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Diode-seeded nanosecond Yb-doped fiber amplifier operating at the repetition rate up to 500 kHz

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The paper presents a laser system developed in MOFPA (Master Oscillator Fiber Power Amplifier) configuration. A pulsed single-mode laser diode operating at the wavelength of 1060-nm was used as a seed. An ytterbium-doped double-clad Large Mode Area fiber pumped by the radiation of 978-nm played a role of an active medium. The developed laser system generated a pulse train with duration ranging from about 11 ns to 200 ns at the repetition rate up to 500 kHz, regulated independently of the system gain. The maximum amplification of the fiber amplifier was 32 dB.

Keywords: double-clad optical fiber, fiber amplifier, pulse generation.

1. Introduction

Pulsed lasers delivering nanosecond pulses of high-peak power at the repetition rate of kHz constitute very useful sources for a number of advanced industrial applications, such as marking, engraving, material processing and others. It has made them a subject of considerable research recently [1–3]. Currently this area is still dominated by Q-switched diode-pumped solid-state lasers operating at 1064 nm and its harmonics. However, within the space of last several years high-power laser systems based on MOFPA (Master Oscillator Fiber Power Amplifier) configuration appear to be very attractive in this context providing greater flexibility, reliability and much lower costs than conventional non-fiber laser systems [4, 5]. Moreover, they are more compact, lighter, more efficient and in many cases they do not need complicated water cooling – which makes the whole amplifier system construction easier.

A MOFPA system is made up of a generator seeding pulses of light and an amplifier of these pulses. A seeding generator can be any pulsed diode-pumped solid state laser or even a semiconductor laser diode while a double-clad active optical fiber, especially Large Mode Area (LMA) fiber fulfils the role of an amplifying medium. In a LMA fiber construction, the core diameter was enlarged and simultaneously the difference between the refractive index of a core and an inner clad was decreased. Such fibers make it possible to generate a basic TEM_{00} mode, reduce amplified spontaneous emission (ASE) signal, raise the power threshold of fiber end-facet damage. The resulting increased mode-field diameter of LMA fiber also reduces the detrimental effects of various nonlinear interactions such as stimulated Raman and Brillouin scattering, thus lifting the limits for achievable output powers.

As far as the dopant of the active fibers is concerned, the ytterbium ions are excellent mainly due to the fact that ytterbium-doped fibers offer high output powers tunable over a broad range of wavelengths, from 975 to 1200 nanometers (typically around 1060 nm) [6]. Ytterbium ions also have a relatively small quantum defect – pump wavelength (915 nm or 976 nm) is close to the lasing wavelength and as a result very little energy is lost to heating. Furthermore, ytterbium has only one excited state and consequently complications arising from excited-state absorption do not appear.

A very interesting MOFPA system solution is the application of a single-mode pulsed semiconductor laser diode operating at 1060–1070 nm as a pulse generator. The efficiency of such coherent light sources is much higher than efficiency of conventional DPSSLs (Diode-Pumped Solid-State Lasers) which results in increasing the efficiency of the whole system.

2. Experimental setup

The setup of a pulsed fiber amplifier is shown in Fig. 1.

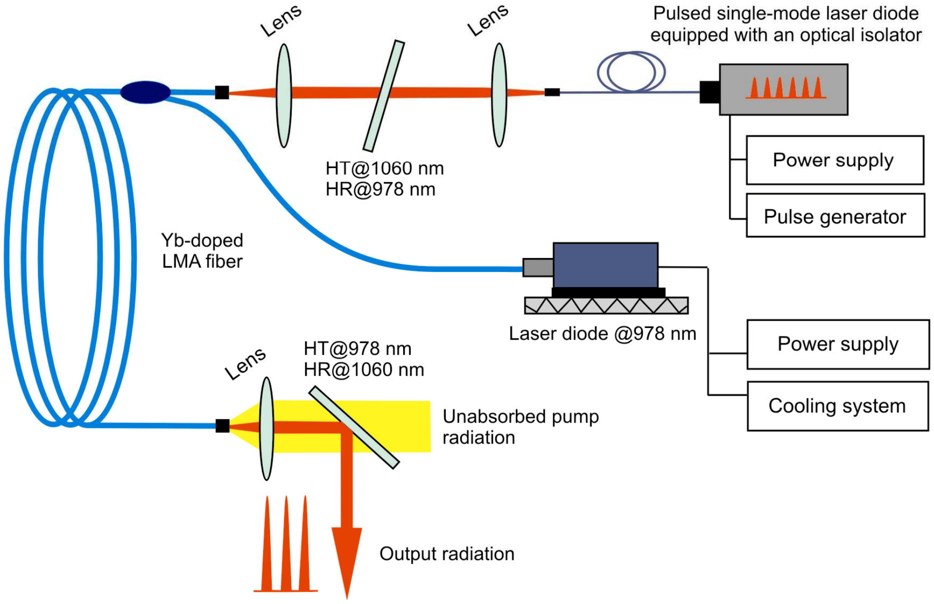

Fig. 1. Experimental setup of the fiber amplifier.

A pulsed laser diode was used as a seed. It was equipped with a single-mode fiber pigtail (polarization maintaining version) with a built-in optical isolator ensuring high Polarization Extinction Ratio (PER) – over 22 dB. The fiber pigtail was terminated by an FC/APC connector to minimize back reflections. The laser diode operated at 1063.91 nm (the spectral width at 3 dB level equalled 0.52 nm) and generated pulses of duration from about 11 ns to 200 ns at the repetition rate up to 500 kHz. The time-energetic characteristic of the diode seed is depicted in Fig. 2 and Table. The seed operated as an electrical-to-optical converter with a bandwidth of approximately 175 MHz. It was supplied by a DC power supply and was driven by electrical pulses with a suitable amplitude. The duty cycle did not exceed 2%, this limitation was imposed by the limited energy storage capabilities of the semiconductor laser.

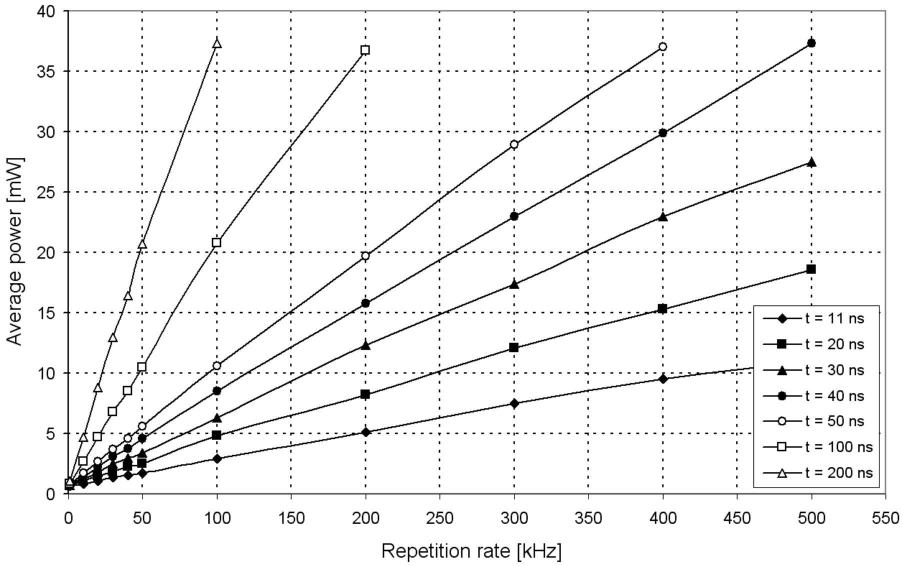

Fig. 2. Time-energetic characteristic of the diode seed.

Table. Statement of values of the pulses generated by the diode seed.

		Pulse duration [ns]						
		11	**20**	**30**	**40**	**50**	**100**	**200**
Repetition rate [kHz]	**1**	670 nJ	690 nJ	710 nJ	730 nJ	750 nJ	850 nJ	1,05 μJ
	10	86 nJ	105 nJ	125 nJ	145 nJ	170 nJ	270 nJ	470 nJ
	20	55 nJ	75 nJ	90 nJ	110 nJ	135 nJ	235 nJ	440 nJ
	30	44 nJ	61 nJ	83 nJ	103 nJ	123 nJ	226 nJ	433 nJ
	40	38 nJ	56 nJ	75 nJ	93 nJ	115 nJ	212 nJ	422 nJ
	50	35 nJ	50 nJ	68 nJ	92 nJ	112 nJ	210 nJ	414 nJ
	100	29 nJ	48 nJ	63 nJ	85 nJ	106 nJ	208 nJ	383 nJ
	200	25 nJ	41 nJ	61 nJ	79 nJ	98 nJ	183 nJ	–
	300	25 nJ	40 nJ	58 nJ	76 nJ	96 nJ	–	–
	400	23 nJ	38 nJ	57 nJ	74 nJ	92 nJ	–	–
	500	22 nJ	37 nJ	55 nJ	74 nJ	–	–	–

The ytterbium-doped Large Mode Area double-clad optical fiber was used as an amplifying medium. The fiber had the core diameter of 20 μm. It was coated with silicone rubber with diameter of 400 μm (octagonal shape). The numerical aperture (NA) of the inner clad to the core and the outer clad to the inner clad were 0.06 and 0.46, respectively. This active fiber module (made by NUFERN) was performed as it is shown in Fig. 3.

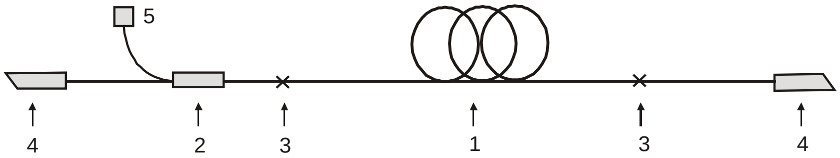

Fig. 3. Diagram of the Yb-doped fiber module. (1) Yb-doped gain fiber (13 dB absorption at 976 nm); (2) pump multiplexer 2×1 and 1-m long 400/440 micron, 0,22 NA pump fiber input; (3) splice (20 micron core to 20 micron core, both 400 micron cladding); (4) SMA-905 angle polished endcap essembly; (5) SMA-905 connector on pump delivery fiber.

The ends of the fiber module (marked in Fig. 3 as “4”) were polished at the angle of 82° in relation to the fiber axis, whereas the pump delivery fiber end was polished perpendicularly to the fiber axis. All the fiber module ends were terminated by SMA-905 connectors. The application of the fused-fiber pump combiner allowed reducing the pump radiation insertion losses as well as making the pump launching considerably easier. In this case, the pump launching efficiency was over 90%. The amplifying signal co-propagated together with the pump signal. Forward pumping (co-propagating) provides higher inversion density at the beginning of the amplifier, and it is appropriate for small signals (high gain) applications because it results in low noise operation. Thanks to applying such a solution there is less danger of the seed damage by pump radiation. The fiber length was specified by NUFERN (it was an optimal length allowing about 95% absorption of the pump radiation).

The active fiber was pumped by a CW laser diode delivering 45 W at 978 nm. It was equipped with 1.5m long transmitting fiber characterized by the numerical aperture of 0.22 and the core diameter of 400 μm. The laser diode was current-controlled by means of a home-made power supply module and was cooled by a water cooling system. To control the working temperature of the diode, a Peltier cell was applied.

The amplifying signal was launched to the active fiber core by means of an optical system consisting of two aspheric lenses and a dichroic mirror (HT@1604 nm, HR@978 nm) situated between the lenses. It allowed focusing the laser beam on the fiber facet to the diameter of 17 microns preserving the numerical aperture below the value of 0,06. The launching efficiency was about 70%.

3. Results

In the MOFPA system, developed time-energetic characteristics of amplified radiation were measured. The measurements were done for three values of the repetition rate (500 kHz, 100kHz i 50 kHz) and for several values of pulse duration (within the range of 11–200 ns). The maximum pump power launched into the active fiber was only 11.5 W, although the pumping diode allowed generating the output power up to 45 W. Since we did not want to destroy the fiber, especially an optical fiber coupler, we did not exceed pump power value of 11.5 W. The experimental results are shown in Figs. 4–7.

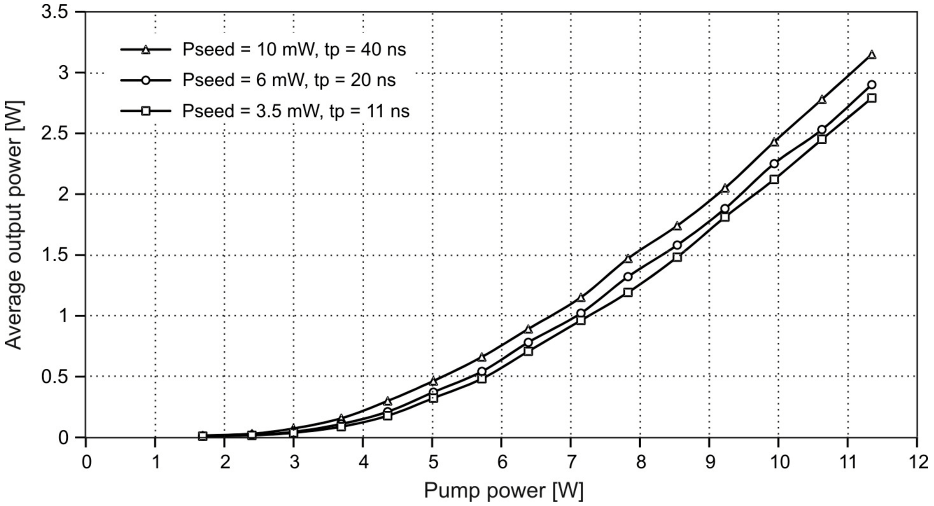

Fig. 4. Average output power of amplified radiation versus pump power launched into the fiber for several values of pulse duration of the diode seed at the repetition rate of 500 kHz.

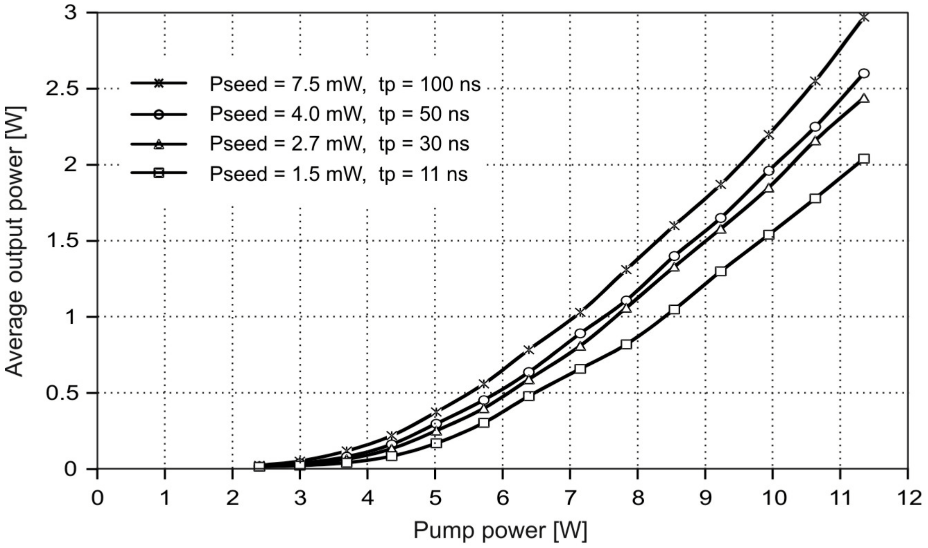

Fig. 5. Average output power of amplified radiation versus pump power launched into the fiber for several values of pulse duration of the diode seed at the repetition rate of 100 kHz.

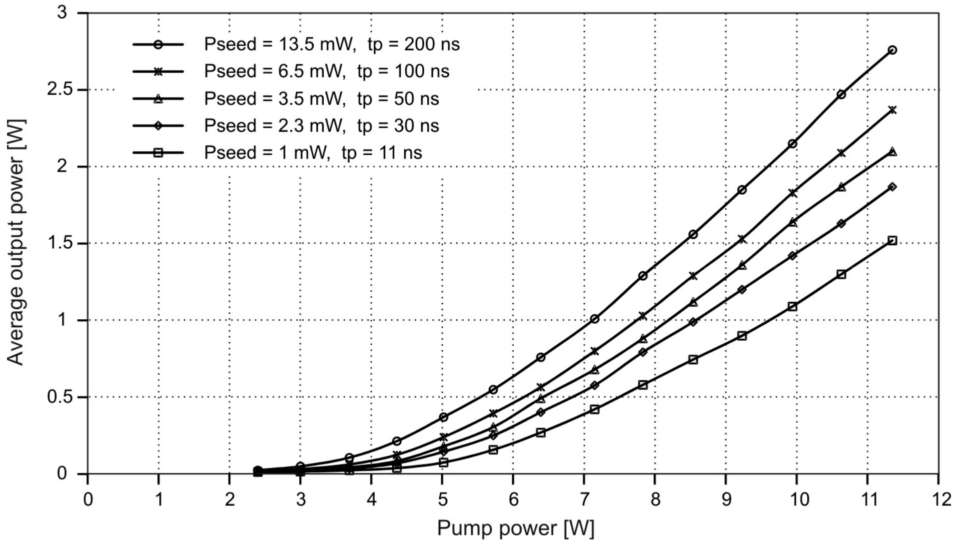

Fig. 6. Average output power of amplified radiation versus pump power launched into the fiber for several values of pulse duration of the diode seed at the repetition rate of 50 kHz.

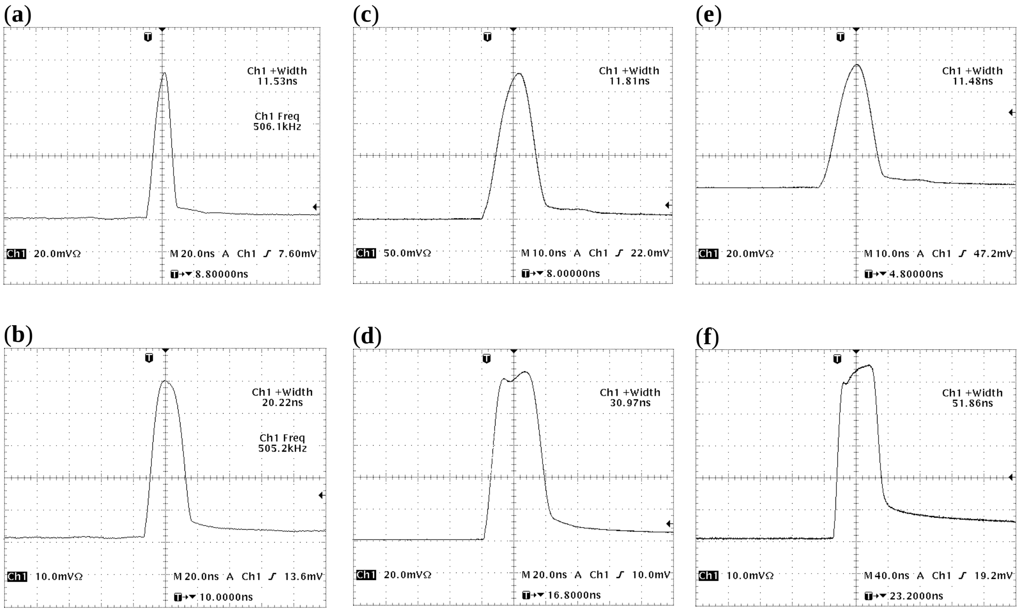

Fig. 7. Exemplary oscilloscope traces of amplified pulses for the repetition rate of 500 kHz (**a**, **b**), 100 kHz (**c**, **d**) and 50 kHz (**e**, **f**) recorded for the launched pump power of 11.4 W.

Figures 4–6 presents the dependence of average output power of the amplified signal versus pump power launched into the active fiber for three repetition rate values: 500 kHz, 100 kHz and 50 kHz and for several values of the pulse duration. The character of the energetic curves presented in all the graphs was very similar. The energy of output pulses rose along with the rise of absorbed pump power and the power value depended on the value of the input signal. At 500 kHz repetition rate the measurement of the energetic characteristic was done for 40 ns, 20 ns and 11 ns pulse duration. The energy of these pulses equaled 20 nJ, 12 nJ and 7 nJ, respectively. After amplifying, for maximum pump power launched into the fiber, the energy of these pulses was 6.3 μJ (about 25 dB amplification), 5.8 μJ (about 27 dB amplification), 5.6 μJ (about 29 dB amplification), respectively. For 100 kHz repetition rate the input pulses of duration: 100 ns (75 nJ), 50 ns (40 nJ), 30 ns (27 nJ) and 11 ns (15 nJ) were amplified to 29.7 μJ (about 26 dB amplification), 26 μJ (about 28 dB amplification), 24.4 μJ (about 29 dB amplification) and 20.4 μJ (about 31 dB amplification), respectively. However, for the lowest repetition rate of 50 kHz, the input pulses of energy 270 nJ (200 ns), 130 nJ (100 ns), 70 nJ (50 ns), 46 nJ (30 ns) and 20 nJ (11 ns) were amplified to the energy value of 55.2 μJ (about 23 dB amplification), 47.4 μJ (about 26 dB amplification), 42 μJ (about 28 dB amplification), 37.4 μJ (about 29 dB amplification) and 30.4 μJ (about 32 dB amplification), respectively.

The maximum MOFPA system efficiency was about 30% and it depended on the input signal value generated by the diode seed. In the system developed, the maximum energy of input pulses did not exceed 300 nJ, while the calculated saturation energy of the active fiber applied was about 300 μJ. This means that the amplifier worked in the regime far from optimal conditions. This also explains the high gain achieved during the experiment. The more energetic pulses were seeding, the higher system efficiency was achieved. The best solution is the case when the amplifier works in a state close to saturation (that is when the amplifying pulse receives the whole energy stored in an active medium), then the system efficiency is the highest.

In the whole range of repetition rate, the time duration of output pulses was the same as the one of input pulses. Therefore, it confirms the thesis that active double-clad fibers are perfectly fit for the amplification of ns-pulses with suitably shaped time characteristics. Applying a pulse generator delivering pulses of short width (single nanoseconds,) it is possible to achieve at the end of the MOFPA stage pulses of identical duration and high energy (depending on absorbed pump power). Exemplary oscilloscope traces were depicted in Fig. 7. Pulses of duration above 20 ns were a little bit deformed. However, these deformations were not caused by the effects occurring during the amplification process, but they resulted from limited abilities of the electronic generator PGP-7 (used in the experiment) controlling the diode seed. In case of fiber amplifiers with pulsed laser diodes as a seed, to achieve high pulse energies and high peak-powers of kilowatts, the gain of over 50 dB is required [7]. It is mainly caused by the low energies derivable from semiconductor diode seeds. When this high gain is achievable in active fibers together with low saturation of amplifying pulses, significant pulse reshaping due to depletion of the inversion in the pulse timescale can occur and this may affect the duration and shape of output pulses in a nonlinear manner [7]. In the MOFPA system developed, the gain achieved was much less than 50 dB and therefore the pulse reshaping did not take place.

4. Conclusions

In conclusion, the master oscillator – Yb-doped fiber power amplifier system seeded by a pulsed semiconductor laser diode operating at 1064 nm – was developed. It delivered pulses characterized by the duration of 11–200 ns, and the energy of μJ regime at the repetition rate up to 500 kHz. The maximum efficiency and gain coefficient equalled 30% and 32 dB, respectively. In the whole range of the repetition rate (50 kHz–500 kHz), the time duration of output pulses did not change with relation to the input pulses.

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