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Record-peak-power all-fiber single-frequency 1550 nm laser

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Abstract
In this paper, we present results on the amplification of 2 MHz linewidth nanosecond pulses in a recently developed ytterbium-free erbium-doped large mode area fiber cladding pumped at 980 nm. A record peak power of 4 kW for single-frequency single-mode silica-based fiber sources near 1550 nm is demonstrated. Pulse instabilities arising in an all-fiber laser scheme from stimulated Brillouin scattering are described.

Keywords: stimulated Brillouin scattering, erbium-doped fibers, high power lasers, pulsed lasers

(Some figures may appear in colour only in the online journal)

1. Introduction

To date, the most impressive results in power scaling of continuous wave and pulsed fiber lasers have been obtained from the use of Yb-doped double-clad fibers [1, 2]. This is a result of the low quantum defect under 915/976 nm pumping conditions and the high pump-to-signal conversion efficiency. Such lasers are widely used for applications such as cutting, drilling, welding, and etching. However, even low-power near-infrared radiation with wavelengths below ~1.4 μm is hazardous for human eyes because it could be focused by the crystalline lens to the retina. This fact restricts the employment of Yb-doped fiber lasers in LIDAR, remote sensing, laser communication links and so on because light scattered from the target could damage bystanders' eyes. As such, operational wavelengths of Er-doped fiber lasers near 1.55 μm are more suitable for free-space applications. However, the power scaling of Er-doped fiber lasers is substantially more challenging because of the low pump absorption cross-section of erbium ions and the cooperative up-conversion that significantly reduces pump conversion efficiency with the growth of erbium concentration. Moreover, applications such as Doppler wind LIDAR and gas sensing require the operation of laser sources in the pulsed regime with tens to hundreds of nanosecond pulses and with spectral widths not broader than several MHz.

Currently, double-clad Er-Yb-sensitized fibers are widely used to increase the output power of fiber lasers at 1.55 μm [3, 4]. However, efficient energy transitions from Yb to Er ions requires a co-doping of the fiber core with a significant amount of phosphorus, which increases the numerical aperture (NA) and therefore limits the diameter of the single mode core. Thus, up to 6 kW of peak power can be obtained from single-frequency multimode Er-Yb fiber lasers (M^2 ~ 5 [5]) and up to 360 W in the single-mode regime [6]. In addition, a significant drawback of such lasers is the ytterbium emission near 1 μm, which presents an eye safety concern. Another opportunity to obtain high output power with low nonlinearity from Er-doped fiber is a core pumping of the fiber with a Raman fiber laser at 1480 nm. Such an approach allows a shortening of the active fiber length in comparison with cladding-pumped schemes. In addition, this approach allows for single-mode operation even in highly multimode fibers because of the significant

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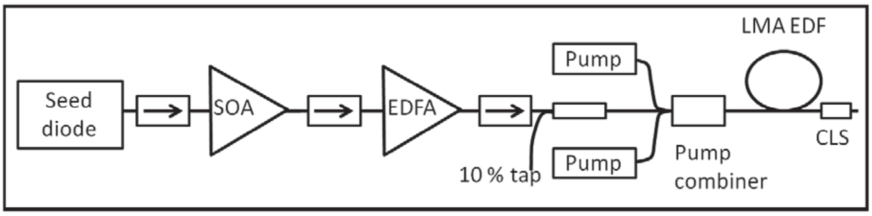

Figure 1. Laser setup.

overlap between signal and pump modes [7]. Therefore, greater than 500 W of peak power before the SBS threshold was demonstrated in the single-mode regime using a 40 μm core Er-doped fiber with NA ~ 0.09 [8]. Nevertheless, exploiting the Raman fiber converter causes the system to be substantially more cumbersome and expensive in comparison with cladding-pumping schemes. In addition, the SBS threshold of the fiber laser could be increased by using special techniques of SBS suppression such as distributed strain [8] or heat gradient [9], but this increases the laser's footprint and may reduce its reliability. Also, taper geometry of the active fiber could increase the SBS threshold [10]; however to date no Er-doped fiber taper lasers have been reported at 1550 nm.

In our recent study [11], a novel design for a single-mode large mode area (LMA) Yb-free Er-doped double-clad fiber with suppressed nonlinearity was proposed. It was shown that exploiting a P_2O_5-Al_2O_3-SiO2 (PAS) glass as a host for Er ions allows one to keep the refractive index of the core low enough to enable the single-mode operation of a fiber with a 35 μm core. An increase of the fiber core diameter allows us to reach an appropriate population inversion level [12], and for this reason to significantly improve the pump conversion efficiency in comparison with standard Al_2O_3-SiO_2 fibers. In this paper, we demonstrate the results of single-frequency nanosecond pulse amplification in LMA PAS Er-doped fibers.

2. Experimental setup

We used a cascaded master oscillator power amplifier (MOPA) laser scheme that is depicted in figure 1. A continuous-wave fiber Bragg grating wavelength-stabilized single-mode diode fiber laser was used as a seed source. The value of the diode linewidth provided by the supplier was 2 MHz. This value was checked by observation of interference in a fiber interferometer with an arm length difference of 100 m. Radiation from this laser was modulated by a fiber-pigtailed semiconductor optical amplifier (SOA) with a 5 kHz repetition rate and 92 ns pulse duration. Next, the pulse train was pre-amplified in a telecom-grade Er-doped fiber amplifier (EDFA) to an average power of 5 mW. This EDFA had a narrowband (0.7 nm) DWDM filter at the output to suppress amplified spontaneous emission (ASE). The last stage of the MOPA was PAS LMA Yb-free Er-doped fiber similar to the one described in [11]. The active fiber was cladding pumped at 980 nm in a co-propagating amplifier scheme. The pump and signal were launched into the active fiber through a commercially available pump combiner, thus providing a robust all-fiber construction of the laser scheme. The input signal port of the pump combiner was a standard SMF 28 fiber, and the output one was a 20/125 μm core/cladding diameter (NA ~ 0.08/0.46) double-clad fiber. A 10% tap fiber coupler was placed before the pump combiner for backward SBS signal monitoring. A cladding light stripper (CLS) was used near the end of the Er-doped fiber to eliminate any unabsorbed pump power, as well as any potential cladding signal modes. An angle-cleaved end of the active fiber was used as the output coupler. As it was shown in [11], the cutoff wavelength of the PAS LMA fiber is ~1700 nm, which, together with the low core/cladding refractive index difference, ensures a single-mode operation regime. This regime was also checked by observation of the transmitted spectrum amplified in the LMA EDFA super luminescence wideband source. The presence of a second mode in this case could be estimated by a beat in the spectrum that corresponds to interference between the fundamental and first high order mode. Our estimation gives part of the high order mode to be less than a few per cent, which coincides with the accuracy level for this method.

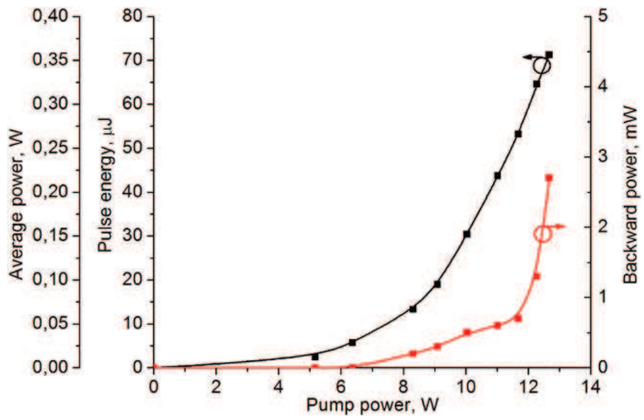

Figure 2. Pulse energy and average power (black), and backward signal (red) from the 3 m amplifier.

3. Observation of instabilities caused by SBS

Initially, we used a 3 m LMA EDF length in the amplifier. The signal pulse energy, average output power at the output of the MOPA, and the backward-propagating average output power are presented in figure 2 as functions of the pump power. The slope pump-to-signal conversion efficiency was 12% with respect to the launched pump power. The highest pulse energy, 70 μJ, was obtained at a pump power of 12.5 W. The peak power, calculated from the pulse shape and its energy, reached a value of 950 W.

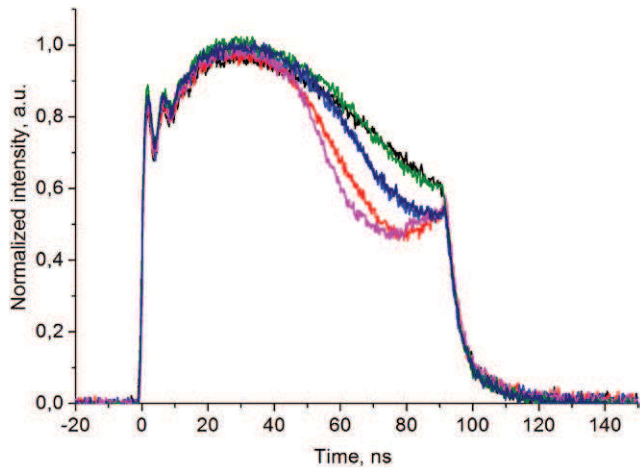

Figure 3. The instability of the MOPA pulses caused by the generation of first-order Stokes pulses.

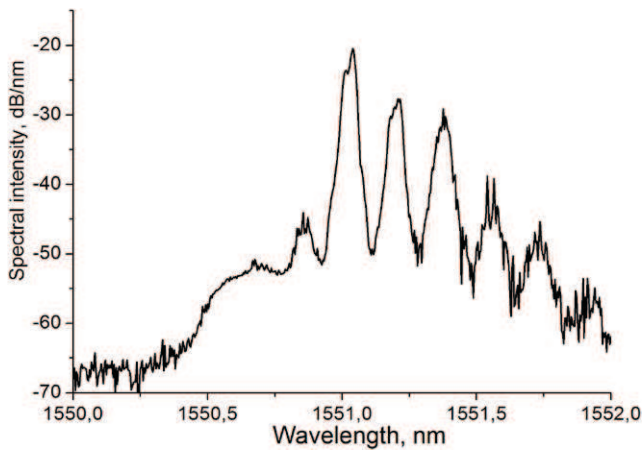

Figure 4. Output spectrum.

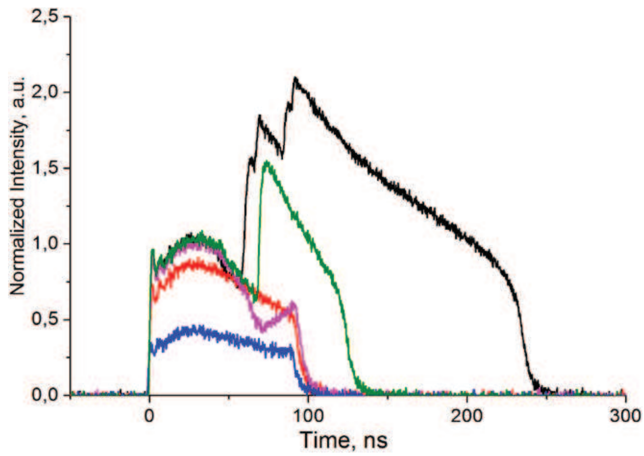

Figure 5. The instability of the MOPA pulses caused by the generation of cascaded Stokes pulses.

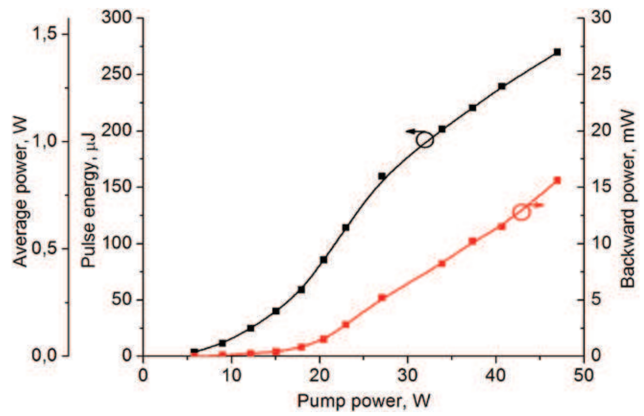

Figure 6. Pulse energy and average power (black), and backward signal (red) from the 1 m amplifier.

Further increasing the pump power led to a substantial increase in the SBS power, as well as to pulse instabilities. Two types of unstable behaviour were observed during the experiment. The first appears in the pump power range from 12.6 to 14 W and results in instabilities of the end part (trailing edge) of the pulse. Figure 3 shows several traces recorded by a photodetector demonstrating such instabilities. This behaviour is associated with the generation of first-order SBS Stokes waves. It should be noted that the 90 ns pulse is extended over ~18 m, which is an order of magnitude longer compared to the length of amplifier. When the leading edge of the pulse passes the amplifier, it generates SBS radiation (1st SBS Stokes signal). In turn, the 1st SBS Stokes pulse propagates in the backward direction and is amplified in the active fiber. The backward propagating power in the observed regime is high enough to achieve saturation of the SBS and significantly decreases the SBS 'pump' power (forward signal). In this case, the power of the forward propagating signal is significantly reduced at the trailing edge of the pulse; therefore, we see a factor of two reduction of the field amplitude (compare, for example, the black and red lines in figure 3). Because the SBS process is internally unstable, the amplitude of the pulse trailing edge is varied between pulses. Note that the power of the 1st SBS Stokes pulse is limited in this regime mainly by the available 'pump' (forward propagating signal at the input of amplifier—average power of 10–20 mW). Similar behaviour of the trailing edge due to SBS was also reported by Dilley *et al* [6]. When the pump power was set to greater than 14 W, another type of instability associated with the generation of higher-order Stokes pulses was realized. Multiple lines appear at the output spectrum, and variations of the pulse amplitudes become much higher (see figures 4 and 5). In this case, reflection of the SBS Stokes wave takes place in the pigtailed fibers. The mode field area of the standard SMF 28 fiber used as a pigtail in an isolator, coupler, and pump combiner is more than five times smaller compared to that of the LMA active fiber. Moreover, the backward signal could be significantly amplified because of the high gain of the EDFA even when the SBS gain reaches saturation. In addition, the backward propagating SBS Stokes signals have high intensity only in a short piece of active fiber near the beginning of the amplifier so that it is still below the SBS threshold of the active fiber. In contrast, when the SBS Stokes pulse propagates through the passive fiber, its amplitude is sufficiently high, and even a few tens of cm of SMF 28 fiber is enough to overcome the SBS threshold. As a result, the passive delivery fiber acts as a mirror for the 1st (then 3rd, 5th and so on) SBS Stokes wave

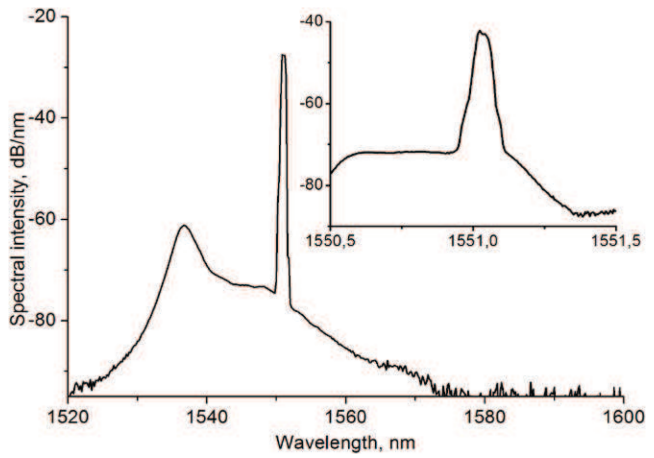

Figure 7. Amplifier spectrum recorded at a resolution of 2 nm. Inset: spectrum of the peak recorded at a resolution of 0.02 nm.

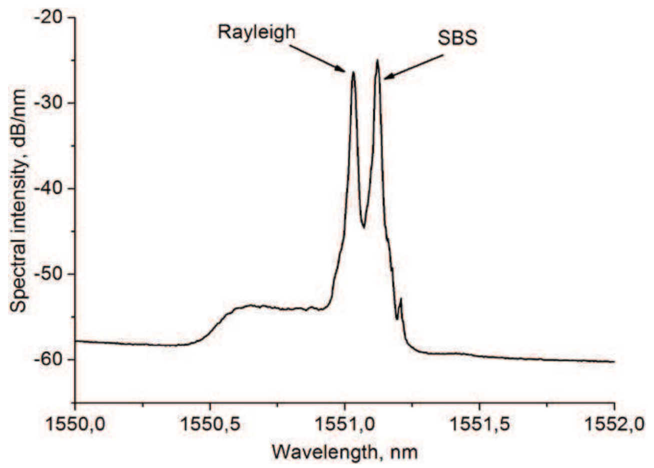

Figure 8. Spectrum of backward-propagating light for the 1 m amplifier.

and generates 2nd (then 4th, 6th and so on) SBS Stoke waves propagating in the forward amplifier direction. Subsequently, the 2nd SBS Stokes pulse is amplified in the Er-doped fiber and overcomes the SBS threshold of the active fiber so that the 3rd SBS Stokes wave is generated. The output spectrum of the MOPA operating in such a regime measured at the amplifier output with 0.02 nm resolution and at a pump power of ~18 W is presented in figure 4, where even 10th Stokes waves could be observed. Figure 5 shows the results of several traces measured by the photodetector. The intensity of 1 in this plot corresponds to the average peak intensity of the pulse train. It can be seen that the leading edges of most of the pulses have approximately the same intensity. In addition, the intensity of a number of pulses is increased significantly at the pulse trailing edge. The reason for this is as follows. If the peak power of the first-order Stokes wave is sufficiently high, it could be completely converted to a second-order Stokes wave before it reaches the isolator. Therefore, a high-energy backward pulse is almost fully reflected by the delivery fibers and returns to the LMA EDF, where it is further amplified. As a result, we observed a pulse with a high-intensity elongated end part (for example, the green curve in figure 5). In addition, this process can be repeated several times, resulting in the formation

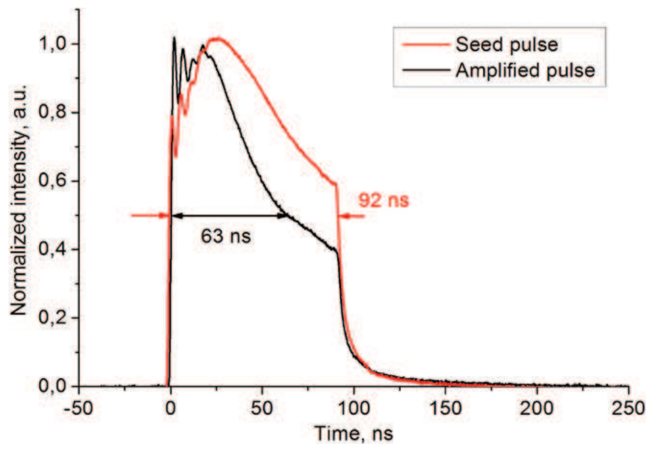

Figure 9. Temporal profiles of the seed and amplified pulse.

of pulses with even higher energy (see the black curve in figure 5). Because such large pulses deplete almost all the stored fiber energy, the next pulse has a lower gain and therefore a lower peak power at the output (see the blue curve in figure 5). The pump power was not increased to a value higher than 20 W during the experiment to avoid isolator damage and fiber breakdown. It is interesting to note that the generation of cascaded SBS pulses in active fiber was previously reported for laser schemes with free-space signal coupling [13]. As far as we know, the instability behaviour associated with the generation of the SBS signal in passive delivery fibers arising from the all-fiber laser format is reported for the first time.

4. Record peak-power amplifier

To increase the SBS threshold and suppress instabilities, we shortened the LMA EDF length to 1 m. In this case, up to 270 μJ of pulse energy was obtained (figure 6). Further increases in the pump power led to instabilities associated with SBS. The amplifier spectrum, indicating a greater than 33 dB signal-to-ASE ratio recorded at maximum energy, is presented in figure 7. The inset in figure 7 shows the absence of any SBS Stokes pulses in the MOPA output. Although the backward power for the 1 m amplifier near the SBS threshold is larger than that for 3 m, the intensity of the SBS signal is not much higher than that of Rayleigh scattering (see figure 8), and a considerable portion of the backward propagating power was contained in the ASE. Because of the short EDF length, only ~25% of the pump power was absorbed. This leads to a decrease of the pump-to-signal conversion efficiency to ~5% with respect to the launched pump power. The decrease of the slope efficiency at high pump power ($\gg$25 W) is associated with a thermal drift of the pump diode central wavelength. For the 1 m amplifier, the pulse shape changed, and its duration decreased to 63 ns (FWHM) owing to inversion depletion following propagation of the forward front of the pulse (figure 9). A peak power of more than 4 kW was calculated in this case, which is, to the best of our knowledge, a record value for single-mode narrow-linewidth silica-based fiber systems operating near 1550 nm. It must be noted that no nonlinear effects except SBS (like four wave mixing [14] or stimulated Raman scattering) were observed in our experiment, which is due to the much higher threshold of this effect. Also, no fiber facet damage was observed during the experiment.

5. Conclusion

In conclusion, we presented an all-fiber single-mode single-frequency nanosecond MOPA system based on a recently developed large mode area double-clad, Yb-free Er-doped fiber. Initially, by using 3 m of active fiber, we obtained 950 W of peak power before the SBS threshold. This value is higher than that obtained in commercial Er-doped fiber [8]. In addition, we demonstrated that our laser scheme exploiting cladding pumping of Er-doped fibers by standard multimode diodes at 980 nm is much simpler, cheaper and more reliable than core pumping by Raman laser, as used in [8]. Two types of amplifier operation instabilities associated with the SBS process were described. It was shown that in an all-fiber format, such instabilities could result in the production of large pulses because of the generation of high-order Stokes pulses in passive delivery fibers. Shortening the fiber length down to one meter allowed us to increase the peak power to more than 4 kW. This peak power, to the best of our knowledge, is a record value reported for single-mode, single-frequency silica-based fiber sources near 1550 nm. This extremely high peak output power was obtained through SBS threshold suppression by combining a large mode field diameter and a shortening of the fiber length of a highly Er-doped fiber at the final stage of optical power amplification.

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