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100-W average-power, high-energy nanosecond fiber amplifier

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ABSTRACT We report on the fiber-based amplification of a Q-switched Nd:YAG thin-disk laser. At repetition rates between 3 and 50 kHz output powers up to 100 W are generated. Pulse energies up to 4 mJ, with diffraction-limited beam quality, are generated in a 30-μm Yb-doped large-mode-area fiber, furthermore pulse energies up to 8 mJ are achieved from a multimode fiber amplifier.

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1 Introduction

Q-switched nanosecond lasers find widespread applications in laser trimming, marking and welding of various solid materials. Further applications can be found in different areas of science and technology. Today diode-pumped rod solid-state lasers are well established in the low-power regime, due to their inherent stability, efficiency and robustness. At high power levels, more complex laser geometries have to be applied to correct for thermally induced distortions (these distortions reduce the efficiency of the laser). Laser systems based on double-clad rare-earth-doped fibers are an attractive technology for compact and very efficient high-power and high-energy short pulse generation. Their main performance advantages, compared to conventional bulk solid-state lasers, result from the combination of beam confinement and excellent heat dissipation. Continuous-wave powers of well above 100 W [1, 2] have been achieved with the cladding pump technique [3]. Rare-earth-doped fiber-based laser systems operating at pulse durations down to sub-100-fs are reported.

The amplification of pulses in fibers is limited by the extractable energy, which is determined by the saturation fluence ε_{sat}, the small signal gain G_0 and the area of the active medium A:

$$E_{ext} = \varepsilon_{sat} A \ln(G_0) = \frac{N_0 h\nu}{\gamma} . \quad (1)$$

N_0 is the total initial inversion, h Planck's constant, ν the signal frequency and γ the saturation factor (three level system: $\gamma = 2$, four level system: $\gamma = 1$) . Ytterbium-doped glass possesses a huge saturation fluence of about 30 J/cm^2. As a rule of thumb, the maximum extractable energy is around ten times the saturation energy [4]. Therefore depending on the core diameter pulse energies from a few 100 μJ (single-mode fiber) up to 10 mJ (multimode fiber) can be extracted from an ytterbium-doped fiber laser or amplifier. Pulses of 7.7 mJ from a multimode (60-μm core diameter) Q-switched ytterbium-doped fiber laser at low repetition rates (500 Hz) are reported [5].

In this contribution we report, for the first time to our knowledge, on a high average power, millijoule system at repetition rates in the multi-10 kHz range. This power range opens up novel industrial and scientific applications of pulsed nanosecond laser systems. In addition, the presented work provides the data for an efficient power scaling of femtosecond fiber-based chirped-pulse amplification systems in the multi-10 W range. Presently, such systems deliver pulse energies in the range of 100 μJ to 1 mJ at subpicosecond pulse duratios and at repetition rates of typically less than 10 kHz [6, 7].

2 Experimental setup

The setup of the high-power and high-energy fiber amplifier is shown in Fig. 1. A Q-switched Nd:YAG thin-disk laser is applied as a nanosecond seed source.. The laser delivers average powers of few watts at repetition rates between 3 and 50 kHz and pulse durations in the range of 70 to 300 ns. At 3 kHz the measured spectral width is 0.4 nm, corresponding to 100 GHz.

We used a 25-m-long low-NA (numerical aperture) large-mode-area (LMA) fiber with a core diameter of 30 μm (NA = 0.06) and an ytterbium doping concentration of 500 ppm (mol) Yb_2O_3. Furthermore a 3-m long 55-μm multimode (NA = 0.19) fiber was applied. The doping concentration of this fiber is 6500 ppm (mol) Yb_2O_3. Both fibers have a 400-μm D-shaped inner cladding with a numerical aperture of 0.38. The fiber amplifier is pumped by a fiber-coupled diode laser at 976 nm. The surface damage threshold of fused silica at 1064 nm is approximately given by [8]

$$22(\Delta\tau_p)^{0.4}\ \mathrm{J/cm^2} , \quad (2)$$

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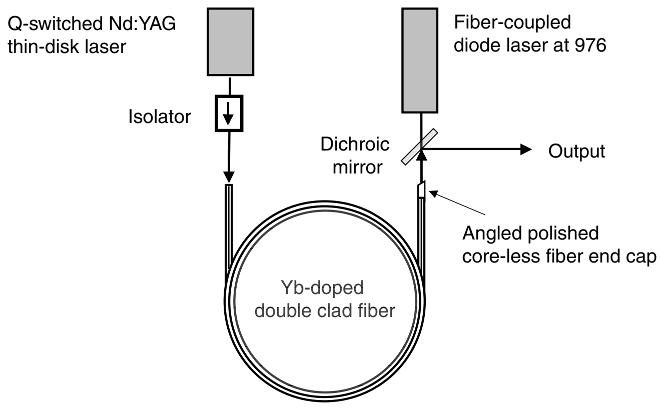

FIGURE 1 Experimental setup

where $\Delta\tau_p$ is the pulse duration (ns). At nanosecond pulse duration the extractable fluence is therefore about one order of magnitude larger than the damage fluence. In the experiment we observed a damage threshold of 0.5 mJ in the case of the 30-µm core fiber ($\Delta\tau_p = 100$ ns), which is in good agreement with (2). To overcome this limitation we splice a 400-µm core-less end cap on the output side of the fiber amplifier. The extension of the beam diameter reduces the fluence and avoids fiber facet damage. The maximum length of the end cap is determined by the diameter of the cap d and the numerical aperture NA of the amplifier core

$$L_{\max} = \frac{d}{2n\mathrm{NA}}\,, \tag{3}$$

where n is the refractive index of the end cap. In the experiment, the length of the end cap is chosen to 1.5 mm in the case of the LMA fiber and the 0.5 mm in the case of the multimode fiber, which stretches the mode field to approximately $\frac{3}{4}$ of the diameter of the end cap.

3 Experimental results

3.1 33-µm *low*-NA *large-mode-area fiber*

Figure 2 shows the maximal extractable pulse energies and average powers as a function of pulse repetition rate in the 30-µm LMA fiber. The obtained values are not limited by available pump power but rather by spurious lasing at another wavelength (between 1080 and 1090 nm) which is observed in the emitted spectrum. At a repetition rate of 50 kHz we were able to produce an average output power up to 100 W, corresponding to pulse energy of 2 mJ. Approximately 140 W of pump power is launched at this power level (70% coupling efficiency). If the repetition rate of the seed source is reduced, the extractable energy increases up to 4 mJ at 3 kHz. Even at this pulse energy we didn't observe any fiber facet damage. The seed power of the Q-switched thin disk laser was sufficient to saturate the amplifier, therefore the portion of amplified spontaneous emission in the output is negligible even at low repetition rates. No polarizing fibers are applied, therefore the output is unpolarized.

Figure 3 shows the emitted spectrum at a pulse energy of 2.0 mJ in singlemode and multimode operation, plotted against the seed spectrum on a logarithmic scale. The 30-µm LMA fiber has a V-parameter of about 5 and supports 4 transverse modes. Coiling the fiber in a radius of less than 10 cm discriminates against the higher order transversal mode through bending losses, and only the fundamental mode is guided and amplified. Although the seed source has a poor beam quality ($M^2 \sim 3$), diffraction-limited beam quality is obtained. We measured a M^2-value of 1.1 at high power operation of the fiber amplifier.

Even at the highest peak power nonlinear effects play a minor role ($\sim$ 20 dB below signal). The spectrum indicates nonlinear effects such as stimulated Raman scattering, spectral broadening due to self-phase modulation and generation of frequency sidebands (frequency shift $\sim$ 3 THz) by degenerated four-wave mixing. Four-wave mixing is only observed when the fiber amplifier emits multimode radiation (without coiling), where the required phase-matching is realized by different propagation constants of different transversal modes [9]. No significant signal is observed in the backward direction, therefore stimulated Brillouin scattering can be excluded.

Due to the amplification process the pulse duration is reduced in the fiber. Figure 4 shows the seed source pulses at a 3-kHz repetition rate, and after amplification to 4-mJ pulse

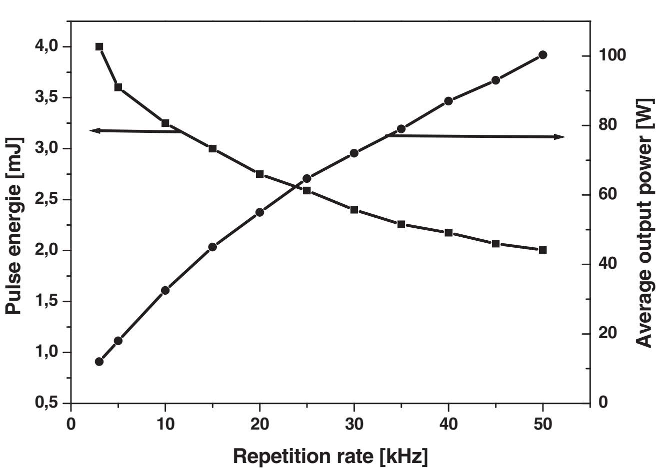

FIGURE 2 Extracted pulse energy and average power as a function of pulse repetition rate

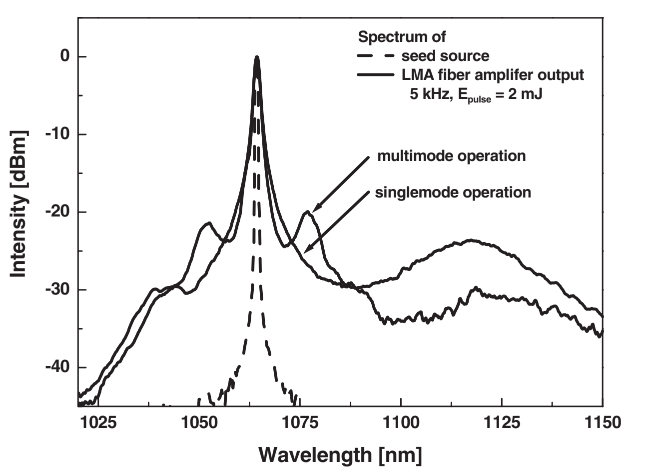

FIGURE 3 Emitted spectrum at 2 mJ pulse energy depending on the beam quality

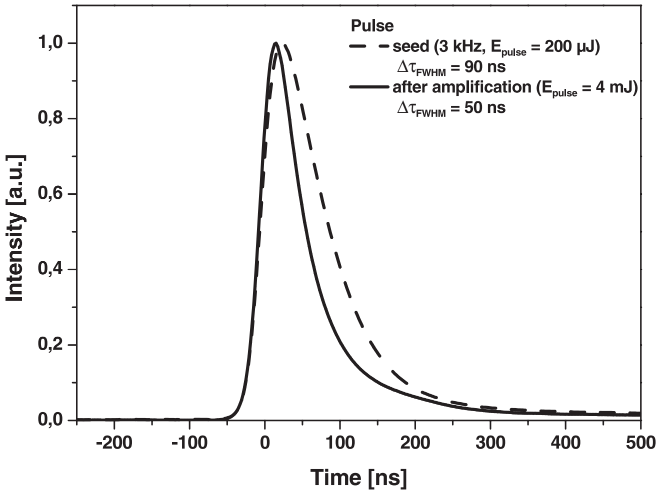

FIGURE 4 Photodiode signal of the nanosecond pulses before and after amplification

energies in the LMA fiber. The pulse duration is reduced from 90 ns to 50 ns, corresponding to a peak power of 80 kW. The pulse shortening factor increases with a decrease of the repetition rate corresponding to a higher energy density in the pulse. Therefore, at low repetition rates a depletion of the stored energy is observed, resulting in a significant pulse shortening of about 50%. This is a well known behavior of highly saturated pulse amplifiers [10].

3.2 55-µm *large-core multimode fiber*

Further energy scaling was possible with compromised beam quality using the 3-m long 55-µm multimode fiber. The small ratio of active core area to pump core area and the high doping concentration ensures sufficient pump light absorption. At a pulse duration of 50 ns we were able to generate 24-W average power at 3 kHz repetition rate and 40-W average power at 5 kHz. This corresponds to a pulse energy of 8 mJ and a peak power of 160 kW. We measured an M^2-value of about 10 at the highest output power. Considering the ratio of the core area of the 30-µm LMA fiber to the 55 µm multimode fiber, one could expect even more pulse energy out of the multimode fiber. Unfortunately the larger number of modes increases the ASE power and the higher NA supports spurious feedback and Rayleigh back-scattering, which limits the energy storage in the multimode fiber [4].

4 Conclusion

In conclusion, we have demonstrated the fiber-based amplification of nanosecond pulses from a Q-switched solid-state laser up to 100 W average power at 50 kHz repetition rate and 4 mJ pulse energy at 3 kHz with diffraction-limited beam quality. Pulse energies of up to 8 mJ were obtained using a multimode fiber amplifier. These results represent an enormous power and energy scaling of fiber-based nanosecond pulse amplification. Fiber lasers and amplifiers with 1 kW average output power are expected in the near future, which will open up new fields of application.

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