Multi-kilowatt peak power nanosecond Er-doped fibre laser

V. V. Dvoyrin, D. Klimentov, J. O. Klepsvik, I. V. Mazaeva and I. T. Sorokina

Abstract — **We report a 2-stage diode-pumped Er-doped fibre amplifier operating at the wavelength of 1550 nm at the repetition rate of 10-100 kHz with an average output power of up to 10 W. The 1st stage comprising Er-doped fibre was core-pumped at the wavelength of 1480 nm whereas the 2nd stage comprising double-clad Er/Yb-doped fibre was clad-pumped at the wavelength of 975 nm. The estimated peak power for the 0.4-nm full width at half maximum (FWHM) laser emission at the wavelength of 1550 nm exceeded 4 kW level. The initial 100-ns seed diode laser pulse was compressed to 3.5 ns as a result of the 34-dB total amplification. The observed 30-fold efficient pulse compression reveals a promising new nonlinear optical technique for generation of high power short pulses for applications in eye-safe ranging and micromachining.**

***Index Terms*— Fiber lasers, Infrared lasers, Optical fibers.**

I. Introduction

ACTIVELY Q-switched nanosecond fibre lasers, particularly those operating in the eye-safe spectral domain in the vicinity of 1.55 μm are highly demanded for numerous applications, i.e., material processing, medicine, sensing [1], and ranging [2, 3]. The emission of Er-doped fibre laser (1.55 – 1.61 μm) fits well the transparency window of the atmosphere. It makes Er-doped fibre laser an excellent candidate for the light detection and ranging applications (LIDARs) [4-10], even in the bad weather conditions (rainy, foggy or snowy). This is essentially important for the ranging on the sea, where the weather is rather changeable and sometimes unpredictable.

Laser peak power and pulse duration are responsible for coverage and resolution of a LIDAR system, whereas pulse repetition rate defines the data acquisition rate. Modern inexpensive semiconductor detectors can resolve pulses of duration of several nanoseconds, and laser systems with high repetition rates of 10-100 kHz allow observation in real-time. Amplified distributed feedback (DFB) laser diodes producing short pulses with a narrow linewidth are widely used in traditional LIDAR systems. Such lasers have low average and peak powers at milliwatt level that leads to difficulties in development of a high-power laser system. Recently, the peak power of 7.6 kW was reported for the Er/Yb-doped master-oscillator-power-amplifier (MOPA) laser system producing 1.2-ns pulses at a repetition rate of 50 kHz with pulse energy of 9.6 μJ [3]. The pulse energy of 290 μJ was achieved in the Er/Yb-doped fibre amplifier chain [4]. This system had a moderate peak power (2 kW) and relatively long pulses of 100-ns duration. Large mode area fibre amplifiers allow producing higher pulse peak powers and energies [11−15]. However, this type of laser sources require the use of free-space optical components, including hybrid bulk-fibre configuration, leading to the poor pulse control and the more stringent requirements to the pump diodes. Other promising approaches towards obtaining pulsed laser action in fibre lasers, that have been implemented, include, e.g. all-fibre oscillators [16, 17], hybrid fibre systems with waveguide saturable absorbers [18], etc. Whereas such techniques are under development now, for practical applications the most straightforward and promising concept is the MOPA configuration with a seed laser diode.

In this paper, we report the development of the Er-doped all-fibre MOPA operating at the transparency window of the atmosphere and generating eye-safe 3.5-ns pulses. The MOPA was based on the FBG-stabilized seed laser diode as opposed to DFB laser diodes normally used in Yb- or Er-doped fibre amplifiers. High output average and peak power of the seed diode laser as compared to typically implemented DFB laser diodes allowed obtaining the peak power of more than 4 kW. However, the most intriguing observation in the course of the work was that the initially relatively long pulses of 100-ns were drastically compressed down to only few nanoseconds as a result of the amplification revealing a useful nonlinear optical technique for short pulse generation.

II. Experimental

The fibre-coupled FBG-stabilized semiconductor laser diode (Princeton Lightwave Inc.) operating at the wavelength of 1550 nm was used as a seed laser for the fibre amplifier, which consisted of the two amplification stages (Fig. 1). The first amplification stage consisted of a piece of the Er-doped silica-based fibre with core diameter of 4 μm. It was core-pumped with two fibre-coupled laser diodes (Fitel Inc.) operating at the wavelength of 1480 nm with up to 300 mW optical power each, 600 mW in total. The second amplification stage utilized a 5-m long piece of a double-clad Yb/Er-doped silica-based fibre with core and clad diameters of 12 and 130

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µm, respectively. It was clad-pumped at the wavelength of 975 nm by a fibre-coupled laser diode (IPG Photonics Inc.) in the co-propagation direction with up to 40 W optical power. The piece of passive output fibre that was spliced to the active fibre was a single mode fibre with 8° angle-cleaved facet preventing the back reflection. The output radiation was a lowest order mode providing an excellent nearly Gaussian beam quality [19]. Pulse trains were recorded with an oscilloscope of 0.5 GHz band and a fast InGaAs semiconductor detector with ~1 ns response time. The emission spectra were measured with an optical spectrum analyzer; a thermal power meter was used for the measurements of the output optical power.

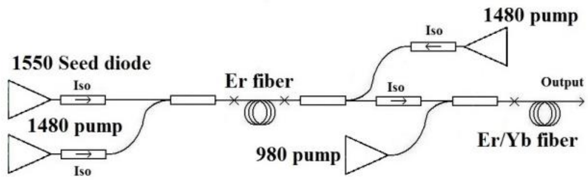

Fig. 1. The schematic of the setup.

III. Results

It was observed that the laser produced a stable pulse train in the whole range of the repetition rates from 10 to 100 kHz at the pump power of about 5 W. The laser output emission was studied at the rates of 10 and 100 kHz. At the maximum current, the seed laser diode produced ~100-ns pulses with the repetition rate of 100 kHz and the average optical power of 4 mW. The average optical power emitted from the first amplification stage amounted to 360 mW corresponding to 20 dB optical gain. The energy extraction from the amplifier was equal to 60%. A weak pulse compression down to 65 ns was already detected (Fig. 2). The full width at half maximum (FWHM) of the laser line amounted to ~0.4 nm and remained nearly unchanged in all the experiments.

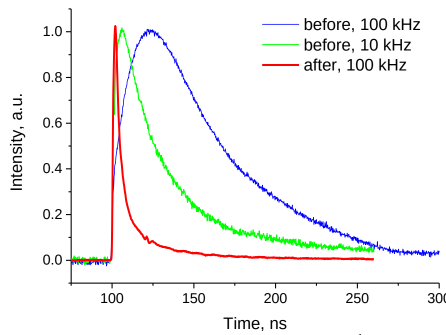

Fig. 2. Pulse shapes before and after the 2nd stage amplifier.

After the propagation through the second-stage amplifier, the pulse duration drastically dropped down. It experienced nearly exponential fall with the pump power increase (Fig. 3). The pulse was compressed down to 3.5 ns at 9.5 W of the output power. At 38 W of the pump power the average output power amounted to 10 W; the corresponding amplifier efficiency was equal to 26% (40% quantum efficiency). No change in the spectral width of the laser line was detected. However, we observed a rise of a broad spectral background, which was negligible at low output powers. Thus, at 1 W of the output power it corresponded to less than 0.5% from the total output power. On the contrary, at the output power of 9 W more than a half of the laser radiation must be attributed to the background (Fig. 4). It is worth noting that the spectral background in the spectra of the emission from the 1st-stage amplifier was negligible.

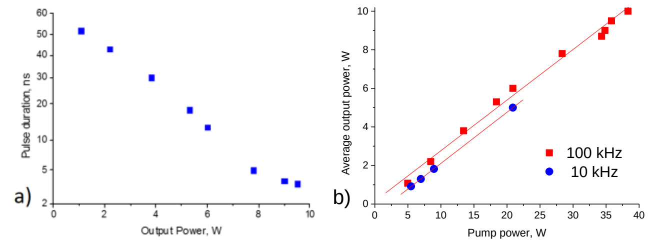

Fig. 3. Pulse compression (a) and laser efficiency (b) in the 2nd stage amplifier.

At the moment, we attribute this background to the amplified spontaneous emission (ASE) known to be the usual reason for similar phenomena in the high-power amplifiers with high optical gain. The estimation of the peak power of the emission under the narrow 1550-nm line (excluding the background fraction from the total output power) is about 4 kW for the most intensive 3.5-ns pulse.

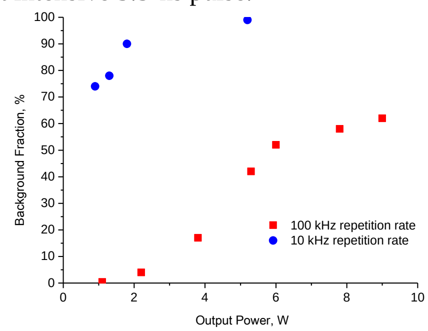

Fig 4. Fraction of the spectral background in the total output radiation.

The optical power of the seed diode operating at 10 kHz repetition rate was equal to 0.6 mW. The optical power of 160 mW corresponding to the optical gain of 24 dB was obtained after the first amplification stage. At the repetition rate of 10 kHz the initial pulse was compressed down to 25 ns (Fig. 2).

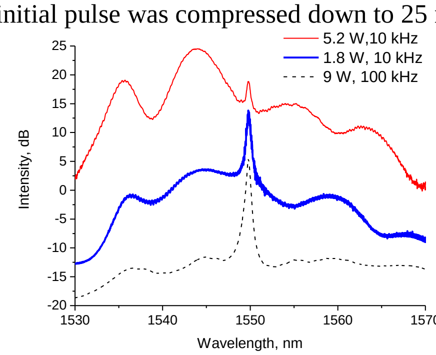

Fig. 5. Emission spectra at 10 kHz and 100 kHz repetition rate.

The slope efficiency of the 2nd stage amplifier operating at the repetition rate of 10 kHz was similar to the previous case consisting of 26%. At the output power from the 2nd stage amplifier of 0.9 W, the pulse duration already amounted to 4 ns. The pulse was further compressed to the shortest duration of 3 ns for the output powers higher than 1 W. At such pump powers, the pulse duration remained nearly unchanged. The fraction of the background in the total emission was greater. At 5 W of the average output power the spectrum was represented by a broad structured band (Fig. 5). The area under the narrow line corresponds to the seed laser and amounts to ~1% from the total spectrally integrated emission.

IV. DISCUSSION

In this study, we investigated the FBG-stabilized seed laser diode as an alternative to DFB laser diodes for Er-doped fibre amplifiers. FBG stabilization allows perfect lock of the laser wavelength. Although the laser line is significantly broader than a typical linewidth of a DFB laser diode, it is narrow enough for the atmospheric transmission window at 1.5 μm, and from practical point of view, the narrow linewidth of 0.4 nm allows the operation in between the intensive absorption lines of the atmosphere after a precise choose of the central wavelength of the FBG-stabilized seed laser diode. The advantage of the FBG-stabilized diode is its high output power. Thus, its average power amounted to 0.5 and 0.4 W at 10 and 100 kHz repetition rate, respectively. At considerably higher repetition rates beneficial for high acquisition rate systems, the average power of such diodes can be increased up to 1-watt level. However, the high output power of the diode is obtained at the expense of the longer pulse durations. Therefore, the most important advantage of this laser is the essential compression of the pulses propagating in the fibre amplifier. At least 33-fold compression has been demonstrated in our experiment. In such system with the external pulse compression, higher average power of the seed laser is allowed that relaxes requirements to the amplifier. In addition, long pulses allow simpler electronic control. The compression phenomenon originates from the predominant amplification of the forward front of the pulse if the pulse energy becomes comparable or higher than the saturation energy. The amplification of the forward part of the pulse leads to the depletion of the gain for its tail because some ions are falling down from the excited state to the ground state when radiation interacts with matter. If the pulse energy is high enough, all the stored energy comes to the pulse beginning and the amplification of its tail becomes negligible. It is expressed in steeping of the pulse front and its overall shortening. This phenomenon is gain-dependent. Thus, pulses with 10 kHz repetition rate have been better compressed in the 1st stage amplifier as compared to the pulses with 100 kHz repetition rate, Fig. 2. The compression was more efficient because the optical gain accumulated during 10 times longer period between the pulses apparently was higher.

Nearly exponential pulse compression is an efficient tool for obtaining short intensive pulses. The 4-kW level peak power corresponding to the narrow spectral component at the wavelength of 1550 nm is reasonably high for the practical applications, i.e. remote sensing and micromachining. The observed spectral background currently attributed to ASE can limit the performance of the system. The detailed study of its origin requiring time-resolved spectral measurements, as well as the implementation of the ASE suppression techniques for this system will be performed elsewhere. However, in time domain the background between pulses was negligible (below detection threshold), therefore its appearance in spectra should not affect the detection in ranging applications. At the present stage, we have demonstrated multi-kilowatt output from a simple system, which can be directly applicable in practice being comparable by pulse duration and peak power to the modern commercial systems. This useful technique is promising for LIDARs development as well, as for compression of the optical pulses down to sub-nanosecond durations.

V. CONCLUSION

In this paper we report the Er-doped laser system based on conventional commercially available fibres and operating at the wavelength of 1550 nm with the average power of up to 10 W. The estimated pulse peak power for the narrow 1550-nm spectral component of 0.4 nm FWHM exceeded 4 kW level. A low-power laser diode operating at the repetition rate of 10-100 kHz was used as a seed laser for the two-stage fibre amplifier. The first stage amplifier consisted of the core-pumped Er-doped fibre whereas the 2nd-stage amplifier was represented by the Er/Yb-doped clad-pumped fibre. The initial pulse duration of ~100 ns was strongly reduced down to 3.5 ns as a result of the 34-dB total amplification revealing a powerful nonlinear optical technique for an intense short pulse production. Further investigation of the pulse compression mechanisms will contribute to the development of novel practical, robust, reliable and highly intense pulsed laser devices for numerous applications, e. g. LIDAR applications.

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