. At a certain voltage this peak was minimized, and above this voltage the peak would again appear. For a given RF filter, the voltage was therefore chosen to minimize this unmodulated signal. Although it is possible the EOM is being driven beyond a π phase shift at these voltages, this does not have any additional effect on the enhancement factor other than to additionally broaden the optical signal. Therefore all plots of the SBS enhancement factor will be against the measured FWHM spectral bandwidth of the optical signal.

A block diagram of the experimental setup is shown in figure 4. A low power single-frequency seed laser is phase modulated, and subsequently amplified through three stages. This signal is then coupled into a passive fiber, where the backwards reflected power is measured through a 0.01% tap. The SBS threshold is measured and compared to the threshold for a single frequency source. According to the theoretical studies [5,6], a linear relationship between the SBS enhancement factor and the linewidth of the broadened laser is expected.

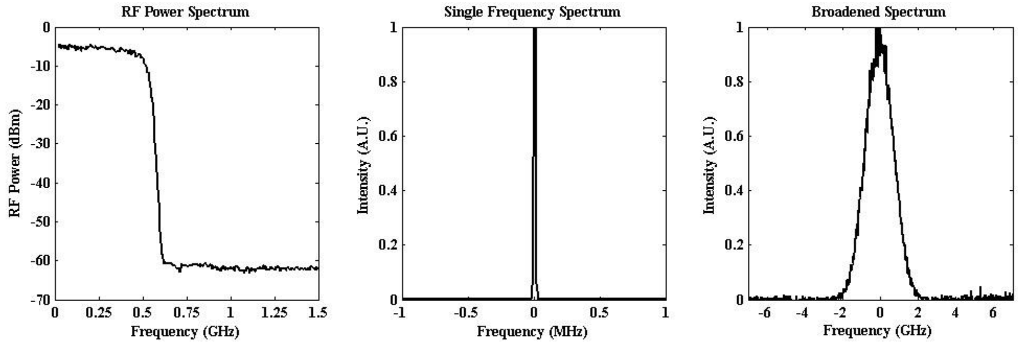

Figure 3: (1) RF power spectrum after 400 MHz low pass filter and RF amplification applied to the EOM. (2) Unmodulated single frequency seed laser resolved through heterodyne interference. (3) The heterodyne measured spectrum of the single frequency seed after phase modulation with the RF spectrum shown in (1).

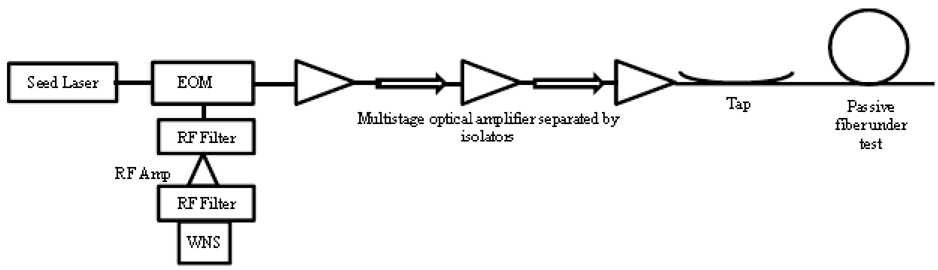

Figure 4: Block diagram of the experiment to test the SBS enhancement factor of the passive fiber as a function of length of the passive fiber and linewidth of the broadened seed laser.

The design of the monolithic fiber amplifier to test the SBS threshold in the passive fiber is intricate. Currently, no high power fiber-coupled isolators exist which could separate the third stage of amplification from the tested passive fiber. A problem arises when the passive fiber is intended to be cutback to 15 m or less. The Stokes wave generated by the passive fiber will then be amplified by both the laser gain and the Brillouin process in the fiber of the third stage amplifier. This can cause large pulsations in the gain fiber causing the destruction of components. In the literature, several definitions for SBS threshold in fiber amplifiers exist, including output power at a reflectivity in the range of 0.01%-0.1%. For this cutback experiment, the threshold was chosen to occur at a reflectivity of 0.01%. At this reflectivity, the backward power was beginning to depart from linear dependence on pump power. At the same time, the reflectivity was still low enough to reduce the possibility of pulsations in the third stage. To further suppress the pulsations, the gain fiber of the third stage was cut short, reducing the efficiency of the amplifier but also reducing the Brillouin gain in the third stage. In order to properly compare the experimental results, the Brillouin bandwidth (ν_b) of the fiber should be measured. This was done using a pump-probe experiment [10,11]. Two single frequency (linewidth < 10KHz) NPRO lasers are used to counter propagate in a fiber, with circulators used to separate the signals and measure the corresponding power levels. A heterodyne is used to measure the relative frequency separations. One NPRO is used to pump the medium, while the second NPRO is temperature tuned to a wavelength approximately 16.1 GHz higher than the pump. For each power level of the pump, the probe NPRO is temperature tuned across the Brillouin gain while the output probe power is recorded. Based on this procedure, the FWHM of the Brillouin gain bandwith (ν_b) as well as the Brillouin gain coefficient (g_b) can be retrieved [10,11].

4. RESULTS

Results of the pump probe experiment are shown in Figure 5. The results show the spontaneous Brillouin bandwidth (ν_b) to be approximately 52 MHz with a Stokes shift of 16.08 GHz, and a g_b of 1.7 x 10^{-11} m/W (Fig 6). Notably, these values are close to those typically measured in silica fibers, and to those used in previously reported numerical models; allowing for experimental results to be compared to the published numerical models.

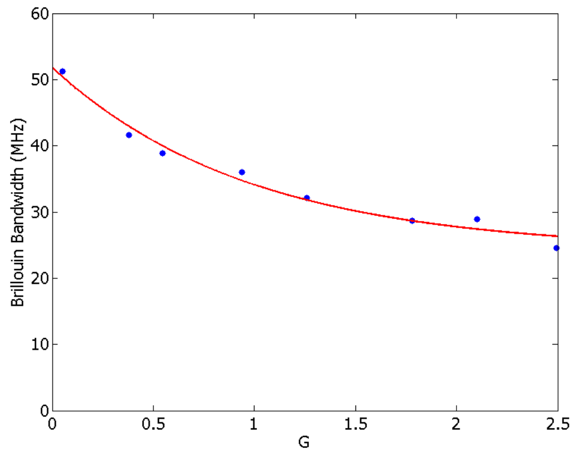

Figure 5: Results of pump probe experiment showing the Brillouin bandwidth as a function of the effective Brillouin gain in the fiber.

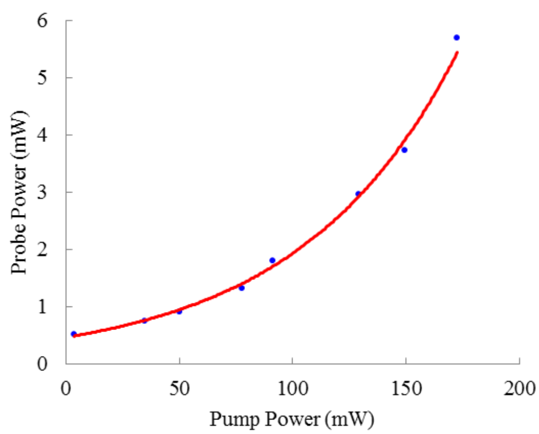

Figure 6: Results of pump probe experiment showing the gain in 75 m of passive 10/125 fiber in order to calculate g_b.

The cutback experiment was performed using fiber lengths from 70 m to 15 m (Fig 7). A maximum enhancement factor of ~18 is reported for a linewidth of 1.47 GHz and a fiber length of 70 m. For all lengths, there is a linear dependence on the linewidth which is in accordance with the simulations in [5]. The models in [5,6] predict that the enhancement factor has little dependence on the fiber length (L) until L <30 m. In our cutback experiment, we saw little decipherable dependence on L for L>20. At 20 m, there was approximately a 6% reduction in the enhancement factor over the L=70 m case. For L=15 m, the reduction was much steeper at 28%. Therefore, the cutback experiment captures the general trend predicted by the models. However, these results are preliminary and future experiments are planned to obtain a more accurate comparison with the theoretical predictions.

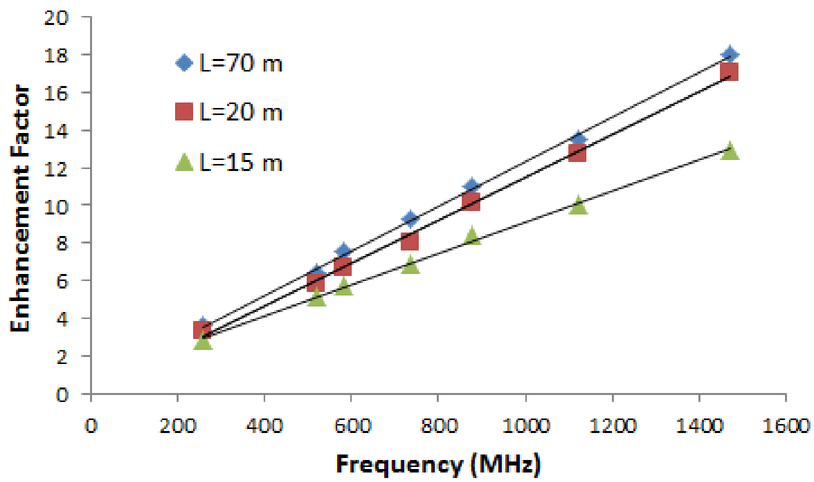

Figure 7: The measured enhancement factor as a function of linewidth and passive fiber length for phase modulation via WNS. The frequency here is taken to be as the FWHM of the random voltage

We also compared the results obtained for WNS with phase modulation through PRBS. A PRBS pattern is typically denoted as 2^n-1. The power (n) indicates the shift register length used to create the pattern. For PRBS phase modulation, the binary '0' and '1' data bits represent phase shifts of '0' and 'π', respectively. Subsequently, a sinc^2 spectral linewidth is generated. Using PRBS modulation, the SBS spectrum can be preferentially altered through appropriate bit rate and pattern length adjustments. PRBS was investigated theoretically in [5]. It was concluded that for length typical of fiber amplifiers (~10 m), patterns at or near $n = 7$ provide the best mitigation of SBS. Longer bit patterns (e.g. n=17,31) were appreciably less effective. It can be argued that for longer bit patterns applied to relatively short fiber length, the period required to generate the full pattern at GHz level modulation is much longer than both the phonon lifetime and the roundtrip time of the light. Therefore the full benefit of SBS suppression is not fully realized. Conversely, for longer fiber length, it is expected that the longer bit patterns would become effective in suppressing SBS.

To validate this and to compare to phase modulation through WNS, our cutback experiments included a study of PRBS using the patterns n=7,15. For PRBS, the modulation frequency in our experiments was varied all the way up to 2 GHz. The results are shown in Figure 8. Clearly, for L=15, the n=7 PRBS pattern is superior to n=15 in suppressing SBS. It also superior to the WNS results we obtained in our experiments at that fiber length for comparable frequencies. If the fiber length is cut even shorter to ~10 m, this pattern is expected to perform even better relative to the WNS as the enhancement factor for the WNS will decrease more rapidly. For L=70 m, both patterns (n=7,15) provide approximately the same enhancement factor. As can be seen, there is a small improvement at this length in the enhancement factor for n=7 over the L=15 m case. However, for n=15, there is a significant improvement as there is now sufficient time for the phase modulation pattern to develop as the Stokes light traverses the fiber.

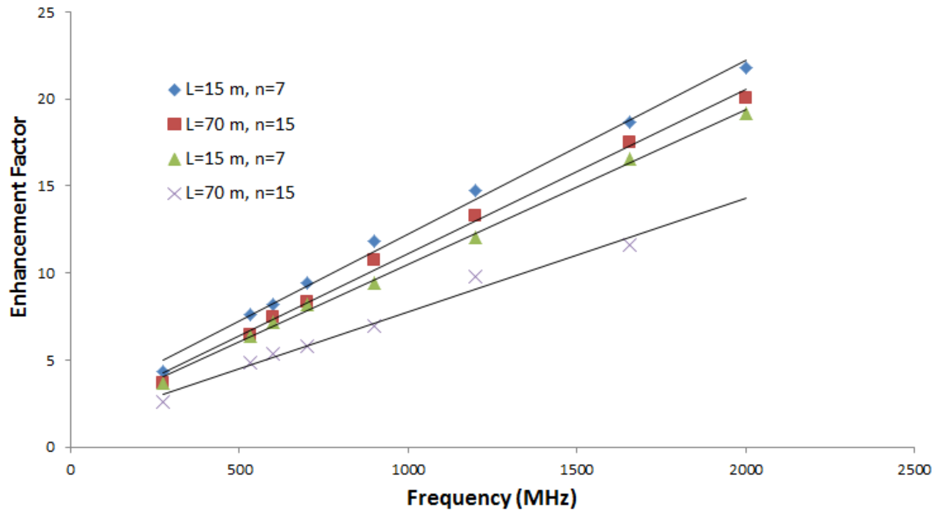

Figure 8: The measured enhancement factor as a function of linewidth and passive fiber length for phase modulation via PRBS. Two patterns are considered (n=7,15). The frequency here is taken to be defined the clock rate.

5. CONCLUSION

A cutback experiment was performed using a WNS phase modulated signal on passive fiber lengths from 70 m to 15 m. Here a varying signal bandwidth from 260 MHz to 1470 MHz was applied. Notably, at an optical bandwidth of 1470 MHz an enhancement factor of ~18 for a 70 m fiber length was attained. As expected from the theoretical models, a small change in enhancement factor was seen in the cutback from 70 m to 20 m, with a more pronounced decrease in seen below 20 m. In addition, the PRBS pattern n=7 is shown to have a weaker dependence on length over the range of fiber lengths investigated in our cutback experiments. Future experiments are planned to obtain a more accurate comparison of the effectiveness of WNS and PRBS in suppressing SBS as well as comparison to the theoretical predictions regarding the dependence of the enhancement factor for both techniques on fiber lengths.

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