Stimulated Brillouin Scattering (SBS) Suppression Techniques in High Power Fiber Amplifiers

Michael W. Zmuda and Craig A. Robin

Abstract-This paper explores the various methods to mitigate SBS in high power fiber amplifiers for military applications. The techniques presented include cascaded fibers with different Stokes shifts due to various Ge-dopant concentrations, using a thermal gradient across the fiber to broaden the gain, and finally, using frequency modulation of the pump beam to broaden the spectrum and increase threshold.

I. Introduction

The desire to develop high power lasers for national defense has been a goal by the United States Air Force for over three decades. Although first application lasers were based on chemical laser concepts, solid state and fiber lasers have many advantages and potential benefits than chemical lasers, including size, weight, and preferable pumping mechanisms. There are several barriers, however, that must be hurdled before such benefits can be realized. Among these barriers include nonlinear effects that limit fiber amplifier output power.

Advanced laser concepts utilizing fiber amplifiers and fiber lasers are limited in power output by stimulated Brillouin scattering (SBS) thresholds. Although stimulated Raman scattering (SRS) is a concern, these effects are typically three orders of magnitude lower than SBS. For SBS, a high intensity source can create an acoustic wave in the fiber through the process of electrostriction[1]. This acoustic wave will then create refractive index variations within the fiber which in-turn scatter the pump light through Bragg diffraction[2]. The scattered light will be Doppler downshifted in frequency by the index grating which is moving at the acoustic velocity. The scattered, or Stokes, wave will beat with the incident pump giving rise to additional acoustic waves (See Figure 1.).

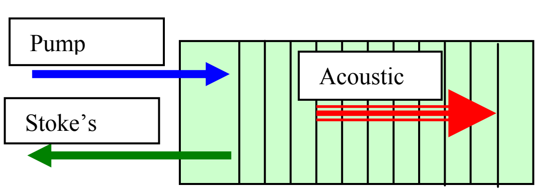

Figure 1: SBS in Single-Mode Fibers

This non-linear self-feeding mechanism is limited by the incident pump power and the lifetime of the acoustic phonons.

As the incident pump power is increased it will reach a maximum threshold in which no additional output power will be realized due to complete conversion to the backward scattered Stokes wave. This is the SBS threshold. The transmitted intensity is "clamped" once SBS threshold has occurred. Increasing the SBS threshold would therefore increase the transmission output potential.

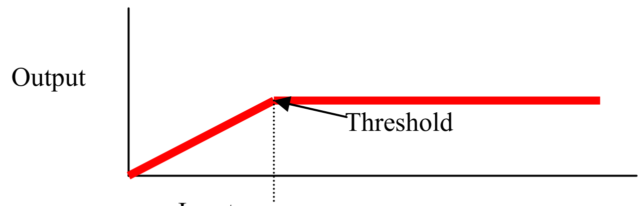

Figure 2: SBS "Clamped" Power Threshold

It has been shown that SBS threshold depends on several factors, including the spectral width of the pump wave, the length of the fiber, temperature, and fiber core diameter [1] [2-6].

Another SBS mitigation technique utilizes phase modulation. Phase modulation of the pump signal has been shown to decrease SBS threshold as well as the effective SBS gain by changing the phase of the pump wave E-field, thus increasing the effective pump wave spectral width.

Figure 3 shows a brief history of published fiber laser and amplifier systems over the past several years. It demonstrates the remarkable improvement in the output power of a single mode beam. The pink line represents commercial single mode product development while the blue line indicates progress in laboratory demonstrations.

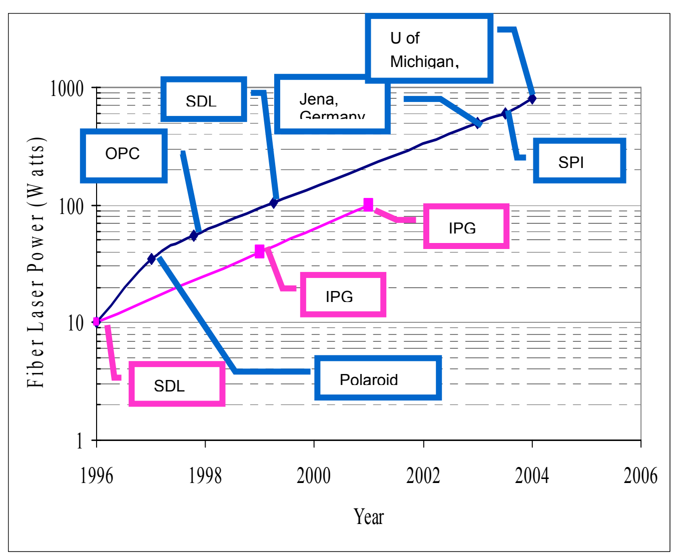

Figure 3: History of Fiber Laser Power Output

More recent results include 410 Watts, single frequency, and high beam quality for a fiber amplifier made by IPG Photonics, and 1 kW achieved by Corning with their SBS suppressive fiber. Many of these output power improvements were made possible with the use of large fiber core diameters. Low numerical apertures and other concepts such as bend loss were used to maintain high beam quality in the output. Unfortunately, it becomes increasingly more difficult to maintain high beam quality as the core size grows, as demonstrated by the M2 value of ~4 for the aforementioned Corning fiber.

Although it would be convenient to bundle multiple fibers together to acquire the required power of tens of kilowatts, power is not the only measure of how useful a laser system can be. If it were, then beam quality would not be a factor limiting the core size of our fiber laser systems. Brightness is a more robust measurement that incorporates not only the power, but also the beam quality as we shall describe. For this reason, SBS mitigation techniques must incorporate the ability to ensure fiber power scaling through coherent beam combination, not just single fiber output power.

II. Theory

Power Threshold

The following estimation for SBS power threshold in fibers was introduced by Smith in 1972 and modified by others to improve its accuracy:

$$P_{th} = C\frac{kA_{eff}}{g_B L_{eff}}\left(1+\frac{\Delta\nu_s}{\Delta\nu_p}\right) \quad \textbf{(1)}$$

Here C is a constant, typically assigned a value of "21" for fibers, and k is a factor relating to the effects of polarization ($1<k<2$), and g_B is the gain coefficient. Although the trends related to this equation remain consistent, the value of the constant C changes depending on the conditions under which the fiber amplifiers operate. From this relationship, it is apparent that larger fiber cores will result in a higher power threshold, while longer lengths result in a lowered power threshold. By increasing the effective area and the seed bandwidth while maintaining short effective lengths, the threshold can be kept very high. In addition, there are limits to the minimum length of our fibers. For amplifiers, fibers must be long enough to fully absorb the pump.

Acoustic Velocity

In examining techniques to mitigate SBS in fiber amplifiers, one must further understand the nature and characteristic of SBS in fibers. Conservation of energy and phase requires:

$$\Omega_B = \omega_p - \omega_s$$
$$k_A = k_p - k_s \quad \textbf{(2)}$$

Where: Ω_B = Brillouin frequency

Subscripts P,S, and A refer to Pump, Stokes, and Acoustic

The Brillouin frequency can be related to the acoustic wavevector through the dispersion relation: (From Agrawal page 356)

$$\Omega_B = \mathrm{v}_A\left|k_A\right| \approx 2\mathrm{v}_A\left|k_p\right|\sin\left(\frac{\theta}{2}\right) \quad \textbf{(3)}$$

If we limit our fiber applications to single mode where only forward and backward directions exist, Equation 3 reduces to:

$$\nu_B = \frac{\Omega_B}{2\pi} = \frac{2n\mathrm{v}_A}{\lambda_p};$$
$$Where\left|k_p\right| = \frac{2\pi n}{\lambda_p} \quad \textbf{(4)}$$

From this we see that the acoustic velocity (v_A) within the fiber core can play a significant role in determining how we might mitigate SBS. By changing the properties of the acoustic velocity within the fiber, one would change the corresponding SBS effect. If the center Brillouin frequency was shifted beyond its width, then the effect of SBS threshold would be mitigated.

Parameters Affecting Acoustic Velocity

To mitigate the effects of SBS, we need to determine the relationship by which physical parameters affect the acoustic velocity in fibers. The equation of motion for a pressure wave stated by Boyd as given by Fabelinskii, 1968, section 34.9:

$$\frac{\partial^2\Delta\tilde{p}}{\partial t^2} - \Gamma'\nabla^2\frac{\partial\Delta\tilde{p}}{\partial t} - \nu_A^2\nabla^2\Delta\tilde{p} = 0 \quad \textbf{(5)}$$

Where:

p=Pressure, t=Time, ρ=Density, v_A =Accoustic Velocity

The acoustic velocity from a pressure wave can be written in terms of thermodynamic variables as follows [1]:

$$\nu_A^2 = \left(\frac{\partial p}{\partial\rho}\right)_s \quad \textbf{(6)}$$

Compressibility is defined as the following [1]:

$$C \equiv \frac{1}{K} = -\frac{1}{V}\frac{\partial V}{\partial p} = \frac{1}{\rho}\frac{\partial\rho}{\partial p} \quad \textbf{(7)}$$

Where:

C=Compressibility, K=Bulk Modulus, V=Volume

For solids and liquids involved in non-diffusive, adiabatic processes [7]:

$$\frac{dT}{T} = -\left(\frac{\beta}{C_T c_V}\right)dV = \left(\frac{V\beta}{c_P}\right)dp \quad \textbf{(8)}$$

Where:

T=Temperature, β=Coefficient of Thermal Expansion

C_T =Isothermal Compressibility; c_V ,c_p =Heat Capacities

We will assume an adiabatic process occurs. This leads to:

$$\Rightarrow -\frac{1}{V}\frac{dV}{dp} = C_T \frac{c_V}{c_p} \quad \textbf{(9)}$$

At room temperature or above, the heat capacities at constant temperature and constant volume are nearly equal (Stowe 479). Both the Debye and Einstein models give heat capacity = 3Nk for temperatures greater than room temperature.

Debye Model:

$$E = 9N_a \frac{(kT)^4}{\varepsilon_{\max}^3} \int_0^{\varepsilon_{\max}/kT} \frac{x^3}{e^x - 1} dx \cong 3N_a kT \text{ @ high temp} \quad \textbf{(10)}$$

Einstein Model:

$$E = 3N_a \frac{\hbar\omega_0}{e^{\frac{\hbar\omega_0}{kT}} - 1} \cong 3N_a kT \text{ @ high temp} \quad \textbf{(11)}$$

Heat Capacity:

$$\frac{dE}{dT} = 3N_a k \text{ @ high temp(300K+)} \quad \textbf{(12)}$$

Compressibility can be measured either at constant temperature or at constant entropy and are related as follows [1]:

$$\frac{C_T}{C_S} = \frac{c_p}{c_V} \Rightarrow C_S = C_T \frac{c_V}{c_p} \cong C_T \quad \textbf{(13)}$$

From **Error! Reference source not found.**(6), (7) and (11) we obtain the following:

$$C_S = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_S = \frac{1}{\rho v_A^2} \cong C_T \quad \textbf{(14)}$$

$$\Rightarrow v_A = \sqrt{\frac{1}{C_T \rho}} = \sqrt{\frac{K_T}{\rho}} \quad \textbf{(15)}$$

The acoustic velocity in a fiber core is equal to the square root of the Bulk Modulus divided by the density. If we assume the densities of our fiber cores do not change within our operating temperature range, then the temperature dependence for the velocity of sound is the temperature dependence of the bulk modulus. Temperature dependence of the bulk modulus must be determined empirically.

$$\Rightarrow v_A = \sqrt{\frac{f(T)}{\rho}}; \quad \textbf{(16)}$$

Where f (T) increases with Temperature

To obtain the f(T) in a fiber, one could conduct an SBS experiment with varying temperatures. From this, the effects and relationships of temperature and densities would be known for the acoustic velocity, and, in turn, the associated effects on SBS.

Coherent Beam Combining

As stated above, achieving effective power scaling for power levels in the tens of kilowatts for military applications requires independent beam combining. Although wavelength beam combining (WBC) is another technique, we shall focus on coherent beam combining (CBC) due to current research focus within the Air Force. Temporally incoherent beams (N) with brightness B1 for each beam combine as:

$$B = \frac{NP}{\Omega(NA)} = B_1 \quad \textbf{(17)}$$

While coherent beams (N) of brightness B1 combine as:

$$B = \frac{NP}{(\Omega/N)(NA)} = NB_1 \quad \textbf{(18)}$$

For CBC, the illustration in Figure 4 depicts the two conditions stated above.

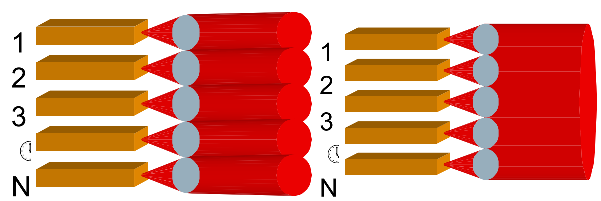

Figure 4: Non-coherent versus Coherent Beam Combining

From this, for coherent beams, we can power scale by the factor "N". In addition, the brightness of each fiber beam is dependent upon the beam quality (M2) according to the definition of brightness given by Fan:

$$B_1 = \frac{CP}{\lambda^2 (M2)^2} \quad \textbf{(19)}$$

Where C = 1 for Gassian Beams

Although fiber amplifiers have been reported to achieve near the kilowatt power, they are done so with large M2 values, thus minimizing their ability to be power scaled through CBC. For low M2, a master oscillator power amplifier array approach can simplify the coherent combination process. If each element of the amplifier array were absolutely identical, no compensation would be required to maintain perfect phasing of each element. Unfortunately, the amplifiers will have slightly different lengths, have small fluctuations in temperature, be pumped at different powers, and have a myriad of other non-uniformities that destroy the phase front at the end of the fiber.

The amount of acceptable variation between elements is strongly dependent on the master oscillator bandwidth. The greater the bandwidth, the shorter the coherence length and therefore the tighter the tolerances. This alone pushes one to use very narrow line width sources. The side effect of that is a reduction in SBS threshold. Typical high power systems being developed today have broad spectral bandwidths to help mitigate SBS, but this also reduces their overall effectiveness for coherent combination. The goal, therefore, should be to increase SBS threshold, while maintaining narrow bandwidth operation with M2 <1.5.

III. Current Large Core And Other Techniques

As discussed, the SBS threshold is proportional to the field diameters of the mode in the fiber. This was the first and simplest mitigation technique. If the power carried by the fiber is spread out over larger area, intensity decreases as does the possibility for non-linear interaction. If beam quality is not an issue, the core size of a fiber can be made large enough to support a fiber amplifier capable of 10-20 kW. This type of industrial laser is commercially available today.

However, if one is concerned with beam quality, as we discussed, a much more stringent parameter is placed on the fiber. One must attempt to scale core size while maintaining single transverse mode operation. Currently the largest truly single mode, step-index fiber has a mode field diameter of approximately 10-12µm. An amplifier, without additional SBS mitigation techniques, with this core size will, at best be capable of ~100W. Fortunately there are a few tricks that allow for larger core fibers to be used. Specifically, waveguide modes are subject to losses if the fiber is bent or coiled. Higher order modes see a greater loss than the fundamental mode in a regular step index fiber. A large mode area fiber, which when un-bent may support 10 transverse modes, can be coiled to filter higher order modes leaving only the fundamental.

Other techniques recently used to mitigate SBS include extremely expensive specially manufactured fibers with varying radial densities or longitudinal stresses to change the response of the acoustic velocity within the fiber region core. Although these techniques has proven success on an individual scale, budget constrained military environments require the use of more readily available—and cheaper—commercial-off-the-shelf components and associated pumping schemes.

Larger core diameters with stringent launch conditions and expensive specialty fibers may require costs associated with peripheral pumps and set-ups that exceed current budget limitations for mass applications. As a result, such approaches, although novel and useful, may not have the ability to be deployed. For this reason, a more thoughtful approach using current capabilities, manufacturability, and within a robust military environment must be considered.

IV. Fiber Density Variation Techniques

There have been several papers identifying the effects of Ge-dopant concentration variations on SBS [4] [5] [7] [8] [9]. Since the Stokes wave is Doppler downshifted by the acoustic velocity in the fiber, changing the acoustic velocity through differential Ge-dopant concentration would change the Stokes frequency accordingly. If the Stokes differential shift is greater than its line width, the effective fiber length for SBS effect would decrease. It was found that a change of 1% in GeO_2-core concentration resulted in a Brillouin line shift of about 94 MHz [9]. Typical Brillouin line widths for this fiber are about 35 MHz, thus changing the dopant concentration by about .35 % would shift the Brillouin frequency by a line width. Mao et al. linked 10 fiber segments, each with differing Brillouin frequencies, differing by at least Brillouin line width, resulting in increased SBS threshold by 10-dB [7]. Tsujikawa et al designed and fabricated optical fiber with varied Dopant concentrations and core diameters resulting in Brillouin frequency that varied linearly through the fiber which increased SBS threshold by 15-dB [8].

At AFRL/DELO, experiments were conducted to verify reported results for the foundation of a more comprehensive, integrated SBS mitigation model. Variations in the Ge dopant concentrations within the core of single mode fibers caused large variations in the SBS gain measurement. We measured the gain in two Nufern fibers. Both had nearly identical numerical apertures, but had a 2% variation in Ge dopant. The Stokes shift changed by nearly 200MHz between the two which is several times the SBS gain bandwidth.

Dopant (%Ge)	**Center Frequency (GHz)**	**Bandwidth (MHz)**
8	*15.7268*	*23.7*
6	*15.9051*	*34.0*

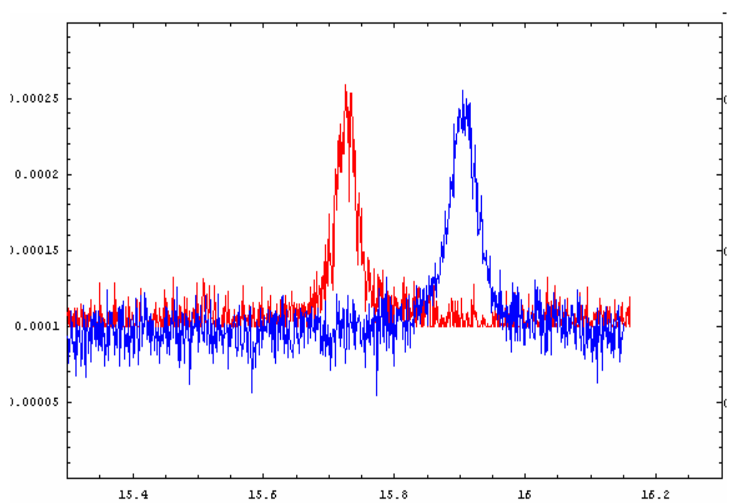

Figure 5: SBS Absorption of Two Nufern Single Mode Fibers

A theoretical model has been developed including the use of differential Ge-dopant concentrations to assist in the determination of the most promising techniques for increasing SBS thresholds within Ytterbium-doped fiber amplifiers, realizing a potential power output increase by at least an order of magnitude. This model explores and predicts SBS threshold as function of differential chemical composition of fibers, including the thermal effects associated with DCF pumping. Narrow linewidth, single mode wave propagation is maintained in order to increase overall effectiveness for future coherent combination. This model explores optimization schemes for combining several fiber segments with differential SBS gain profiles. Ytterbium-doped Double Clad Fibers were manufactured with a variety of core densities to validate the model. Core densities between fibers varied significantly enough to ensure a change in the acoustic velocity which met model requirements for shifting SBS gain center frequency. Changes in fiber core densities were created without impact to optical or other physical properties. Results of tests agreed with model predictions, providing a significant increase in SBS threshold. Validated model predicts at least a gain in SBS threshold by a factor of ten.

V. Thermal Variation Considerations & Techniques

Another AFRL/DELO approach to the reduction of SBS gain is to control the temperature within the fiber. A thermal gradient causes different Stokes shifts at each point within the fiber, thus creating an inhomogeneous broadening within the fiber. This could be implemented in a fiber wrapped around a spool with a strong thermal gradient across it. Also, an understanding of the thermal effects to the acoustic velocity could lead to the incorporation of the natural temperature differential found within a fiber amplifier into a more comprehensive model.

To determine the effects of temperature on SBS, and also to assist in the development of an analytical model for SBS mitigation designs, we conducted thermal SBS experiments using single mode fiber. Our initial measurements were collected by immersing the fiber in a water bath. It was determined that water would act as an excellent moderator and thermally efficient thermal soak medium for the time required to conduct our experiments. Absorption characteristics of the fiber were analyzed to ensure hydration would not impact our results.

A water pump circulated the water throughout the bath, thus keeping the water at a uniform temperature. We brought the temperature to the highest value and began to take measurements as the bath cooled down.

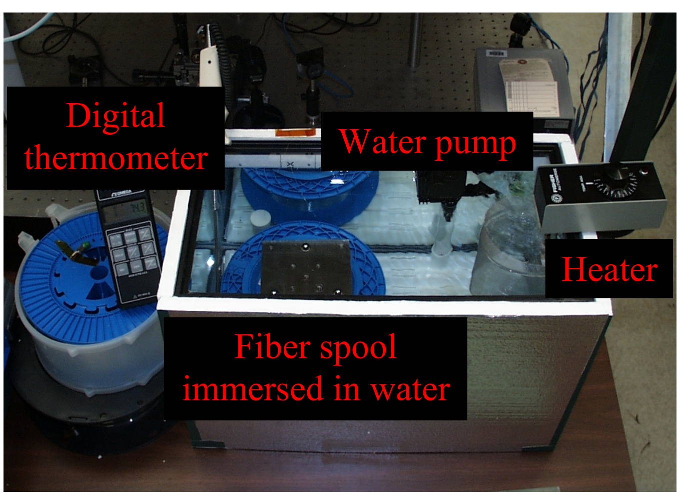

Figure 6: SBS Absorption of Two Nufern Single Mode Fibers

Our results were used acquired for several runs to acquire consistent results. It was determined that that a change in temperature of 1 degree result in shift in the Stokes frequency by .93 MHz. Since typical SBS widths are about 35 MHz, a temperature differential of 38 degrees will shift the Stokes frequency out side of the previous response.

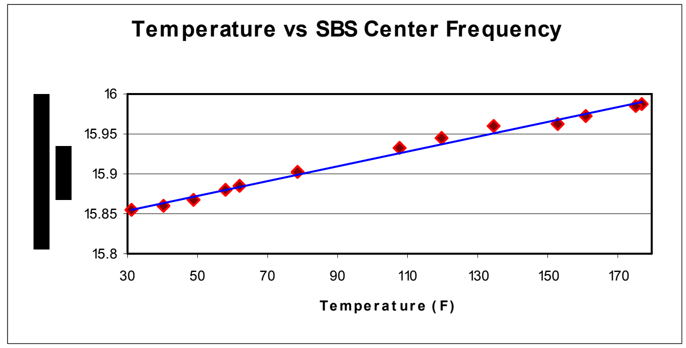

Figure 7: Effects of Temperature on Stokes Frequency

These results were used to determine the overall impact on the acoustic velocity, specifically, to determine the f(T) for V_A. From this, a more accurate model was developed to predict the effect of temperature changes on DCF for the design of a SBS mitigated amplifier without the need for a unique an expensive fiber design.

VI. Phase Modulation Techniques

So far we have looked at how to change the physical characteristics of the fiber to mitigate SBS. Another technique would be to manipulate the incoming laser source so that SBS already present has less of an impact. If the source were broken up into different frequencies with lowered power per frequency, SBS would see each frequency independent of the others. One method might be to phase modulate the source prior to entrance into the fiber.

Phase modulation of the pump signal has been shown to decrease SBS threshold as well as the effective SBS gain by changing the phase of the pump wave E-field, thus increasing the effective pump wave spectral width. Lichtman et al. investigated the effects of modulation on SBS gain [3]. Theoretical results showed that SBS threshold depends on the ratio between the spontaneous Brillouin line width and the bit rate [3]. Lichtman et al. demonstrated that phase modulation would increase SBS threshold [3]. Recent research efforts at AFRL/DELO have demonstrated SBS suppression by phase modulation in single mode fibers. Experiments in August 2002 through November 2002 have demonstrated a decrease in Brillouin frequency output by at least a factor of two through phase modulation of the pump signal.

The experimental set-up is shown in figure 8. Here the source is modulated with modulation frequencies of 100, 200, 300 and 400 MHz are compared to no modulation with a common modulation depth. The results are shown in Figure 9. An SBS seed signal was beat against the source to ensure separation of frequency. As the seed signal laser was heated closer to the source laser, it scanned frequency responses with a known frequency differential from the source. The responses and associated peaks represent the Stokes frequencies and relative amplitudes responding to the various source frequencies and amplitudes. To ensure benefits of such a scheme, corrective modulation scheme is required at the output.

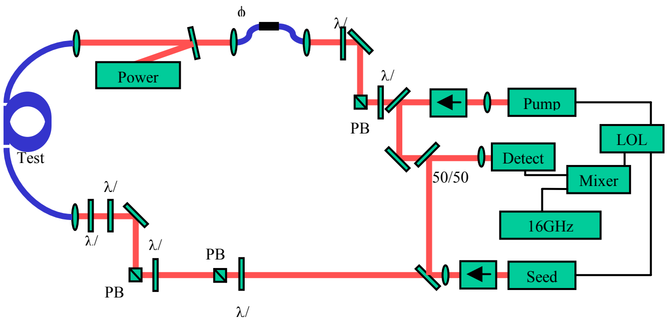

Figure 8: SBS Modulation Scheme Set-up

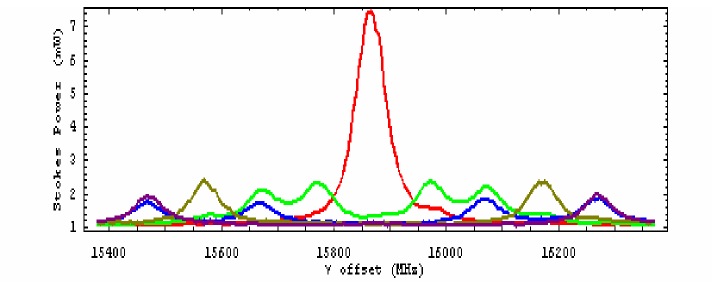

Figure 9: SBS Seed Response to Phase Modulation

In an effort to increase SBS threshold for future high power fiber amplifier applications, additional modulation schemes were identified, modeled and tested. Phase modulation of the signal source prior to entering the fiber spreads the input beam spectrum into "sidelobes" with overall lowered peak powers. The modulation depth and frequency of the phase modulator determine the number of sidelobes and relative peak powers. With a modulation frequency greater than the SBS gain bandwidth, the increase in SBS threshold will be inversely proportional to the decrease in the peak sidelobe. The sidelode properties were modeled to determine the effect on SBS threshold. The sidelobe peak maxima were determined to be proportional to the nth Bessel function evaluated at the modulation depth. These results are shown in Figure 10 below:

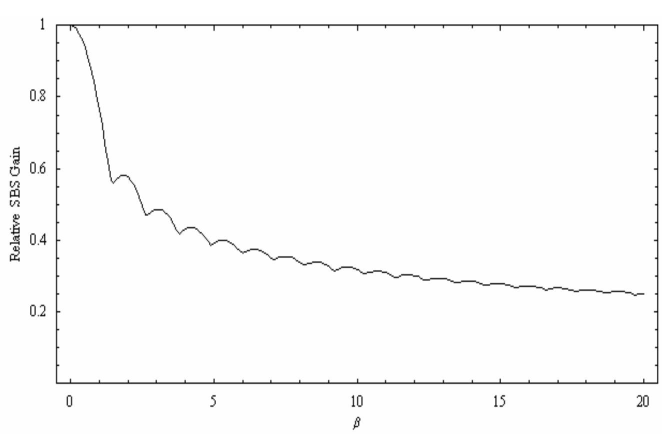

Figure 10: Model of Modulation Depth versus SBS Gain

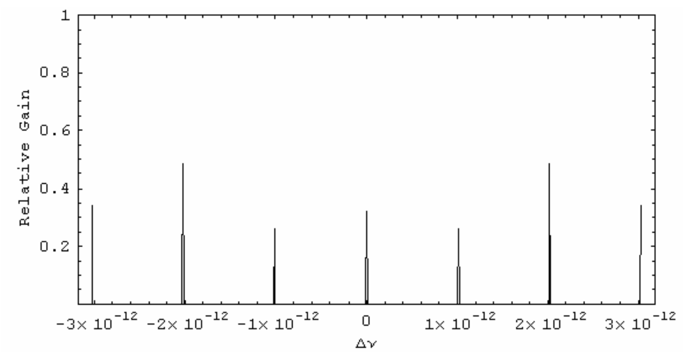

Figure 11: Relative SBS Gain due to Phase Modulation

Modulation depth controls the peak spectral component of the pump beam and therefore the relative SBS threshold

It was determined analytically that a 2.63 increase in SBS threshold was possible with a strong modulation depth of about 5. Source signals were phase modulated with a polarization maintaining Lithium Niobate phase modulator prior to entering a single mode non-polarization maintaining fiber. An SBS seed source with varying input frequencies was used to evaluate the SBS gain profile for each phase modulation scheme. Validation of the theory and model was successful with a demonstrated factor of two increase in SBS threshold using lowered modulation depth of about 2.5.

Passive fiber was used to quantify the SBS gain for different fiber types under a variety of conditions. For clarification, the "pump" indicates the SBS pump (not a pump for a fiber laser or amplifier). The "seed" is then the beam used to probe the SBS gain. Two lightwave electronics NPRO lasers were used for the SBS gain measurements. One was used to pump the fiber, the other used to probe it. Their frequency separation was actively controlled using a Lightwave Electronics Laser Offset Locking Accessory. The seed polarization was controlled using a ½ wave plate and a ¼ wave plate just before the input into the fiber. This allowed for control of the polarization so gain measurements could be collected with the seed beam both co- and cross-polarized with the pump. The phase modulator in the upper portion of the schematic was used only for the portion of the experiment investigating the effects of phase modulation on the SBS gain.

Using a lithium niobate phase modulator, we were able to demonstrate a gain reduction in the fiber by spreading the spectrum of the input pump beam. This creates sidelobes at the modulation frequency which have a lower overall peak. Assuming the modulation frequency is greater than the SBS gain bandwidth, the reduction in SBS threshold is governed by the amount of power in the most prominent sidelobe which is proportional to the nth Bessel function evaluated at the modulation depth.

This concept can be clarified as follows: The phase modulation depth controls the magnitude of each spectral component in the pump beam. Since each spectral component is outside the gain bandwidth of the others they must create a

Stokes signal independently, thus threshold is increased to the point where the peak spectral component reaches threshold.

VII. Conclusions

SBS mitigation techniques have been presented to increase the overall laser output power for use in military applications. Although many companies have sought novel and promising concepts and demonstrations, the solution will likely be a combination of techniques that utilize standard industry practices and manufactured components in order to mitigate costs. The most promising solution is the utilization of standard DCF cores and pumping schemes, combined with cascading fibers of varying dopants, utilizing novel modulation schemes and the natural temperature differentials found in active fiber amplifiers. To ensure the efficiency of design, a comprehensive model must be developed to accurately incorporate all these features with the greatest effectiveness and efficiency. The next step in the Air Force research area is to implement the information gained from these basic measurements into a fiber amplifier system. Cascading different fiber segments together will allow for increased power transmission through the amplifier while maintaining a beam that is useful for high power coherent beam combination.

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