Hybrid bulk/fibre MOPA system based on Yb:KYW laser

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ABSTRACT

In the present work we present results of studies of hybrid sub-picosecond systems based on a solid-state Yb:KYW laser and a side-pumped fibre ytterbium amplifier manufactured using GTWave technology, which makes it possible to remove completely from the fibre amplification path any discrete optical elements. When the system was pumped with 12 W of CW radiation at 980 nm 0.9-ps output pulses with energy 40 nJ were generated at the repetition frequency of 100 MHz and the average radiation power 4 W. The centre wavelength of the system could be detuned within 1035–1055 nm (pulsed mode) and 1030–1070 nm (CW mode). Details are given of the layout of the femtosecond Yb:KYW laser developed with the use of saturable absorber mirror and chirped mirrors. For the first time gain coefficients of fibre GTWave Yb amplifier were measured within the generation range of the Yb:KYW laser. The developed system is a promising source of controlled super-continuum radiation, since the radiation pulse wavelength may be tuned around the zero dispersion wavelength of standard holey fibres (1040 nm) designed for super-continuum generation when pumped in this spectral range.

Keywords: Yb:KYW laser, hybrid bulk/fibre system, fiber amplifier, sub-picosecond laser system

1. INTRODUCTION

Solid-state lasers with active media based on single crystals of potassium-yttrium ($KY(WO_4)_2$ – KYW) or potassium-gadolinium ($KGd(WO_4)_2$ – KGW) tungstate doped with ytterbium ions possess a number of features [1–3] that have been spurring active research in the domain of these lasers. One major attractive property of Yb:KYW/KGW lasers is their ability to be directly and efficiently pumped with standard diode lasers emitting in the range of 975–980 nm. Spectral domain of generation of Yb:KYW/KGW lasers lies around 1010–1080 nm [4] with a maximum of radiation output power in the vicinity of 1045-nm wavelength. Presence in active Yb:KYW/KGW media of gain bands with typical width of several dozens of nanometres allows implementation in such lasers of femtosecond pulse generation with less than 100 fs pulse duration [5]. When longer pulses are generated their central wavelength can be, correspondingly, tuned in a range of up to ~ 70 nm. Another important feature of Yb:KYW/KGW lasers is the fact that their output wavelengths fall within the gain band of fibre-based ytterbium amplifiers. The highest gain of fibre Yb amplifiers is reached around 1070 nm, however the short-wavelength wing of gain band in these amplifiers covers the spectral range of Yb:KYW/KGW laser generation, thereby allowing the use of fibre Yb amplifiers in combination with solid-state Yb:KYW/KGW master oscillators.

Such hybrid bulk/fibre systems for generation of powerful sub-picosecond pulses within the spectral range of Yb:KYW/KGW generation have already been used before and demonstrated sufficiently high efficiency with the added benefit of relatively simple implementation. The average output power of a hybrid system based on Yb:KYW/KGW lasers may reach more than 100 W [6] while delivering sub-picosecond pulse durations and pulse repetition rates on the level of 100 MHz. Usually, in fibre-based optical amplifiers of such systems a double-clad Yb-doped fibre is used and the pump radiation is fed into the amplifier through a dichroic mirror placed, as a rule, in the path of the beam exiting the amplifier (counter-propagating pump). Guiding the pump radiation into an optical fibre amplifier through discrete optical elements (lens, mirror) obviously complicates the system and does not allow full realisation of possible advantages inherent in optical fibre amplification systems. Moreover, free-space optics creates discontinuities in multi-stage fibre systems, thereby introducing open intervals with bulk optics. The presence of such open intervals considerably weakens “fibre advantages” of such systems.

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GTWave technology of fibre optical amplifiers developed recently [7] makes it possible to guide the pump radiation into the active fibre directly through a standard quarts fibre. Using this technology allows elimination of any discrete optical elements from the fibre amplification train. In the present work, reported for the first time are results of investigation into hybrid bulk-fibre sub-picosecond systems based on a Yb:KYW laser and an ytterbium amplifier implemented with GTWave technology.

2. EXPERIMENT

In our experiments a Yb:KYW laser was used that was developed at the Laser Systems Laboratory of the Novosibirsk State University in collaboration with JS Company Tekhnoscan. The cavity layout is shown in Fig. 1. The 3.3-mm thick Yb:KYW crystal with 10% concentration of Yb^{3+} ions is set at Brewster angle. Pumping of the crystal was carried out along crystallographic axis *b* (Np) by a laser diode array delivering up to 3 W at wavelength of 975 nm. The array had 4 laser diodes whose radiation was first collimated by a micro-lens and then focused into the crystal through an aspherical lens with 65-mm focal length. Waist diameter of the pumping beam inside the crystal was approximately 80 µm. The active element of the laser was placed in a cooled optical mount.

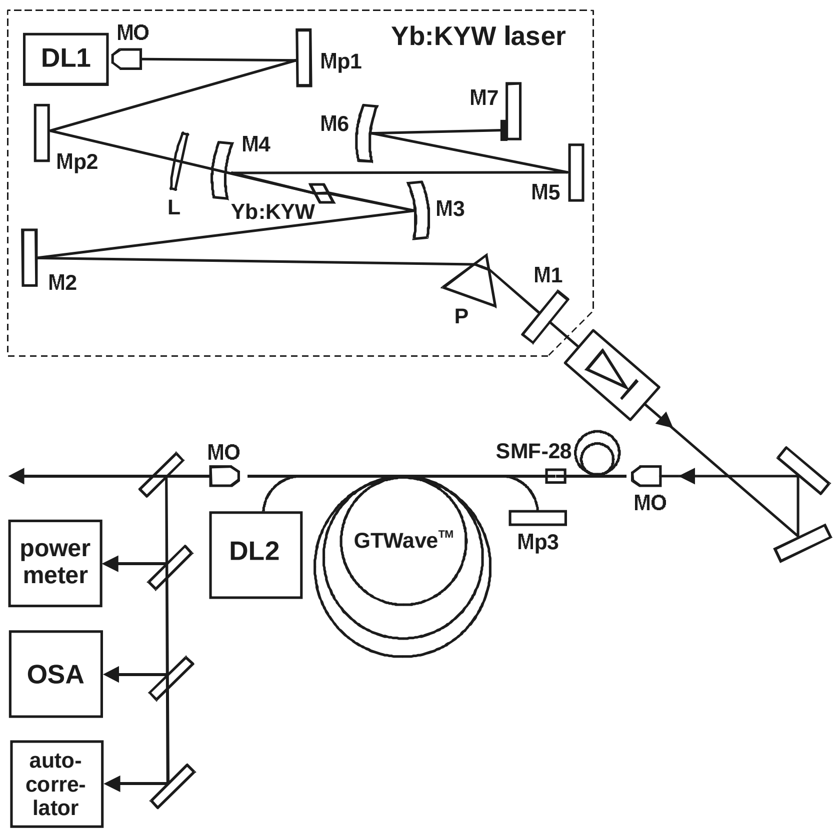

Fig. 1. Schematic experimental setup: DL1/2 – pump diode laser, $Mp_{1/3}$- reflecting mirrors for pump radiation, M1-M7 - mirrors of Yb:KYW laser, L – lens, P – prism, FI - Faraday isolator, MO - microscope objective.

Passive mode-locking of the Yb:KYW laser was started by a saturable-absorption mirror. Limit absorption of the mirror linearly drops from 2.7% at 1030 nm to 1.8% at 1060 nm, relaxation time is 500 fs, saturation energy density is 70 μJ/cm^2. In order to compensate for the group velocity dispersion two chirped mirrors were used, each of which provided approximately 500 fs^2 of negative group velocity dispersion within the range of 1040–1070 nm for a single reflection of radiation from the mirror. These mirrors together with the saturable-absorption mirror M7 ensured a stable mode-locked generation and pulse duration of about 250–300 fs depending of the radiation wavelength. In Fig. 2, a typical auto-correlation function of pulses and their spectrum are given. Output pulses were not close to being transform-limited, which indicated incomplete compensation of group velocity dispersion in the laser cavity. Maximum average output power of the laser when pumped with 3 W from the laser diodes amounted to 200 mW at 1045 nm.

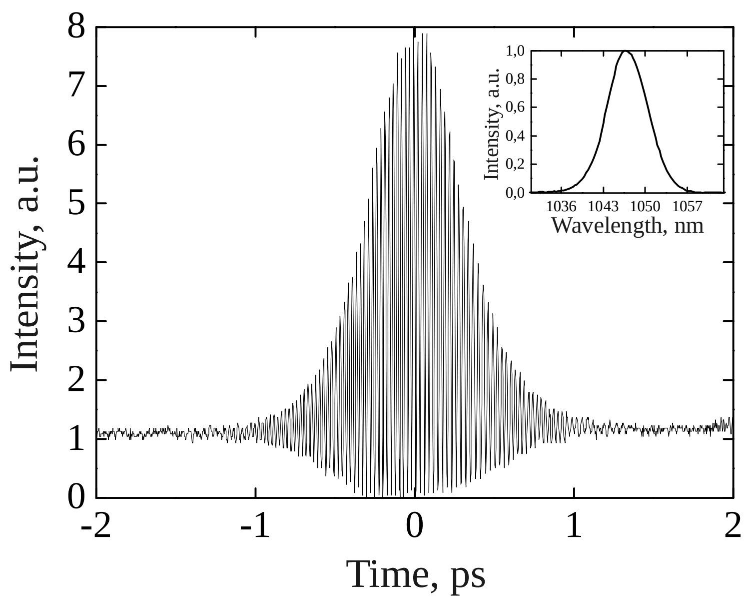

Fig. 2. Autocorrelation function of the pulse intensity of the Yb:KYW laser.

Both in mode-locked and in CW generation the output radiation wavelength was adjusted by a prism inserted before the output mirror of the cavity. Central wavelength of the laser radiation could be tuned in pulsed mode from 1038 to 1053 nm and in CW mode from 1030 to 1070 nm.

The output radiation of the Yb:KYW laser was guided into the Yb fibre optical amplifier (core diameter 15 μm) with the help of two mirrors and a micro-lens. For elimination of optical feed-back a Faraday isolator was inserted between the laser and the amplifier. As a result of optical loss in Faraday isolator and micro-lens the radiation power at the entrance to the fibre optical amplifier was 130 mW.

The amplifier was pumped with an array of diode lasers emitting at 980 nm and delivering combined output of 8 W. The output fibre of the laser diode module was spliced to the pump input fibre of the GTWave amplifier, both fibres being the standard 125-μm core type. A small fraction of the pump radiation (~10%) coming out of the “pump” fibre was returned by a mirror (mirror MP3 in Fig. 1). The output power after the amplifier was 4 W with the Yb:KYW laser operating in both CW and pulsed modes. Top view of experimental setup is shown in Fig. 3.

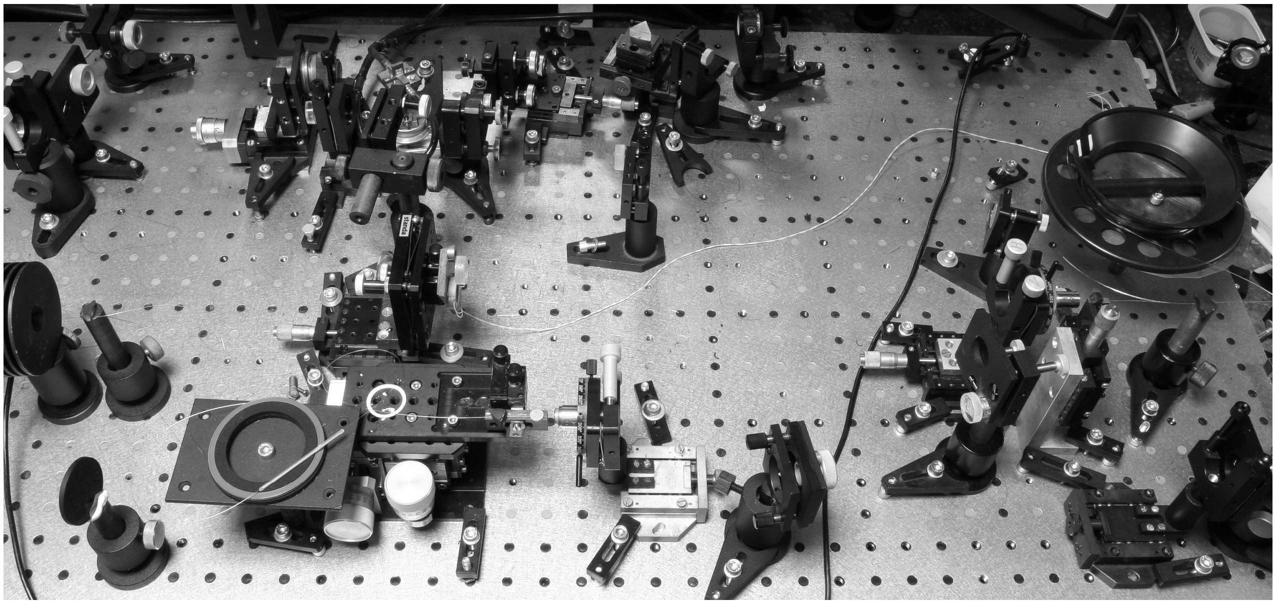

Fig. 3. Top view of experimental setup.

In Fig. 4 are given spectra of the amplified radiation for both modes of the Yb:KYW laser. The spectrum of amplified CW radiation contains a noticeable additional peak in the maximum gain range around 1070 nm. The spectrum of amplified pulsed radiation consists of only one peak with the width of approximately 10 nm. The duration of amplified pulses measured with an auto-correlator did not exceed 0.9 ps. (Fig. 5). Extension of pulses at the exit of the amplifier is caused by phase modulation acquired by pulses while travelling along a relatively long (4 m) fibre amplifier. If required, the amplified pulses can be compressed down to the initial duration (250–300 fs) and even less with the help of standard pulse compression methods using two diffraction gratings or a micro-structured fibre [8]. The energy of amplified pulses amounted to 40 nJ at the repetition rate of 100 MHz.

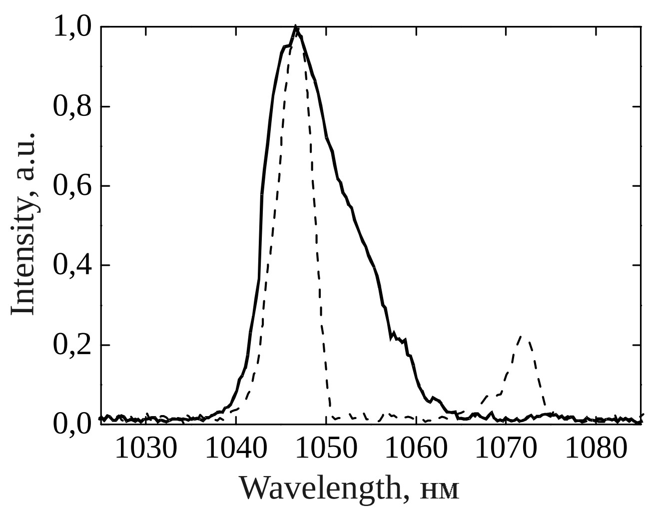

Fig. 4. Spectrum of amplified radiation: dashed line – CW radiation, solid line – pulse radiation.

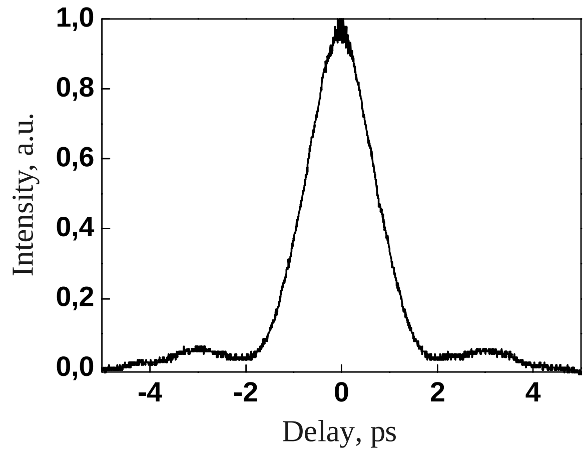

Fig. 5. Autocorrelation function of the amplified pulses
(noncollinear scheme of measurements)

It is important to note high efficiency of the fibre GTWave amplifier in operation at wavelengths around 1045 nm: the power of amplified radiation was about 50% of the pump power (Fig. 6). Wavelength 1045 nm corresponds to the maximum of output power of the Yb:KYW laser, however differs considerably from the wavelength of the maximum gain of the Yb amplifier (approximately 1070 nm). In insert of Fig. 6, an experimentally determined dependence of studied GTWave amplifier's gain upon the wavelength of master oscillator is presented for the amplifier pump power 8 W. Maximum small-signal gain measured at 1065 nm is 14.8 dB, while the gain for 1045 nm is 10.9 dB.

The GTWave ytterbium amplifier we used is somewhat less efficient than fibre amplifiers with double-clad fibre used in hybrid systems [6, 9]. Nevertheless, easy operation of the GTWave amplifier and its fairly high efficiency constitute, in our opinion, a valuable advantage of MOPA systems.

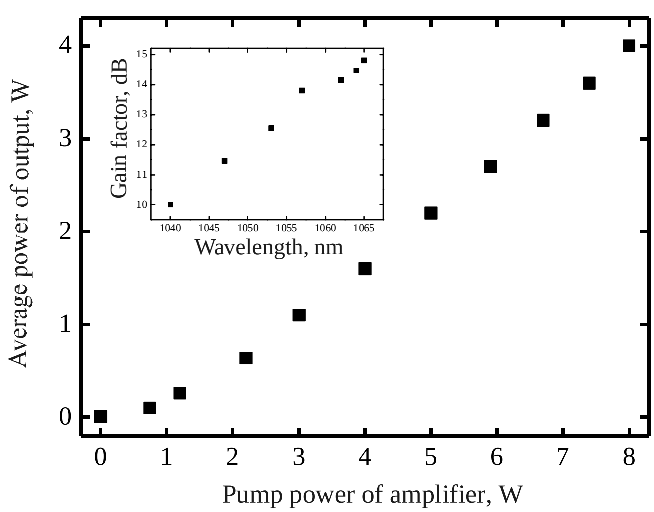

Fig. 6. Experimental results of measurement of average output power versus pump power of amplifier.

Insert: experimentally determined spectral dependence of studied GTWave amplifier's gain.

4. SUMMARY

The trend for growth of hybrid bulk/fibre laser systems observed lately is well explicable: in such systems it is possible to combine both advantages of fibre-based technologies and those of discrete laser-optical devices. In the system we implemented, using a mode-locked Yb:KYW laser has the advantage of wavelength-tuneable sub-picosecond pulses, whereas GTWave fibre optical ytterbium amplifier provides an undeniable benefit of high efficiency and ease of use. In this perspective, the proposed hybrid design is preferable to fully bulk or fully fibre laser systems.

Ytterbium GTWave amplifier studied in the present paper will provide high gain not only in systems with solid-state Yb:KYW/KGW lasers, but also with many other lasers that use active media doped with ytterbium: Yb:CALGO, Yb:glass, Yb:BOYS, Yb:SYS, Yb:GdCOB, Yb:YVO_4, Yb:CaF_2.

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