502 Watt, single transverse mode, narrow linewidth, bidirectionally pumped Yb-doped fiber amplifier

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Abstract: High power operation of narrow linewidth optical fiber amplifiers is usually limited by the onset of stimulated Brillouin scattering. In this paper, we present results demonstrating over 500 Watts of power in a single mode beam from a fiber designed to suppress stimulated Brillouin scattering through a reduction in the overlap of the optical and acoustic fields. Simulations demonstrate the potential for this fiber to achieve greater than 1000 Watts of output power.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (290.5900) Scattering, stimulated Brillouin.

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1. Introduction

The power of single transverse mode Ytterbium-doped fiber laser oscillators has increased dramatically in recent years with several reports of powers in excess of 1 kilowatt [1-3]. In such laser oscillators, the linewidth is typically tens of nanometers. This broad linewidth is of no consequence for many applications, such as materials processing, where simply high power and good beam quality are desired. However many applications, including coherent beam combination, nonlinear frequency conversion, ladar and LIGO, require high output power, good spatial beam quality and narrow linewidth operation to be combined in a single device. High power, narrow linewidth signals can generally be realized using a master-oscillator, power amplifier (MOPA) configuration rather than a laser oscillator where, due to typical cavity lengths of several meters, the discrimination of closely spaced longitudinal modes is difficult.

The primary limitation on the output power from narrow linewidth devices is the onset of stimulated Brillouin scattering (SBS). SBS occurs in an optical fiber when the signal propagating in the core generates an acoustic wave through the process of electrostriction. The acoustic wave scatters light in the reverse direction and reduces the forward propagating power [4]. The use of large mode area fibers to decrease the optical intensity in the fiber core has been used to raise the SBS threshold but the maximum output power from narrow linewidth optical fiber amplifiers is still limited to approximately 100 Watts [5]. Power levels as high as 264 Watts for a polarized output and 500 Watts unpolarized have recently been achieved through the use of a pump induced thermal gradient in a counter-pumped fiber amplifier [6]. The temperature gradient changes the frequency shift associated with Brillouin scattering and decouples the SBS gain between sections of fiber at different temperatures. Raising the SBS threshold in this way is most readily achieved with single-ended pumping which maximizes the temperature gradient in the fiber. Distributed pumping or two-ended pumping schemes will reduce the thermal gradient [7] and increase the SBS gain relative to single-end pumping. Externally applied thermal gradients have also been demonstrated to raise the SBS threshold [8]. However the power level achieved with this technique remained below 200 Watts and was limited by thermal degradation of the polymer based outer cladding.

An alternative approach to raising the SBS threshold in optical fibers is to reduce the overlap between the optical and acoustic modes of the fiber. Several methods have been proposed to achieve this. In [9], a 3 dB improvement in SBS threshold was achieved in a telecommunications fiber by an appropriate choice of refractive index profile that minimized the acousto-optic overlap while maintaining the desired optical properties. However, such an approach is difficult to implement on low numerical aperture, large mode area (LMA) fibers without creating significantly non-Gaussian modes. A reduction in the acousto-optic overlap can also be achieved by careful selection of the dopants in the core and cladding regions of the fiber. In one example [10], the core of a fiber was doped with alumina (Al_2O_3) to create an optical waveguide but an acoustic anti-guide. Another recent proposal, analyzed in detail in [11], is to use a combination of alumina and germania (GeO_2) doping in the fiber core to spatially separate the optical and acoustic fields. Fibers with this design have recently been shown to be capable of achieving over 500 Watts of power in a single-mode output, without the onset of SBS, even with bidirectional pumping [12].

In this paper we present a detailed description of the operation of a high SBS threshold fiber with 500 Watts of output power under bidirectional pumping conditions. We also discuss experiments, coupled with numerical modeling, to estimate the effective SBS gain coefficient in LMA fibers using the high SBS threshold design of [11] and operating in the single-mode regime. Further numerical modeling of these fibers suggests that single-mode output powers in excess of 1000 Watts could be realized with a unidirectional pumping scheme.

2. 500 Watt narrow linewidth amplifier

A high power MOPA was constructed using a fiber manufactured according to the design of Fig. 5 in [11] with a graded alumina and germania dopant profile in the core. The fiber had a

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core diameter of 39 um, a hexagonal inner cladding diameter of 420 um and an outer cladding diameter of 520 um. The measured numerical apertures of the core and inner cladding were found to be 0.05 and 0.30 respectively. In contrast to the fibers described in [11], the Yb_2O_3 concentration was increased to 1 wt-% to allow for a shorter fiber to be used. The pump absorption in the inner cladding of the fiber was measured to be 3.2 dB/m at 976 nm.

A schematic of the MOPA constructed using this fiber is illustrated in Fig. 1. The signal source is a commercially available fiber laser generating 100 milliWatts of power at a wavelength of 1064 nm with a spectral width of 3 KHz. The output from this source is amplified to a power level of 5 Watts in a pre-amplifier comprising 4 meters of a conventional polarization maintaining Yb-doped double clad fiber with a core diameter of 20 um. This fiber was coiled to a diameter of 70 mm to remove higher order modes resulting in an M^2 value of 1.06 at the pre-amplifier output. The output of the pre-amplifier is then launched in to the power amplifier stage constructed using the high SBS threshold fiber described above. This fiber is pumped bidirectionally with fiber coupled laser diode stacks. Each pump source is capable of delivering up to 400 Watts of power at a center wavelength of 976 nm in a 400 um core, 0.22 NA fiber. A beam splitter, comprising an anti-reflection coated wedge with 0.3% reflectivity per surface, is placed between the two amplifier stages. This provides monitoring of the output power from the pre-amplifier and also of backward propagating light from the power amplifier stage. The optical spectrum and average power of the backward light are monitored continuously during the experiments to observe the onset of stimulated Brillouin scattering. Each stage of amplification is separated by >60 dB of isolation. This was found to be necessary to suppress parasitic oscillations in the amplifier system that were capable of damaging the output end of the power amplifier stage.

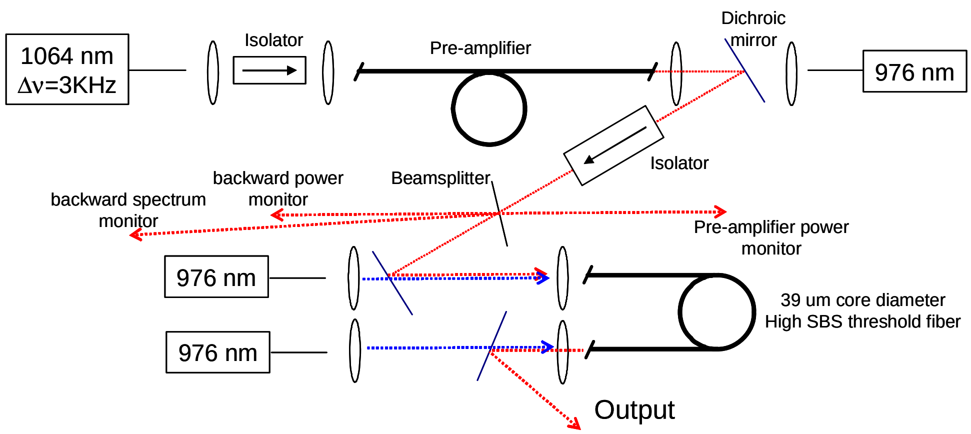

Fig. 1. Schematic of two stage amplifier system with high SBS threshold fiber

Initial experiments used 8.5 meters of the high SBS threshold fiber to ensure complete absorption of the pump radiation and prevent any interaction between the pump sources. Also, the fiber was coiled to suppress amplification of any high order modes. The output power as a function of total incident pump power is plotted in Fig. 2 and shows that a pump limited output power of 502 Watts was achieved. Measurements of the beam profile, shown in Fig. 3, show excellent mode quality and demonstrate single mode operation with an M^2 value of 1.4. The spectrum of the amplifier output is plotted in Fig. 4, with a resolution of 0.1 nm, for the maximum output power of 502 Watts. The spectrum shows no signs of parasitic lasing or significant levels of amplified spontaneous emission.

The backward propagating power is plotted in Fig. 5 as a function of the forward output power from the amplifier. The power level in the backward direction does not exhibit any sudden increase which indicates that we are still below the SBS threshold. The spectrum of the backward propagating light was also recorded and is plotted in Fig. 6 for the cases of 100 and 500 Watts of forward output power. With only 100 Watts of output power, the backward

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spectrum is dominated by Rayleigh scattering of the injected signal. The two subsidiary peaks, more than 20 dB below the main peak, are caused by Stokes and anti-Stokes Brillouin scattering within the fiber. At 500 Watts of output power the Stokes peak is almost equal in magnitude to the Rayleigh scattered peak, indicating a significant increase in the relative level of Brillouin scattered light and showing that although the output power is still pump limited, we are approaching the SBS threshold.

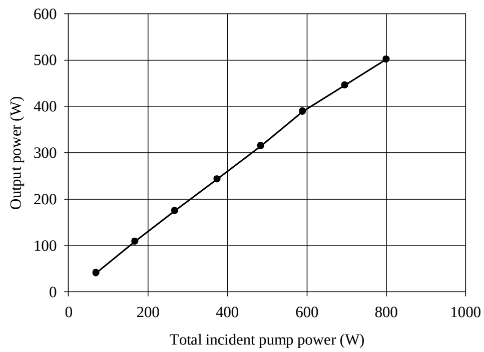

Fig. 2. Output power from 8.5 meter long, high SBS threshold fiber amplifier as a function of incident pump power.

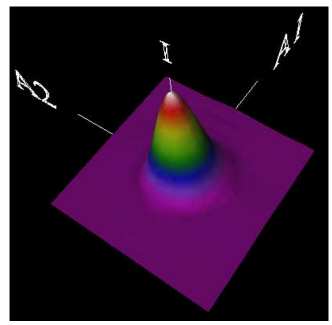

Fig. 3. Beam profile of single-mode amplifier output at 500 Watts

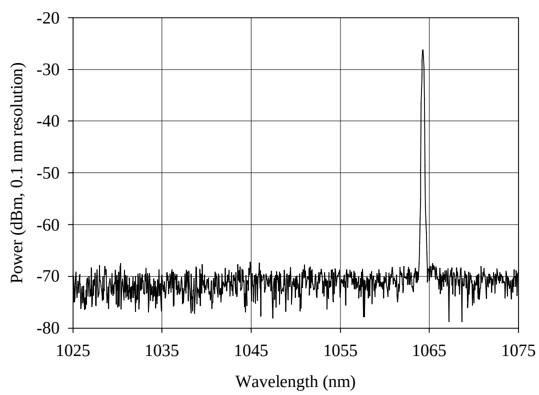

Fig. 4. Output spectrum of high SBS threshold amplifier with 502 Watts of power

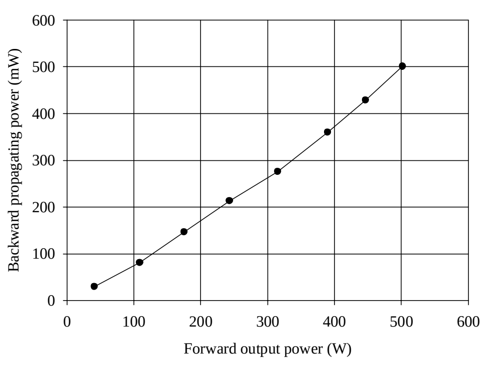

Fig. 5. Backward propagating power measured as a function of forward output power for an 8.5 meter long amplifier.

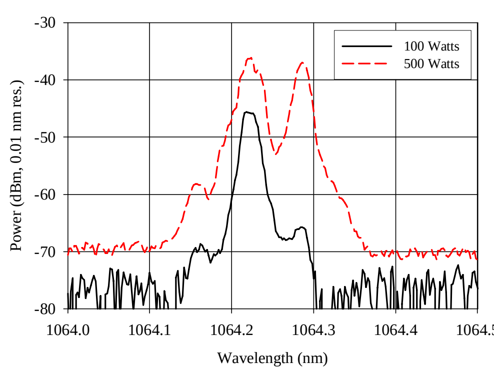

Fig. 6. Spectra of backward propagating light for 100 Watt and 500 Watt output powers from an 8.5 meter long amplifier.

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To obtain further information about the level of Brillouin scattering within this fiber, the amplifier experiment described above was repeated using 13 meters of the 39 micron core, high SBS threshold fiber. With this length of fiber the onset of SBS was clearly observed at a forward output power of only 300 Watts. This is clearly seen by the sudden increase in backward propagating power shown in Fig. 7. The SBS is also clearly observed in the spectral regime, shown in Fig. 8, where the Stokes peak is now 8 dB above the Rayleigh scattered signal.

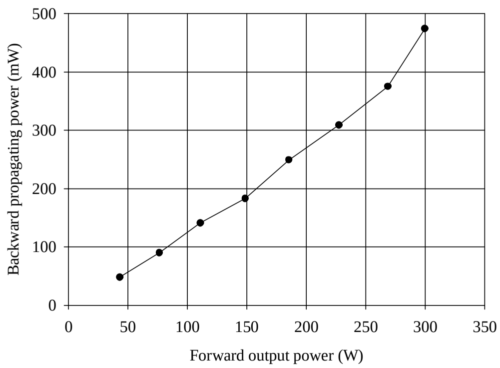

Fig. 7. Backward propagating power measured as a function of forward output power for a 13 meter long amplifier.

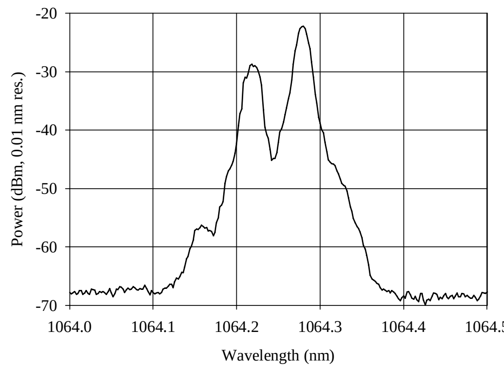

Fig. 8. Spectra of backward propagating light at 300 Watts of output power from a 13 meter long amplifier.

3. Modeling

To predict the performance of the high SBS threshold fibers in other configurations, particularly single end pumped amplifiers, it is useful to obtain a value for the Brillouin gain coefficient. This has been found by applying a numerical model, which takes in to account the bidirectional pump configuration and corresponding pump induced temperature gradient [13], to the data presented in [11] and section 2 above.

The model is first applied to the data showing the SBS threshold of the fiber labeled LMA-2 in Fig 7 of [11]. To find the peak value of the Brillouin gain coefficient, a three-step process was performed. First, the pump and signal power distributions along the fiber were found from the amplifier rate equations without including SBS. Secondly the calculated

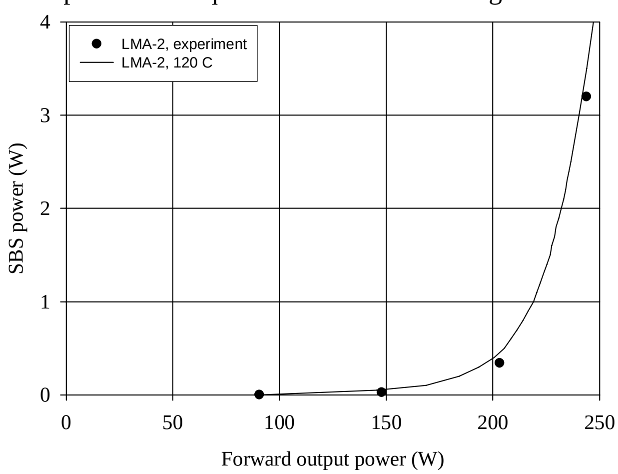

Fig. 9. Numerical simulation of LMA-2 data from [11]. Symbols represent experiment data and the solid line the simulation results.

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pump and signal powers were used to estimate the temperature distribution using the method mentioned in [7] and assuming convective cooling. Finally the Brillouin gain coefficient was found by varying its value until the signal and SBS powers agreed well with the experimental results. Figure 9 plots the results of the simulation along with the experimental data for the LMA-2 fiber. Note that the data from [11] has been scaled to account for the reflectivity of the beam splitter used to monitor the Brillouin scattered light.

The temperature gradient mentioned here is the temperature difference between the hottest and coolest spots in the fiber. In the two-end pumped experiments presented here, the pump power at each end of the fiber is always the same and the temperature gradient is approximately the temperature difference between the end and the middle point of the fiber. The temperature coefficient for the Brillouin frequency shift was 1.6 MHz/K [6]. With an estimated temperature gradient of 120 °C, the model found the Brillouin gain coefficient of the LMA-2 fiber to be 0.9×10^{-11} m/W. This is substantially lower than the value of 5×10^{-11} m/W for bulk silica materials that we would expect to observe in a step index fiber [14].

We next applied the model to the data of Fig. 7 showing the onset of SBS in a 13 meter long, 39 um core diameter amplifier. Using the Brillouin gain coefficient found for the LMA-2 fiber predicts a SBS threshold of 310 Watts with a temperature gradient of 80°C, which is in very close agreement with the observed threshold of 300 Watts. The model also predicts a threshold of 542 Watts for the 8.5 meter long amplifier at a temperature gradient of 110°C. This is in good agreement with the experimental data of Fig. 6 which suggest that our pump limited output of 502 Watts is close to the SBS threshold.

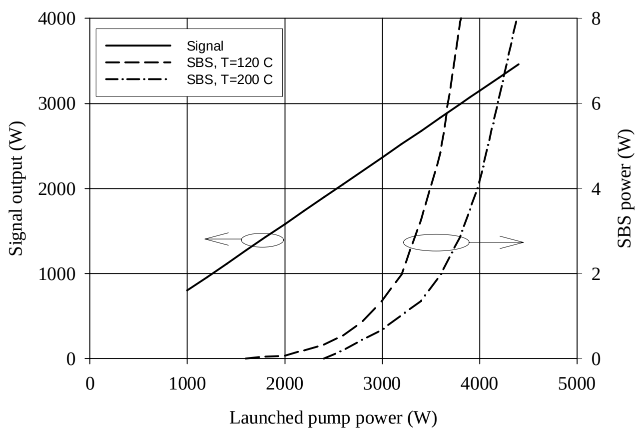

Fig. 10. Predicted signal and SBS powers for a counterpumped amplifier with 120 and 200 °C temperature gradients

The model was then used to predict the performance of the 8.5 meter long amplifier using only a counter-propagating pump configuration for temperature gradients of 120 and 200°C. It is assumed that these different temperature distributions can be achieved using active thermal control which may be necessary to prevent overheating at such high power levels, in contrast to the passive convective cooling used in the experiments described in this paper. As plotted in Fig. 10, it is clear that in this configuration the fiber is capable of generating more than 2000 Watts without the onset of SBS. This represents an improvement of more than a factor of 4 over the bidirectional pumping scheme. By combining this fiber with high power, high-brightness laser diodes, such as those reported in [15], it is expected that the 1 KW hurdle for narrow linewidth amplification in optical fibers will soon be cleared.

It should be mentioned that the model is also capable of including other effects such as beam quality and polarization state of the fiber amplifier and analyzing their impacts on SBS characteristics. To include the effect of beam quality an overlap factor [13] calculating an effective average intensity over the core region is used in the model. To reflect the fact that the fiber is not pure single mode, it is assumed that the spot size is approximately the same as the core diameter and thus results in an overlap factor of 0.86. Similar to that, the polarization

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states can also be added to the model by applying a polarization factor which is between 1 and 2. However, in practice this approach may not reflect real behavior of a high power amplifier. For example, a high power amplifier needs an isolator between the pre-amplifier and the power amplifier. In most cases, the seeded signal becomes linearly polarized after the signal passes a high power isolator which is often polarization dependent. For a non-PM fiber, the polarization states of the signal along the fiber amplifier thus strongly depend on fiber properties. Without measuring detailed information about the polarization states along the fiber, it is difficult to choose adequate polarization factor. For this reason, we assumed that the signal's polarization state remains linearly polarized through most of the fiber and is slightly deteriorated at the output end. In other words, the model treats the signal as linearly polarized. This may slightly affect absolute values of Brillouin gain coefficient. Nevertheless, in general the modeling results are in excellent agreement with our experimental results.

4. Conclusion

In conclusion, we have experimentally demonstrated single-mode, SBS-free operation of a narrow linewidth fiber amplifier with 502 Watts of output power using a bidirectional pumping configuration in a high-SBS threshold fiber. A combination of experiment and modeling has been used to estimate the SBS gain coefficient of the amplifier fiber and show that it is significantly below the value expected for the bulk material. Simulations demonstrate the potential of this fiber to achieve output powers in excess of 1000 Watts.

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