Recent Progress on Power Scaling Narrow Linewidth Fiber Amplifiers and Their Applications

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Power scaling of single mode Yb - doped fiber lasers operating at around 1064 nm has now reached the 10 kW level making it suitable for a variety of high power industrial material processing applications[1]. However, progress on narrow linewidth, single frequency fiber amplifiers has been much slower because of the fundamental limitations from fiber non-linearities such as stimulated Brillouin scattering (SBS) in the optical fiber. In this paper we discuss the physics of SBS, the fiber and amplifier designs that overcome this limitation and through optimization have allowed narrow linewidth fiber amplifiers to achieve output powers exceeding 1 kW for the first time. We also discuss some of the applications enabled by the latest advances in fiber technology.

Key Words: Fiber amplifier, Single frequency sources, Beam combining

1. Introduction

The adoption of high power fiber lasers as an industrial material processing tool has been ongoing for several years, with commercial suppliers offering single mode CW lasers based on Yb-doped fiber operating around 1064 nm at power levels up to 10 kW.[1] Commercial activity is now expanding into other markets and operating wavelengths, including the medical and scientific laser markets. One key enhancement enabling penetration into the scientific market has been the improvements in high finesse fiber amplifiers, which are now capable of delivering single frequency linewidths (< 5 kHz) together with excellent beam quality and stable linearly polarized output at 1064 nm and as such making them a viable alternative to traditional Nd:YAG solid state lasers. Fiber based systems meeting these specifications, have steadily progressed in the last few years from a few Watts of single frequency output power, initially to the 10's Watts and more recently into the 100's Watts power level.[2] This power scaling has been achieved with developments in the Yb-doped fiber technology, including the development of suppression/mitigation techniques for SBS and improvements in the overall amplifier design. The latest generation of high finesse, high power fiber amplifiers now deliver power levels exceeding what is available from commercial solid-state single frequency sources and are opening up new scientific applications as a result of the higher power levels, stable optimized performance and high reliability.

2. The problem of SBS in Fibers

SBS in fibers has long been studied with particular reference to telecommunication applications, where the effect of long fiber lengths (10's of km's) can reduce the SBS threshold into the mW regime and dramatically limit the signal power that can be transmitted. In today's rare-earth doped high power fiber lasers/amplifiers, the fiber lengths are much shorter, typically of the order of a few meters to a few 10's of meters. As a result, the SBS threshold is much higher, in the range of a few Watts to hundreds of Watts. The effect of SBS on the transmitted signal is seen as a rapid rise in the back-reflected Stokes wave, rising exponentially as the output power exceeds the SBS threshold and essentially limiting the transmitted power.[3]

In optical fibers the SBS threshold may be simply estimated from the following equation (1):

$$P_{th} \approx \frac{21bA_{eff}}{g_B L_{eff}} \tag{1}$$

where g_B is peak Brillouin gain ($3–5 \times 10^{-11}$ m/W in a silica fiber), A_{eff} is the optical mode effective area, b an overlap factor between the acoustic and optical mode and and L_{eff} is effective nonlinear length for the fiber.

The acoustic frequency involved in SBS is ~16GHz at optical wavelength of ~1μm in silica fibers and has a spectral bandwidth of ~50 MHz, as determined by the acoustic damping of the silica glass. The SBS threshold may be loosely defined as the output power value that generates sufficient backward-propagating Stokes power that it approaches the launched input power the fiber amplifier. SBS typically has the lowest threshold among all nonlinear effects and can also be a limit in optical fiber telecommunication systems. Since it is a highly coherent process, SBS can be significantly suppressed by spectral broadening to beyond the SBS gain bandwidth. When the bandwidth of a laser $\Delta\nu$ is significantly larger than Brillioun spectral bandwidth $\Delta\nu_{SBS}$, the SBS threshold is increased by a factor $\Delta\nu/\Delta\nu_{SBS}$. In telecommunications, optical carrier wave is modulated to effectively suppress SBS, and a recent review of high power fibers offers more details of SBS limits in fibers.[4]

One simple means to increase the SBS threshold is to enlarge the fiber core diameter and thereby the effective mode field, using so called large mode area (LMA) fibers. The other important parameter which impacts the SBS threshold is the

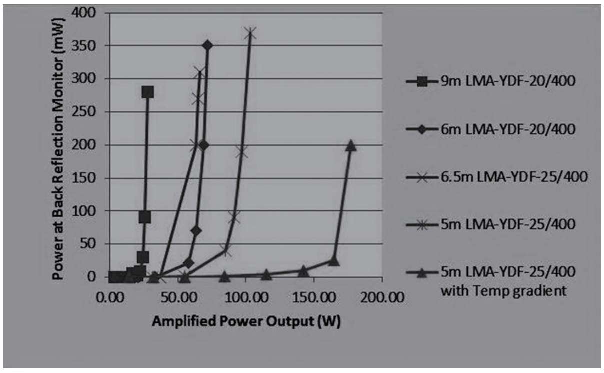

Fig. 1 Back reflection power monitor Vs the amplifier output power is an excellent measure of the SBS threshold of single frequency devices, which can be raised above 50 W by employing LMA fibers with 20 or 25 μm core diameter along with shortening the fiber lengths from 9 m to 5 m. In addition a temperature gradient can be used to further increase the threshold to over 150 W.

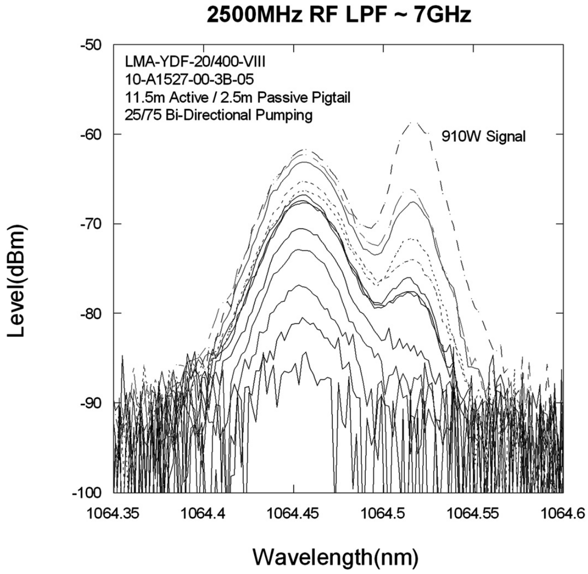

Fig. 2 The measured backward propagating signal for a high power single frequency fiber amplifier as the output power is increased steadily towards 910 W, showing the Rayleigh scattered signal at 1064.45 nm and the Stokes shifted Brillioun signal which rapidly increases as the SBS threshold is approached. In this amplifier the input signal linewidth to the amplifier broadened to 7 GHz to raise the SBS threshold to 900 W.

overall fiber length used in the amplifier. Examples of the measured SBS threshold for several different fiber amplifiers, based on LMA fibers with a range of core diameters and fiber lengths are shown in Fig. 1. By scaling the core diameter from that of standard telecom fibers (typically around 5–10 μm core diameter) to a state of the art LMA fibers with 20 or 25 μm core, the SBS threshold can be raised above 50 W, for fiber lengths relevant to commercial amplifiers (typically 5 –10 meters). With the latest generation of LMA fibers a number of techniques, such as coiling[5] and mode matching,[6] can be used to maintain beam quality in the amplifier and it is indeed possible to achieve near-diffraction-limited beam quality from fibers with core diameters up to at least 25 μm. Thanks to this new generation of fibers, it is now possible to amplify narrow linewidth, polarized sources to power levels suitable for some of the latest leading edge scientific applications, such as atom trapping and cooling and to power levels exceeding commercially available solid state sources.

3. Schemes to raise the SBS threshold in fiber amplifiers

The onset of SBS may be characterized by looking at the backward propagating signal at a wavelength close to the signal, 1064.45 nm in this example shown in Fig. 2. The rapid rise in the Stokes shifted signal at 1064.5 nm can clearly be seen as the SBS threshold is approached (~900 W in the example shown in Fig. 2). Operation of the amplifier at power levels higher than this can be difficult, adding to the noise and sensitivity of the amplifier to acoustic noise and vibration as well as back reflection from the down-stream optical components since at this point, the SBS stimulated wave may now exceed the injected power into the final amplifier stage. In Fig. 2, the SBS threshold has been significantly raised compared with the LMA fiber amplifiers indicated in Fig. 1, which were limited to 150 W. In this case the threshold is raised through a reduction in the spectral overlap between the signal and the Brillouin gain spectrum (~50 MHz). In this case, the amplifier was operated with a signal linewidth broadened to 7 GHz, rather than a single frequency source. Linewidths of region 1–10 GHz are useful, particularly for experiments involving beam combining (either spectral or coherent)[7] and the current generation of LMA fiber amplifier are capably of amplifying these linewidths to > 1 kW without reaching an SBS limitation.[8]

In other applications, the use of these broader linewidths is not an acceptable scheme to raise the threshold. Amplification of single frequency sources into the 500W regime have been demonstrating using fiber waveguides that suppress the SBS gain, by reducing spatial overlap (radially) of the acoustic and optical modes, through compositional adjustment of the fiber.[9] Other schemes that vary the SBS spectrum longitudinally along the length of the fiber include creating a temperature gradient and UV exposure of the fiber.[10] Progress on all these technologies continues although to date none have been employed in commercial products.

4. Very large mode field diameter fibers

Another promising parameter that may increase the SBS threshold further, is the move towards even larger mode field diameters over the 20–25 μm core diameters already discussed. The challenge in that case is to design fibers that can operate with good beam quality and deliver single mode operation under practical conditions such as bending and coiling. Technologies such as photonic crystal fiber (PCF), amongst others, have shown many promising designs for achieving this. One technology in particular, namely the leakage channel fiber (LCF) first demonstrated and studied extensively by Liang Dong[11] meets several key requirements. More specifically it has an all-glass structure and is able to be coiled for packaging purposes. An example of the bend performance of one of these all-glass 50 μm core LCF designs is shown in Fig. 3, corresponding to single mode LP01 mode operation in all coil diameters except around 22 cm, where the LP11 is favored.[12] Work continues on these new fibers with the most recent results showing low loss LP01 operation and single mode performance spanning the 1–2 μm region.[13,14] The operation of these very LMA fibers in single frequency amplifi-

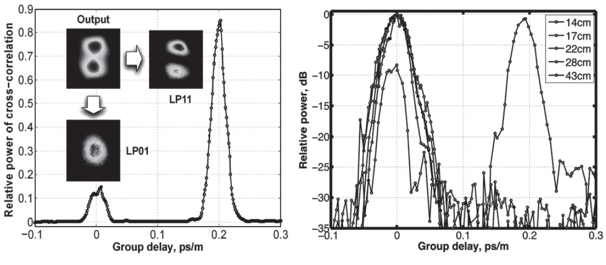

Fig. 3 C2 measurements on a 7 m length of all-glass leakage channel fiber with 50 μm core diameter at various coil diameters, showing single mode operation over a range of coil diameters[12)] between 14 cm and 43 cm (right figure). The resonant mode coupling seen at 22 cm diameter coil shows the presence of a higher order LP_{11} mode using this measurement (left figure).

ers is expected the further raise the SBS threshold and help with power delivery of light over longer distances.

5. Atom trapping & cooling

Optical dipole traps[15,16)] created by tightly focused off-resonance laser beams were initially proposed for laser cooling and trapping of neutral atoms. Early work with these traps was plagued by short trap lifetimes due to excessive atom heating. Laser intensity noise and pointing instabilities were quoted as the main heating mechanisms. The advent of very stable high power fiber lasers has overcome these limitations and quantum degenerate gases are now routinely created and studied in optical traps. With the new generation of fiber amplifiers, optical dipole traps have become an essential tool spearheading the frontiers of research in ultracold atomic and molecular physics. Tests of fundamental symmetries, atomic frequency standards, single atom trapping, creation of quantum degenerate gases, and the development of scalable quantum information processing systems are some of the research lines where optical traps are now widely utilized. Optical lattices formed by two counter-propagating optical traps is another technique, benefited from the recent development of the high-power narrow-linewidth fiber lasers, for confining neutral atom qubits with sub-wavelength precision, coupling neutral atoms into a cavity mode and studying quantum phase transitions in quantum gases. At the MIT-Harvard center for ultracold atoms (CUA), they routinely use fiber amplifiers to trap quantum degenerate gases as a means to study the interaction effects on the evolution of these clouds, such as Bose-Einstein Condensate of ^{41}K. In this case, traps formed using a 5 W laser beam were produced from a fiber amplifier with beam waist of 150 μm and the temperature of the cloud (bout 400 nK) held in the optical trap for long durations [see reference 16 for more details]. These conditions impose an extreme stability requirement on the trapping laser beams in order for the heating rate to be suppressed below a few nK/s. In these experiments, the interaction between atoms was manipulated using Feshbach resonances which were induced by exposing the trapped atoms to a uniform magnetic field and an example of a Feshbach resonance may be between two isotopes of potassium, ^{41}K and ^{40}K. Here the trapping potential is created by two 100 μm crossed laser beams at λ = 1064 nm using a 40 W fiber amplifier. Plans are underway to utilize fiber amplifiers operating at even higher power in the future to make deeper traps for capturing more atoms. This will allow experiments with ultracold quantum gases to be carried out with the higher signal to noise ratio.

6. Gravitational wave detection

The preferred single frequency source of the gravitational wave detection community has historically been the solid state laser. More recently however the Observatoire de la Côte d'Azur, Nice, France has been evaluating high power fiber amplifiers for the next generation of European gravitational interferometers, VIRGO.[17)] Their current systems employ 10 W single frequency solid state lasers based on non-planar ring lasers such as non-planar ring oscillator (NPRO) or monolithic isolated single-mode end-pumped ring (MISER) but the next generation systems are being designed with improved sensitivity and so require > 100 W power, combined with low frequency noise spectral density (~10^{-6} Hz.Hz$^{-1/2}$), stable linear polarization and relative intensity noise (RIN) < 10^{-8} Hz$^{-1/2}$. Raising the SBS threshold in fiber amplifiers while maintaining good spatial beam quality to the > 100 W level may be achieved through improved fiber/waveguide design such as SBS suppressing fibers, or by external SBS suppressing techniques such as applying a temperature gradient along the fiber length.[18)] Experiments raising the SBS threshold to ~150 W by using a simple temperature gradient along the length of a LMA fiber amplifier have been demonstrated, as shown in the amplifier schematic in Fig. 3. The temperature gradient has the effect of shifting the Brillouin frequency in different sections of the fiber amplifier, providing an inhomogeneous broadening of the SBS gain along the fiber and raising the overall SBS threshold for the amplifier. In the first set of experiments at Nice, such a fiber amplifier was used in conjunction with an Nd:YAG single frequency seed source. The suitability of a simple servo loop acting on the amplifier pump diodes to suppress the RIN value was demonstrated, reducing the noise in this experiment to 4.10^{-9} Hz$^{-1/2}$, between 20 Hz and 1 kHz. Other measurements validated the polarization and beam stability, combined with the intrinsic attraction of all-fiber systems (simplicity, maintenance, efficiency, beam quality and cost) make this an attractive solution for next generation of gravitational wave interferometry.

7. Other applications and wavelengths

These stable, single-frequency PM high power sources are also ideal for coupling to optical cavities used in resonant frequency conversion. Recently, by frequency doubling the output of a high power 40 W single frequency amplifier (SFA), 32 W of 532 nm light was generated[19)]. High power visible sources are of interest in display and scientific applications, such as pumping high power Ti:sapphire lasers. Furthermore, these high power visible sources may be used in turn to generate wavelengths deeper into the UV through sum frequency mixing of different wavelengths to generate a true solid state 193 nm source.[20)] Frequency doubling of Yb-doped fiber lasers operating at 976 nm has enabled blue (488 nm) fiber based sources operating at high power with low noise[21)] and with excellent wall plug efficiency. By doping the LMA fibers with Er or Tm-ions, operation at 1550 nm and 2000 nm respectively opens up a host of new wavelengths for low noise, stable single frequency sources at important wavelengths for sensing[22)] and coherent wind shear,[23)] as well as operating at "eyesafer" wavelengths. In some of these cases the SBS threshold is higher at these longer wavelengths than at 1064 m, with over 600 W of single frequency light generated at 2050 nm from a LMA Tm-doped fiber amplifier already demonstrated.[24]

In addition to single frequency sources, there is interest in high power "narrow" linewidths, in the few GHz regime, for beam combining, either spectral or coherent.[25,26] In this application, aimed at high power laser weapons, the requirement for kW's of power per amplifier is essential primarily to reduce the number of elements needed for scaling the total combined power into the 10's kW. In this case the SBS threshold, which scales with the linewidth of the seed source at linewidths over ~50 MHz, is increased into the kW regime by using linewidths in range 5–10 GHz, again using commercial LMA fiber technology. Sources that produce these "intermediate" linewidths may be grating based fiber lasers or broadened single frequency source using external modulators for the linewidth control. Current state of the art PM-LMA fiber amplifiers can deliver > 1 kW with linewidths < 10 GHz, as shown in Fig. 4, although the non-PM versions are now achieving higher power levels.[27] The problem of delivering high power narrow linewidth, is partially solved by deploying the Yb-doped final amplifier stage in a remote head configuration, as shown in Fig. 5, where the low power seed signal together with the multimode pump diode power are delivered over a long fiber length to the final Yb-doped LMA fiber amplifier stage. These small, compact units are ideal for beam combining experiments where 10 or more amplifiers may be required to generate the targeted power level.

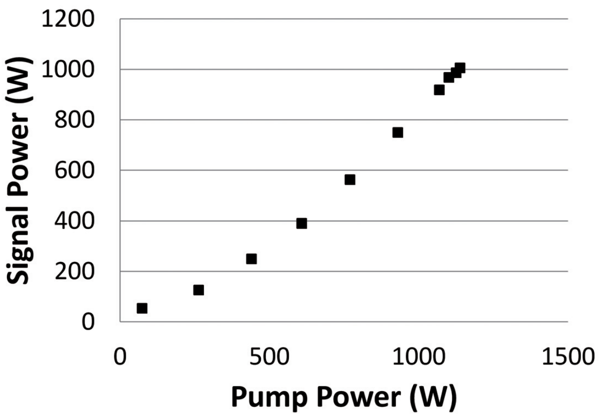

Fig. 4 Output signal power Vs pump power for a narrow linewidth PM fiber amplifiers operating with 1 kW CW output power and amplifying a 7 GHz linewidth seed sources without reaching the SBS limit.

Fig. 5 Small, compact and lightweight fiber amplifiers with remote high power amplifier head have enabled kW level fiber amplifiers to overcome SBS in the delivery fiber and improve their use in the lab for beam combining experiments.

8. Conclusion

We expect further power scaling of commercially available narrow linewidth fiber amplifier sources, including single frequency devices operating at the 100–200 W power level, in support of the maturing scientific market. The adoption of SBS suppressing techniques and further scaling of core size and mode field are possible tools to enable this new generation of commercial devices. Applications would include atom trapping and cooling, as well as non-linear conversion and gravitational wave detection amongst others. Applications for broader (GHz) linewidth fiber amplifiers delivering > 1 kW output power with single mode beam quality include spectral and coherent beam combining.

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