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Highly dynamic and versatile pulsed fiber amplifier seeded by a superluminescence diode

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Abstract We propose and investigate a high power superluminescence diode (SLD) as a pulsed seed source for a highly dynamic and versatile pulse fiber amplifier system. The SLD provides, contrary to conventional Fabry–Pérot laser diodes, a smooth and broad output spectrum which is independent of the input pulse parameters. The output pulses from the SLD are as short as 10 ns with up to 150 mW peak power. Moreover, the pulses can be directly shaped by modulating the injection current of the SLD. Pulse shaping in an amplifier configuration is demonstrated without the observation of stimulated Brillouin scattering (SBS) due to the provided spectral bandwidth of 10 nm FWHM. Further spectral shaping was realized with a band pass filter in the amplifier chain.

1 Introduction

Fiber integrated master oscillator power amplifier (MOPA) systems generating nanosecond to microsecond pulses with variable pulse shape, pulse duration, pulse repetition frequency and pulse energy are interesting for a wide range of applications due to their unparalleled adaptability [1–4]. These systems, based on a pulsed diode laser serving as the seed source, have been so far demonstrated with up to 27 mJ pulse energy and up to 2.7 MW peak power at an M^2 value of 6.5 [5]. In case of diffraction-limited output, up to 100 W of average power and up to 4 mJ of pulse energy have been achieved by fiber amplifying a Q-switched bulk laser [6]. Additionally, it was recently shown that there exists an analytical solution for pre-compensating the pulse distortions (caused by gain saturation) accumulated in the amplifier chain for arbitrary pulse shapes [7]. All this transforms fiber integrated MOPA systems in extremely versatile devices for science and industry.

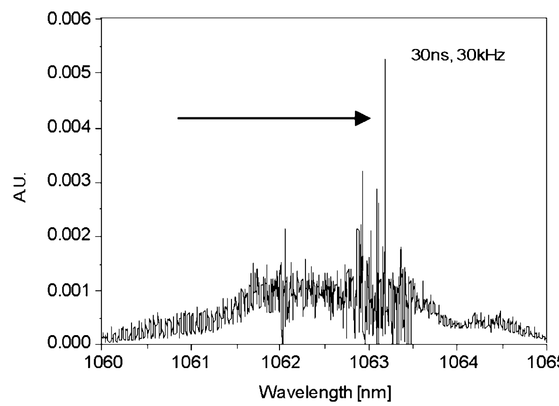

Fig. 1 Typical output spectrum of a pulsed Fabry–Pérot diode with 30 ns, 30 kHz, 0.7 W pulses. The spectral peak is marked with an *arrow*

Most MOPA systems are seeded by Fabry–Pérot diode laser seed sources. Unfortunately, pulsed Fabry–Pérot diode lasers have a tendency to emit a spectrum having randomly occurring features of very high spectral brightness due to the low number of longitudinal modes emitted from the short cavity. A typical output spectrum of a pulsed Fabry–Pérot diode laser investigated in our lab with 30 kHz repetition rate, 30 ns pulse duration and 0.5 W peak power is shown in Fig. 1. Features like the marked peak in the spectrum lead to a low threshold for stimulated Brillouin scattering (SBS), which not only can lead to severe distortions of the output pulse shape but that can also damage the amplifier system due to the strong back-propagating Brillouin signal. This issue is one of the main challenges for further power scaling of

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fiber MOPA systems employing pulsed Fabry–Pérot diode lasers as the seed source [8, 9].

Several approaches exist to overcome this problem. In [9], a pulsed Fabry–Pérot laser diode is combined with a fiber Bragg grating in a pigtail to form an external resonator (which increases the number of longitudinal modes). The output of this arrangement is then modulated by an electro-optic modulator. The high complexity of this source, requiring two function generators, a pulsed diode laser and an external modulator, makes this approach unattractive for e.g. industrial setups. In addition, the use of an external resonator places limitations on the time-scale of the (direct) modulation of the laser diode. In [10], a cw source is carved with an external modulator, thus generating pulse trains with high flexibility. This approach, on the other hand, has the major drawback of requiring external modulators with an extinction ratio substantially higher than the duty cycle of the pulsed source in order to prevent the amplification of a cw background. Additionally, in this approach a large amount of energy is lost during the modulation process, which substantially reduces the efficiency of this source.

In this contribution we demonstrate, for the first time to the best of our knowledge, a novel approach for a diode seeded fiber MOPA system requiring neither external modulators nor external resonators. This approach employs a pulsed superluminescence diode as the seed source. A superluminescence diode (SLD) is a diode laser with the emitter facets antireflection coated and/or tilted. This ensures that over a large span of the pump current the SLD will not reach the laser threshold, leading to a smooth output spectrum free of any longitudinal modes. The bandwidth of the SLD depends on the gain material, the length of the gain region and gain narrowing effects, which can all be tailored for the corresponding application [11]. The very low finesse of the cavity of the SLD results in a photon cavity lifetime approaching the single pass time. A semiconductor and package design optimized for low parasitic capacity should allow for rise times in the picosecond regime. Given the almost total absence of any resonator dynamics, the SLD (in combination with a suitable driver circuit) is a promising current-to-light converter capable of emitting pulsed light from the sub-nanosecond to the cw regime in a linearly polarized, diffraction-limited beam with a smooth output spectrum.

2 Experimental setup and results

For our experiment we used a commercially available PM fiber pigtailed SLD [12] with a center wavelength of 1045 nm, a FWHM bandwidth of 10 nm and a maximum non-lasing output power of 150 mW. The SLD was driven with a driver circuit receiving the control voltage from a function generator. The fiber pigtail was terminated with an angle polished fiber connector in order to protect the SLD from back reflections. A cw slope measurement reveals the nearly linear correlation between pump current and output power (Fig. 2). The electronic circuit was able to drive the SLD with a peak power of ∼50 mW at a cut-off frequency of ∼400 MHz. Thus, it was possible to generate shaped pulses down to pulse durations of 10 ns with arbitrary shape, as can be seen in Fig. 3a–c. The pulse shape of the current input is marked gray, while the output pulse shape is marked black. The output spectrum of the corresponding pulse shapes is shown in Fig. 3d and exhibited no dependence either on the pulse shape or on the repetition rate. The output spectrum remained free of any longitudinal mode structure or, by that matter, of any other feature with high spectral brightness. When operating the SLD at higher currents with a more powerful (but in this case slower) driver with 10 kHz, 100 ns square pulses, the laser threshold is reached at a peak power of ∼200 mW, and spectral spikes show up in the spectrum (Fig. 4). The weak ripple structure of the spectrum at lower peak powers is a common artifact of SLDs since the finesse of the cavity is never completely zero. The obtainable lasing-free peak power of >150 mW makes the SLD an interesting candidate for seeding a fiber MOPA system with variable pulse shapes. However, considering e.g. a pulse duration of 20 ns, a repetition frequency of 20 kHz and a peak power of 100 mW results in an average power of only 40 μW. It is thus important to estimate the cw background caused by amplified spontaneous emission when amplifying seed signals of this low average power. For this purpose we have simulated a core pumped ytterbium doped fiber amplifier with 6 μm core diameter and 500 mW of pump power at 976 nm seeded with the average power of 40 μW at 1045 nm from the SLD. To be able to estimate the ASE content, we reduced the simulated signal bandwidth to 1 nm. This enables us to determine the spectral signal to ASE ratio by comparing the ASE base line with the signal peak in the spectrum as shown in Fig. 5. Assuming the use of a band-pass filter with 10 nm bandwidth around the signal wavelength, the residual ASE

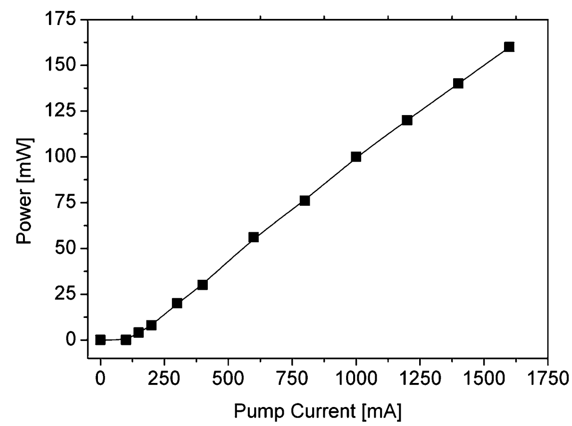


Fig. 2 Power/current slope of the SLD

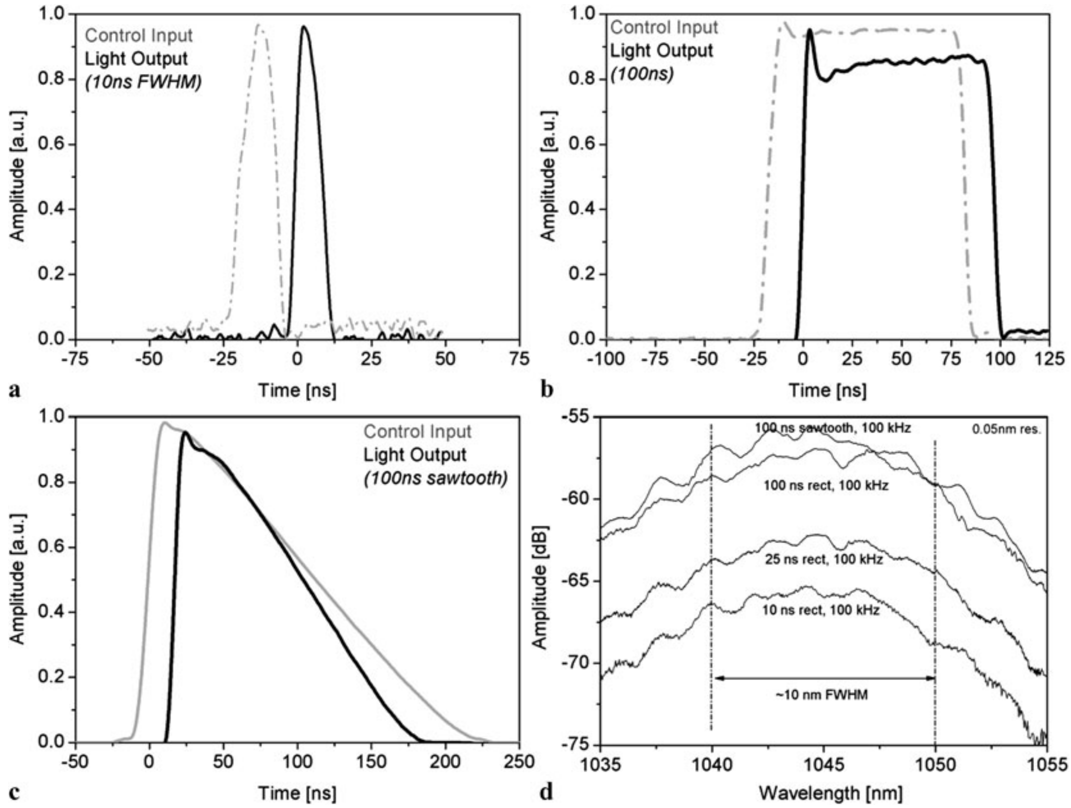


Fig. 3 Power output at a peak power of 50 mW for: **a** Gaussian pulse, **b** square pulse, **c** triangular pulse. **d** Corresponding output spectra

content in this case is <40 μW while the amplified output signal has an average power of ∼3 mW. This corresponds to an ASE content of ∼1%, which is acceptable for most applications and shows the importance of the band pass filter as an ASE filter.

Using the results from the simulation, a core pumped, co-propagating fiber amplifier with the above-mentioned parameters was built. The output spectrum was filtered with a 4 nm band-pass filter, resulting in an output power of ∼1.5 mW. Keeping in mind that the real signal FWHM bandwidth of 10 nm was cut to 4 nm by the band pass filter, the simulated signal power was reduced by a factor of 2.5 from 3 mW to ∼1.2 mW, which agrees well with the experimentally obtained output.

For further experiments, the filtered output of the first amplifier stage was coupled into a second fiber amplifier consisting of 2 m Ytterbium doped double-clad fiber with a 10 μm core and a 125 μm cladding. This fiber was pumped with a 5 W fiber coupled diode laser at 976 nm wavelength, allowing for an average output power of up to 1 W. A schematic of the entire setup is shown in Fig. 6. The average seed power of 1.5 mW for the second stage was sufficient to generate noticeable pulse distortion due to gain saturation. This led to output pulses exhibiting shapes with exponential decays as described in [7]. This distortion has been partially pre-compensated by seeding the amplifier

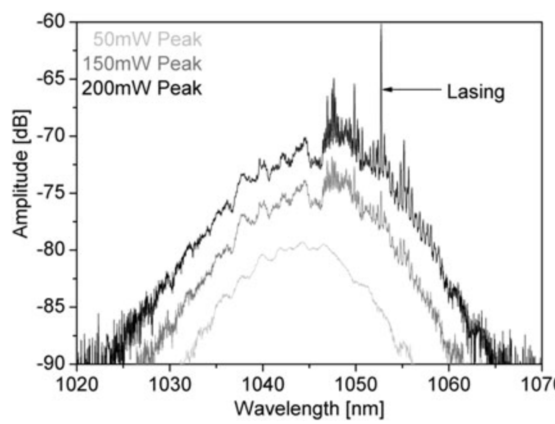


Fig. 4 Spectral output of 100 ns, 10 kHz pulses at different peak powers. The *arrow* marks onset of lasing

chain with pulses having the shape of a linearly increasing ramp, providing an example of the pulse shaping capabilities of this setup. The results are represented in Fig. 7. It can be seen that the seed source is fast enough to compensate for gain saturation even in the case of a pulse duration of 10 ns. The output spectrum of the system is shown in Fig. 8 and represents a smooth and continuous peak with a FWHM bandwidth of ∼4 nm, explaining why we observed no SBS no matter what seed pulse parameters we have used. This can be easily retraced when comparing the critical input peak power P_{cr} for SBS in the second stage of the discussed fiber amplifier. For a seed signal having a spectral bandwidth $\Delta\upsilon_S$ in the magnitude of the Brillouin bandwidth $\Delta\upsilon_{Br}$ of 10 MHz (in fused silica) and for a seed signal having a bandwidth of 4 nm (~1 THz), the increase of the critical peak power for SBS is in good approximation proportional to the ratio of the discussed bandwidths, according to the expression for the critical peak power for SBS: $P_{cr} = \sim 21 A_{eff}(1 + \Delta\upsilon_S/\Delta\upsilon_{Br})/g_{Br}L_{eff}$, where A_{eff} denotes the effective mode field area in the fiber core, and g_{Br} denotes the Brillouin gain coefficient for fused silica [13]. In case of the second amplifier stage in the experiment, at 1 THz bandwidth the critical input peak power for SBS would be increased by five orders of magnitude, which is by far enough for the discussed demands.

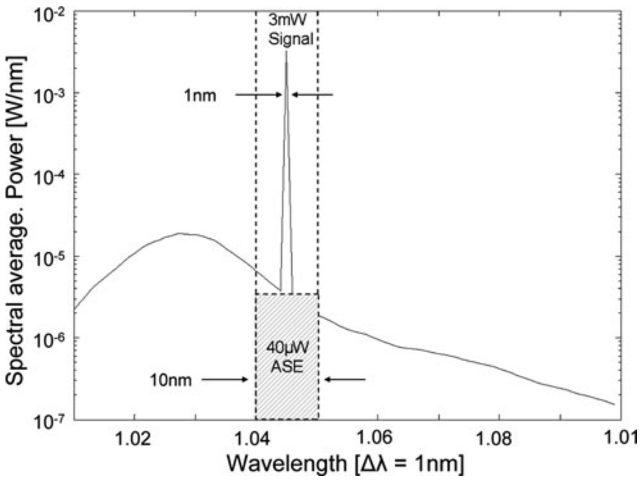


Fig. 5 Simulation of the spectral signal to ASE ratio when amplifying a 40 µW seed signal at 1045 nm wavelength in a core pumped ytterbium doped fiber amplifier

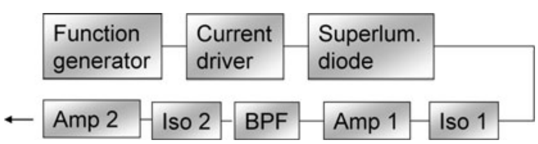


Fig. 6 Double stage fiber amplifier setup, ISO = Isolator, BPF = Bandpassfilter, Amp = Amplification Stage

3 Conclusion and outlook

To summarize, we have demonstrated for the first time to the best of our knowledge, a high performance fiber MOPA

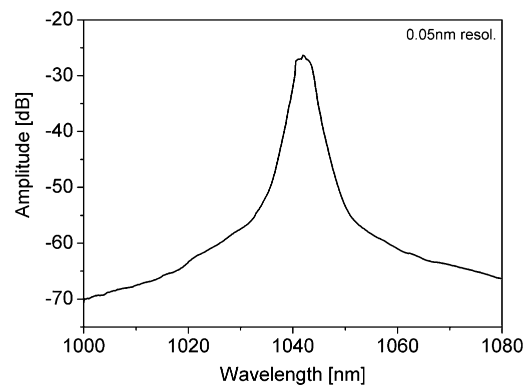
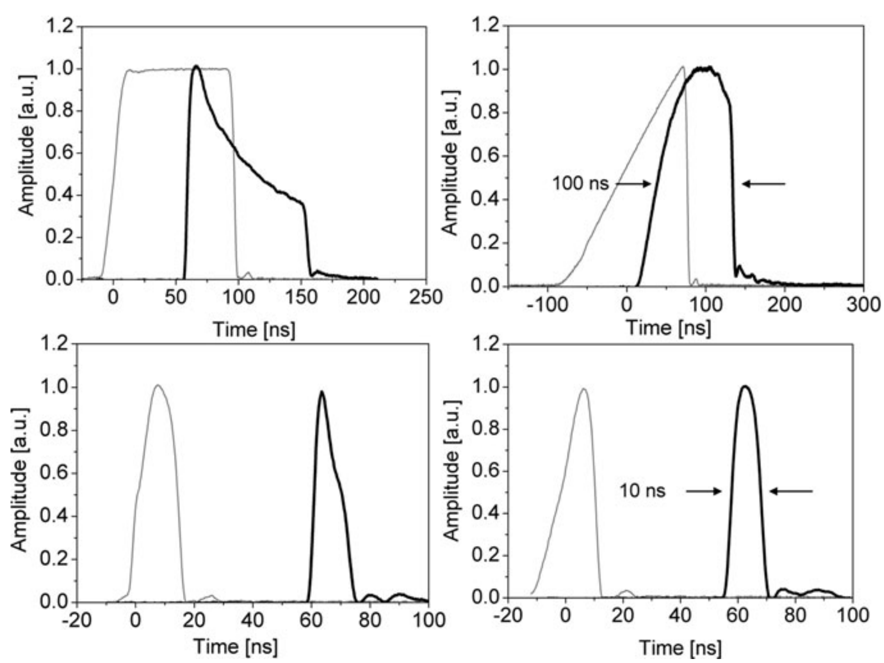


Fig. 8 Output spectrum of the MOPA system at an average power of 1 W

Fig. 7 Output of the MOPA system with unshaped (*left*) and shaped (*right*) 100 ns and 10 ns pulses at a repetition rate of 10 kHz. Input pulse shape is marked *gray*, output pulse shape is marked *black*



system seeded by a superluminescent diode (SLD). A key advantage of the present configuration is its highly dynamic pulse-shaping on time-scales as short as 10 ns without the onset of stimulated Brillouin scattering in the subsequent fiber amplifier chain. In particular, the SLD, which works as a super-radiator well below its laser threshold, delivers a smooth 10 nm FWHM output spectrum without any sharp spectral features and peak powers of up to 150 mW. By adding band-pass filters between the fiber amplification stages, the spectrum can also be shaped to be sufficiently narrow for e.g. efficient frequency conversion without losing too much effective gain between the amplifier stages. The response time of the SLD was mainly limited by the driver electronics to a value of <5 ns, allowing one to shape pulses with a duration of 10 ns or above. An improved design of the driver module and further optimization of the SLD semiconductor structure will provide shaped pulses on a sub-nanosecond time-scale, since the SLD exhibits a very short photon cavity lifetime. Thus, SLDs are optimal seed sources that allow for the generation of arbitrary pulses from the sub-nanosecond to the cw regime free from the limitations imposed by SBS as in case of Fabry–Pérot laser diodes as the seed source. The simplicity of the approach reinforces the applicability of this concept. We thank JT Optical Engine for providing us with the driver electronics. This work was partially funded by the German Federal Ministry of Education and Research (BMBF Deutschland).

References

1. V.N. Tokarev, A.F.H. Kaplana, J. Appl. Phys. **86**, 2836 (1999)
2. A. Bogaerts, Z. Chen, D. Autrique, Spectrochim. Acta, Part B, At. Spectrosc. **63**, 746 (2008)
3. A. Vogel, V. Venugopalan, Chem. Rev. **103**, 577 (2003)
4. W.R. Harp, J.R. Dilwith, J.F. Tu, J. Mater. Process. Technol. **198**, 22 (2008)
5. M.-Y. Cheng, Y.-C. Chang, A. Galvanauskas, Opt. Lett. **30**, 358 (2005)
6. J. Limpert, S. Höfer, A. Liem, H. Zellmer, A. Tünnermann, S. Knoke, H. Voelckel, Appl. Phys. B **75**, 477 (2002)
7. D.N. Schimpf, C. Ruchert, D. Nodop, J. Limpert, A. Tünnermann, F. Salin, Opt. Express **16**, 17637 (2008)
8. C. Ye, P. Yan, L. Huang, Q. Liu, M. Gong, Laser Phys. Lett. **4**, 376 (2007)
9. A. Malinowski, K.T. Vu, K.K. Chen, J. Nilsson, Y. Jeong, S. Alam, D. Lin, D.J. Richardson, Opt. Express **17**, 20927 (2009)
10. US patent 20080261382
11. V. Shidlovski, *Superluminescent Diodes. Short Overview of Device Operation Principles and Performance Parameters* (2004). SuperlumDiodes Ltd
12. Innolume, www.innolume.com
13. G.P. Agrawal, *Nonlinear Fiber Optics* (Academic Press, San Diego, 2001)