Power scaling of single-frequency ytterbium-doped fiber master oscillator power amplifier sources up to 500 W

(Invited Paper)

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Abstract

We discuss continuous-wave single-frequency master oscillator – power amplifier (MOPA) sources based on ytterbium-doped fibers (YDFs) with particular attention to their recent dramatic advances and our up-to-date experimental results. This includes a 402 W plane-polarized MOPA source and a 511 W random-polarized MOPA source. In these MOPAs, the final-stage high-power amplifier could operate with high efficiency of 70% – 80% and even more, and a high gain of over 20 dB in a near diffraction-limited beam. We could see at least 7 dB enhancement of the stimulated Brillouin scattering (SBS) threshold for the 402 W polarization-maintaining (PM) YDF. In fact, we did not see any sign of SBS even at the highest output power. We eventually observed SBS appearance at around 500 W for the non-PM YDF. The observed SBS strengths were far weaker than expected in theory unless we allowed for the Brillouin gain reduction from thermal Brillouin gain broadening induced by the quantum-defect heating.

Index terms: Optical fiber amplifiers, Optical fiber lasers, Brillouin scattering, Ytterbium

I. Introduction

In recent years dramatic advances in fiber laser technologies have made possible conventional single-strand cladding-pumped fiber lasers with output powers beyond a kilowatt with high beam quality [1]-[4]. The highest output powers are reached with ytterbium-doped fibers (YDFs) in relatively simple configurations that generate broadband laser output. YDFs are preferred because of their superb spectroscopic characteristics and the unmatched performance of high-power multimode diode sources suitable for pumping of YDFs. Also, more refined fiber sources operating in a range of regimes are approaching the kilowatt level [5]-[7]. In general, such high-power cladding-pumped fiber lasers require fiber lengths of several meters or even longer in order to achieve sufficient pump absorption. Unfortunately, in such a long cavity, single-longitudinal-mode, i.e. single-frequency, operation is hindered by instabilities and effects such as spatial hole-burning. The large gain bandwidth of rare-earth doped fibers often leads to linewidths of the order of 10 nm [1]-[3], typically, in the absence of any linewidth-narrowing features. This is still adequate for many important applications, e.g. in material processing including high-precision welding, cutting, and marking of metals and ceramics. However, the resultant linewidth, even after spectral narrowing via components such as fiber Bragg gratings in the cavity [8], is too broad for many interesting applications that require high-power single wavelength radiation with a very narrow linewidth, such as gravitational wave detection, free space optical communications, range finding, lidar, parametric wavelength conversion in resonant cavities, and coherent beam combination. Rather, high-power single-frequency master oscillator – power amplifier (MOPA) configurations are considered for these more demanding applications.

In a MOPA, a relatively low-power seed is amplified though one or several amplifiers. Control and stabilization of single-frequency sources is much simpler at low powers. Thus, MOPAs open up the possibility of highly-controllable high-power single-frequency radiation with opportunities for tunable, frequency-swept, and pulsed operation [9]-[10]. Because of the cavity-free traveling-wave nature of the amplifiers, the spectral purity of the seed source can be maintained with a minimum of phase noise added by effects such as thermally induced path-length variations, as demonstrated in [11] at modest output power levels. In particular, high-power, single-frequency fiber sources are of interest for coherent beam-combination. The small emitter size and overall compactness of high-power fiber devices simplify the use of a large number of lasers for power-scaling. This can lead to conceivably arbitrary powers in a diffraction-limited beam [12] and can be another route to the power scalability that is ultimately required for many applications in science, industry, and defense. This has motivated the recent intense attention to research in this field. A key breakthrough has been the suppression of stimulated Brillouin scattering (SBS), which otherwise limits the single-frequency output power of typical fiber amplifiers to 100 W or less.

Here we discuss the state-of-the-art of single-frequency YDF MOPA sources. We include a brief review of recent results, their fundamental features, and our up-to-date experimental results with over 400 W of linearly polarized output power with a polarization-maintaining (PM) fiber and over 500 W of randomly polarized output power with a non-PM fiber. Only at the 500 W we finally encountered the SBS threshold.

II. Single-Frequency Amplification and Stimulated Brillouin Scattering

Single-frequency fiber amplifiers for power-scaling of single-frequency sources, is more challenging than fiber amplifiers and lasers for broad linewidths [1]-[4]. The problematic combination of narrow linewidth, long interaction length, and tight confinement of the optical field in an optical fiber can already at low power lead to SBS. This needs to be avoided. It is a nonlinear interaction with acoustic waves in the fiber, which is caused by the inevitable photo-elastic effect [13]. The critical power for SBS scales nominally as

$$\sim \frac{1}{g_{B,eff}} \cdot \frac{A_{eff}}{L_{eff}},$$

where $g_{B,eff}$, A_{eff}, and L_{eff} are the effective values for Brillouin gain coefficient, mode area, and fiber length [13]. If we assume a linearly polarized single-mode beam in a fiber with parameters of $g_{B,eff} = 5\times10^{-11}$ m/W (where no Brillouin broadening is involved [13]) and $A_{eff}/L_{eff} = 100\ \mu m^2/5$ m, the critical power for SBS is only ~ 8.4 W. These parameters are typical, or even somewhat optimistic, for a conventional single-mode fiber. However, the critical power in such a fiber is much too low for coherent beam combination for high-power applications. Thus, overcoming SBS is crucial for the ultimate power-scaling of single-frequency sources. Large cores and short fiber lengths help to mitigate SBS but they are limited in scaling by various factors, such as fabrication precision, requirement of single-mode operation, maximum doping concentration, etc. For further power-scaling, we need to steer our attention to the suppression of the effective Brillouin gain coefficient $g_{B,eff}$. This can be done by spatially, in transverse as well as longitudinal directions, varying the material composition, stress, and/or temperature of the optical fiber. The fiber geometry, e.g. core diameter, can also be varied. Such non-uniformities in the medium spectrally broaden the Brillouin gain, which eventually reduces the peak gain [13], [14], i.e. the value of $g_{B,eff}$.

Early single-frequency YDF MOPAs reached output powers in the range of a watt to a couple of tens of watts without having significant spectral or spatial degradation [15], [16]. Following the burst of power from fiber lasers [1]-[4], the single-frequency output power was further extended to the 100-W level by the use of a large-core, double-clad YDF and a pump source that was much superior to previously used ones [17]. The final-stage power amplifier utilized a 9.4 m long fiber with a 28 μm diameter, 0.06 numerical aperture (NA) core. The large-core design could mitigate SBS to a degree, but SBS still limited the output power to 110 – 120 W. Indeed SBS rather than, e.g. launched pump power, was found to limit further power-scaling, and no steps had been taken to reduce the effective Brillouin gain coefficient. By contrast, a more recent demonstration of a 264-W MOPA [18] with a 6.5 m long, 25 μm diameter core, YDF, showed that significant further power-scaling of the single-frequency output power was possible if the effective Brillouin gain coefficient was reduced. In Ref. [18], this was achieved with a temperature gradient along the fiber, produced by the varying thermal dissipation from the amplification cycle, as the pump power is absorbed and gradually decreases along the fiber. The Brillouin frequency shift depends on the temperature, so with a varying temperature, the Brillouin gain peak wavelength shifts along the fiber. This leads to an effective broadening and reduction of the total Brillouin gain. The maximum output power of 264 W was limited by the pump power available by the time of the experiment. Neither SBS-induced nonlinear increase in backscattered light nor spectral broadening of the output beam was observed. Attempts to model this thermally-induced Brillouin gain broadening [19], [20] have verified the effect theoretically. Configurations with external temperature control of different segments of the gain fiber have also been used for further experimental investigations of the effect [21]. More recently, an output power of 350 W was reached with a 5-m long fiber with a core of 30 μm in diameter. The fiber core was engineered with materials of different acoustic velocity in order to reduce the Brillouin scattering [22]. In addition single-frequency fiber-based sources at over 100 W of output power are now commercially available [23].

Although the single-frequency output powers are lower, the pace of progress matches or even exceeds that of conventional broad-line fiber lasers. This is driven by advances in fiber and diode technology, and with further progress a demonstration of a kilowatt single-frequency source will not be far away. Even today, if we consider coherent or incoherent beam combination [12], the resultant output power level that is in reach with employing current single-frequency sources with a few hundred watts of output power is far higher than that of a single-unit source. Thus, we should not underestimate the rather potential impact of these devices and the achievements to date.

In the next section we will discuss in detail our experimental results on single-frequency MOPAs based on PM and non-PM YDFs, capable of generating 400 to 500 W of single-frequency output power.

III. Experimental Results: 402 W PM YDF and 511 W Non-PM YDF

The MOPA systems used in our experiments comprise a 1060 nm, 80 mW, plane-polarized YDF DFB laser (master oscillator) with a linewidth below 60 kHz (resolution-limited), three intermediate YDF amplifiers, and a final amplifier that is based on a large-core YDF for high-power operation. See Fig. 1. The seed power for the final power amplifier is ~ 3 W and a 975 nm diode-stack-based pump source provides up to 1.2 kW of power incident onto the YDF at the maximum driving current. The final power amplifier uses counter-propagating pump and signal beams in order to minimize the effective length and also to obtain a self-sustained, approximately exponential temperature gradient along the gain fiber. The temperature gradient may lead to substantial Brillouin gain broadening [18] and the short effective lengths helps to further suppress SBS. Two double-clad YDFs are investigated for the final amplifier. The fiber ends are held in temperature-controlled metallic V-grooves that are designed to prevent thermal damage to the fiber. The mid part of the fiber is cooled via unforced convection. Both fiber ends are cleaved at an angle of ~ 8 degrees to eliminate signal feedback for core modes. For the PM-YDF, a half-wave plate aligns the seed polarization to a birefringence-axis of the final-stage fiber to excite a single polarization mode.

The PM fiber used for the final amplifier was fabricated by SPI Lasers. The fiber has a ~ 25 μm diameter core with an NA below 0.06. The inner cladding is D-shaped and has a 380 μm diameter, and a low-index polymer coating for the outer cladding provides a nominal inner-cladding NA of 0.48. The fiber incorporates a pair of borosilicate stress rods, and the core birefringence is 2×10^{-4}. The average absorption coefficient of the fiber is 2 dB/m under the given pumping condition, and the fiber length is ~ 6.5 m. We had previously demonstrated 264 W output power from the same fiber (although not the same piece) without being limited by SBS [18]. The substitution of the lower-power pump source used previously with the more powerful one enabled further power-scaling. The output power characteristics are shown in Fig. 2, where we finally reached 402 W of output power. For these measurements the seed source and the intermediate amplifiers were run at full power, while the pump power to the final-stage amplifier was varied according to Fig. 2. The signal output beam was diffraction-limited ($M^2 < 1.1$) and linearly polarized (polarization extinction ratio > 16 dB). The overall slope efficiency with respect to the launched pump power was 72%. The dimension of the inner cladding of this fiber is insufficient for efficient launch of the pump source we used. The pump coupling efficiency was below 50%. This is unfortunate, given that the maximum power was still limited by the available pump power that could be coupled into the fiber (~ 560 W). There was no roll-over or significant SBS back-scattering even at the highest output. Both a roll-over and a strong back-scattering are signatures of SBS. The monitored backscattered power is shown in Fig. 3, vs. signal output power. This can consist of several components. While any signal back-reflected at the output end of the fiber would not be coupled back into the core because of the angled facet, the inner cladding could still guide it because of the much higher inner-cladding NA (NA = 0.48). Since the amplification of signal light propagating back through the cladding is negligible, this component will be proportional to the signal output power. Furthermore since the signal is strongly amplified before reflection at the output end and the Fresnel reflection is relatively strong (~ 4%), this component will dominate over any other (quasi-) linear contributions, such as Rayleigh backscattering and Fresnel reflection from the input facet. On the other hand, SBS would cause a nonlinear increase in the backscattered signal with respect to the forward output power. A quite rapid nonlinear increase may well be expected if SBS occurs [17]. Furthermore, if the back-scattered power is large enough, it can cause the forward signal power to roll over or instabilities in the amplifier. However, we could not see any nonlinear increase for the whole range of signal power for the PM YDF, as seen in Fig. 3. We presume this SBS-free operation was due mainly to the Brillouin gain broadening introduced by the longitudinal temperature gradient along the amplifier fiber. This has also been expected in the theoretical analyses in Refs [19] and [20]. However, experimentally, it remains unclear of what SBS-free power level this fiber could be reached with higher pump power. Although we did not measure the linewidth of the output beam due to the limited availability of measurement equipment at the time of the experiment, previous results [17], [18] suggest that the linewidth change at this power level would not be significant in the absence of SBS.

We further preliminarily explored the possibility of power-scaling of the MOPA system by employing another YDF that had a bigger inner cladding. This improved the pump launch. The fiber was fabricated at the Optoelectronics Research Centre (ORC). It has a 43 μm diameter core with an NA of 0.09 and a D-shaped 650 μm diameter inner cladding with an

NA of 0.48. The average absorption coefficient is ~ 1.5 dB/m under the given pumping condition, and the fiber length is ~ 9 m. This fiber is not polarization-maintaining.

This non-PM YDF reached a fiber-limited maximum output power of 511 W, as shown in Fig. 2. The overall slope efficiency with respect to the launched pump power was 80%. An efficiency drop at around the maximum output was observed, although it seems very small (see Fig. 2). Here, there was a clear evidence of SBS. A nonlinear increase in the backscattered power at over 500 W of output power was detected (Fig. 3), in a fashion similar to when SBS occurred in the 100-W level MOPA system described in Ref. [17]. Further attempts to increase the pump power were hindered by instabilities in the amplifier. Even with the relatively large core of this fiber, the relatively low core NA and optimized excitation of the mode that saturates the Yb ions in the core led to the output beam quality close to diffraction-limited ($M^2 = 1.6$).

Thus, SBS was eventually observed. We believe this is the first reported result of SBS in a high-power fiber amplifier in which substantial Brillouin gain broadening is expected to occur [18]-[20]. The SBS is indeed suppressed in both of the high-power YDFs. Already at 402 W, the plane-polarized result is more than five times (7 dB) higher than the estimated SBS threshold in the absence of thermal gain broadening [13], and SBS was still not observed. In case of the non-PM YDF, the random polarization and slight multi-mode nature might also affect the SBS threshold, and thus, it is not straightforward to compare the theoretical and experimental data. However, even with those factors, the power at which the onset of SBS was observed is far higher than expected in the case without considering Brillouin gain broadening.

We attribute this substantial Brillouin gain reduction to the spectral gain broadening mainly by the longitudinal temperature variation. While we have not directly verified the Brillouin gain broadening, it should be possible to measure a variation of the Brillouin frequency shift along the fiber, as is done in fiber-based distributed temperature sensors [24], and it is also possible to measure the overall Brillouin gain spectrum of a fiber. Recently, we have measured the temperature variation along a fiber in a separate experiment, showing that a temperature difference between the fiber ends of 130 K can be resulted in an erbium-ytterbium co-doped fiber when it is unidirectionally pumped at 975 nm [25]. The measured temperature variation closely followed the expected exponential distribution of absorbed pump power. This additional experiment, combined with estimates of the pump power absorption [26], allows us to estimate the temperature gradients of our YDFs while we did not directly measure them: The temperature differences between the fiber ends are estimated to 190 K for the PM YDF and 140 K for the non-PM YDF at the maximum output power under the unforced convection cooling condition. At these temperature differences, we estimate the SBS threshold to ~ 450 W and ~ 400 W in the PM and non-PM fibers, respectively, if we assume that the signal beam operates in a single mode with a single polarization. Note that this ignores the cooling by the metallic holders at both fiber ends.

It should be possible to further increase the SBS threshold. A higher pump absorption rate could be utilized to increase the temperature difference (up to thermal damage limits) and also to reduce the device length. This hints that our current fiber designs were not far off the kilowatt target. In fact, a narrower pump spectrum, as obtainable through stabilization with volume Bragg gratings, locked to the narrow Yb absorption peak could increase the pump absorption to the point where a kilowatt of output power would be feasible. Higher pump brightness helps too, as it would allow us to launch more pump power and reach the fiber-limited single-frequency output power also with the PM YDF. The fiber parameters can be further optimized, as well, in particular, the Yb concentration and the core and cladding dimensions. Fiber and diodes improvements will soon allow fiber sources to be scaled beyond the kilowatt level also in the single-frequency regime. However, there is still a limit by the maximum tolerable temperature that the fiber can sustain. All-glass structures such as air-clad fibers [2], perhaps with a metal coating, should allow for higher temperatures. It is also possible to induce higher temperature differences with external heaters and coolers. Other Brillouin gain suppression techniques, such as tapering the fiber, applying distributional stress, introducing compositional variation in the longitudinal and/or transversal direction of the fiber, etc., can also be considered for further increase of the SBS threshold, by themselves or in conjunction with thermally induced gain broadening. An important issue yet to be addressed, is how much the Brillouin gain is suppressed when suppression techniques are combined. In any case, any suppression technique must not compromise high power performance, through photodarkening, excessive propagation loss, or reduction in mode size, for example.

IV. Conclusion

We have discussed high efficiency, high power, 1060 nm, single-frequency MOPA sources based on high-gain YDF amplifiers. We experimentally observed that the undesirable SBS was significantly alleviated in such high-power single-frequency fiber MOPAs. This is attributed to Brillouin gain broadening induced by a longitudinally varying fiber temperature. An output power of 402 W was reached with a PM YDF. This result is already more than five times (7 dB) higher than the estimated SBS threshold power in the absence of thermal gain broadening [13], and SBS was still not observed. With a non-PM YDF at a slightly degraded beam quality, ($M^2 = 1.6$), SBS was finally observed at an output power of 511 W. We believe this is the first report on the onset of SBS in a high-power fiber amplifier with significant self-induced thermal broadening of the Brillouin gain. It is a first experimental data point for comparison with theoretical models of amplification-induced thermal broadening of SBS, which have yet to be experimentally verified. A higher temperature difference within the amplifier fiber would lead to a higher SBS threshold. We believe that this is realistic, and that it can be obtained by increasing the pump absorption rate, by using external heaters or coolers, or by engineering the heatsinking [21]. Extrapolations of experimental data that account for progress in fiber and diodes suggest that a kilowatt of output power with a diffraction-limited beam is entirely feasible. Advanced fiber designs e.g. with compositional variations in transverse and longitudinal fiber directions can further be exploited in conjunction with the Brillouin gain broadening via the pump-induced self-sustained temperature gradient.

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Figure captions

Fig. 1. Experimental arrangement. YDFA: YDF amplifier; DM: dichroic mirror; BS: beam splitter; FR: Faraday rotator; WP: waveplate; SF/SM/SP: single-frequency/single-mode/single-polarization.

Fig. 2. Signal output power vs. final-stage pump power.

Fig. 3. Backscattered power vs. signal output power.

Fig. 1

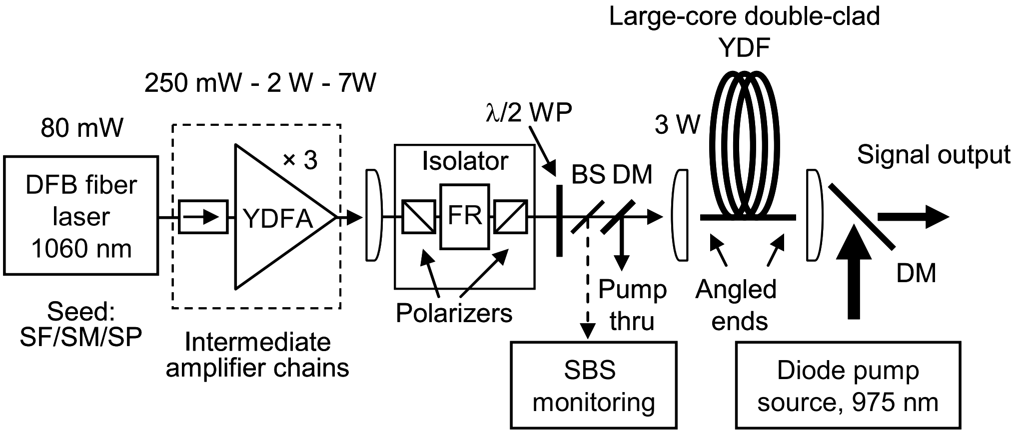

Large-core double-clad YDF
250 mW - 2 W - 7W
80 mW
λ/2 WP
3 W
× 3
Isolator
BS
DM
Signal output
DFB fiber laser 1060 nm
YDFA
FR
Seed: SF/SM/SP
Intermediate amplifier chains
Polarizers
Pump thru
Angled ends
DM
SBS monitoring
Diode pump source, 975 nm

Fig. 2

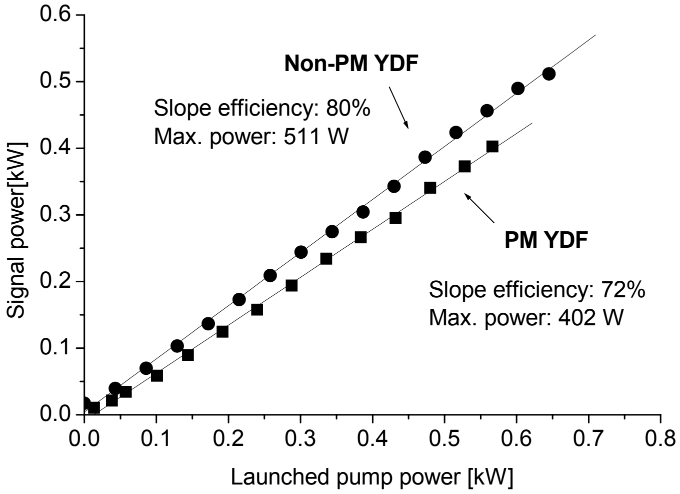
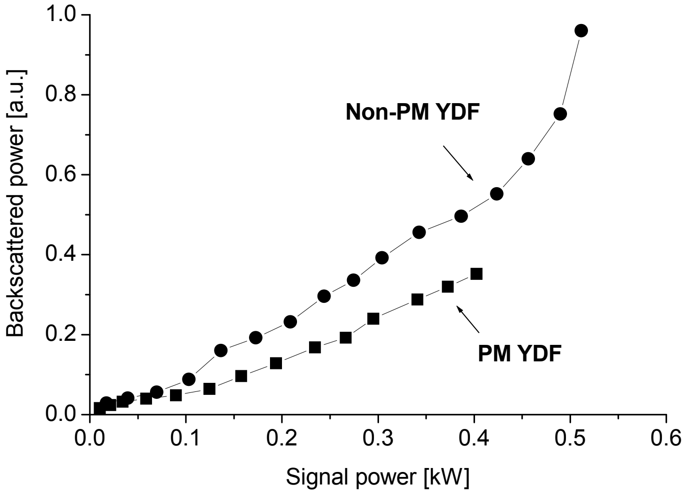

Non-PM YDF
Slope efficiency: 80%
Max. power: 511 W
PM YDF
Slope efficiency: 72%
Max. power: 402 W
Signal power[kW]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Launched pump power [kW]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Fig. 3


Non-PM YDF
PM YDF
Backscattered power [a.u.]
1.0
0.8
0.6
0.4
0.2
0.0
Signal power [kW]
0.0
0.1
0.2
0.3
0.4
0.5
0.6