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Discrete-fibre subpicosecond oscillator – amplifier based on a Yb : KYW laser

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Abstract. **A hybrid subpicosecond system based on a Yb : KYW laser and a Yb fibre amplifier made by using the GTWave technology is studied. The system pumped by the 980-nm, 12-W cw radiation emits 0.9-ps, 40-nJ pulses at a pulse repetition rate of 100 MHz and an average power of 4 W. The central emission wavelength of the system can be tuned in the pulsed regime from 1038 to 1053 nm and from 1030 to 1070 nm in the cw regime. The gain of the Yb fibre GTWave amplifier is measured for the first time within the tuning range of the Yb : KYW laser.**

Keywords: *solid-state laser, Yb : KYW, fibre amplifier, ultrashort laser pulses.*

1. Introduction

Solid-state lasers based on ytterbium-doped potassium – yttrium tungstate $KY(WO_4)_2$ (KYW) or potassium – adolinium tungstate $KGd(WO_4)_2$ (KGW) single crystals feature a number of advantages [1 – 3] stimulating extensive developments and studies associated with these lasers. The main attractive feature of Yb : KYW/KGW lasers is that they can be directly efficiently pumped by standard diode lasers in the region 975 – 980 nm. The Yb : KYW/KGW lasers emit in the spectral region between 1010 and 1080 nm [4] with the maximum output power at $\sim$ 1045 nm. Because Yb : KYW/KGW crystals have broad amplification bands of width of a few tens of nanometres, they can be used to generate femtosecond pulses shorter than 100 fs [5]. Upon generation of longer pulses, these lasers can be tuned within $\sim$ 70 nm. Another important property of Yb : KYW/KGW lasers is that their emission wavelengths fall within the amplification band of Yb-doped fibre amplifiers. The maximum gain in Yb fibre amplifiers is achieved at a wavelength of $\sim$ 1070 nm; however, the short-wavelength wing of their amplification band overlaps the emission region of Yb : KYW/KGW lasers, which allows the use of Yb fibre amplifiers together with master Yb : KYW/KGW oscillators.

Such comparatively simple hybrid discrete-fibre systems have already been used to generate efficiently high-power subpicosecond pulses in the emission region of Yb : KYW/KGW lasers. The average output power of Yb : KYW/KGW hybrid systems emitting subpicosecond pulses at a pulse repetition rate of $\sim$ 100 MHz can achieve a few hundreds of watts [6]. In fibre amplifiers in such systems, double-clad Yb-doped fibres are commonly used, and pump radiation is coupled to the amplifier through a dichroic mirror, which is located, as a rule, in the beam emerging from the amplifier (the so-called counter pumping). Coupling pump radiation into a fibre amplifier with the help of discrete (bulk) optics (lens, mirror) obviously complicates the system and prevents the use of possible advantages of fibre amplifiers in full measure. In addition, the use of discrete optics produces discontinuities in fibreoptic systems with several amplification stages, which now contain open regions with bulk optics. The presence of such regions substantially reduces ‘fibreoptic advantages’ of these systems.

The GTWave manufacturing technology of fibre amplifiers [7], which was recently developed, permits coupling pump radiation into an active fibre directly through a standard silica fibre. This technology allows one to exclude completely any discrete optical elements from the fibre amplification path. In this paper, we studied a hybrid bulk – fibre subpicosecond system based on a Yb : KYW laser and a Yb-doped fibre amplifier fabricated by using the GTWave technology.

2. Experiment

We used in experiments a Yb : KYW laser developed at the Laboratory of Laser Systems at the Novosibirsk State University in collaboration with the Tekhnoscan Joint-Stock Company. Figure 1 shows the scheme of the laser resonator. A 3.3-mm-thick Yb : KYW crystal doped with Yb^{3+} ions at a concentration of 10 % is oriented at the Brewster angle. The crystal was pumped along the optical axis N_m by a 3-W linear diode laser array at a wavelength of 980 nm. The polarisation of pump radiation was directed along the crystallographic axis N_p. The linear array contained four laser diodes (ML500-SP Milon module). The radiation from laser diodes was first collimated by a microobjective and then focused by a lens with a focal distance of 55 mm into the crystal. The diameter of the pump-beam waist in the crystal was about 80 μm. The active element of the laser was located in a cooled mount.

Passive mode locking in the Yb : KYW laser was obtained by using a mirror with a saturable absorber. The saturable absorption of this mirror linearly decreases

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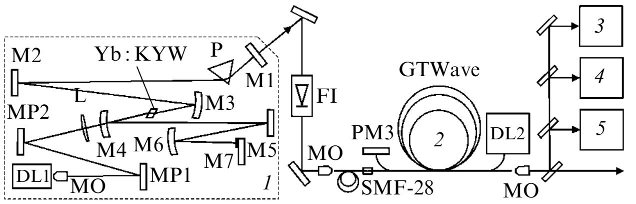

Figure 1. Scheme of a hybrid bulk – fibre laser system based on a Yb : KYW laser: (*1*) scheme of the Yb : KYW laser; (M1 – M7) mirrors of the Yb : KYW laser; (M1) output mirror; (M2, M5) dispersion-compensated mirrors; (M7) saturable-absorber mirror; (P) prism; (L) focusing lens; (PM1 – PM3) pump mirrors; (MO) microobjective; (FI) Faraday isolator; (DL1, DL2) diode pump lasers; (*2*) GTWave fibre amplifier; (*3*) scanning autocorrelator; (*4*) spectrum analyser; (5) power meter.

from 0.9 % at a wavelength of 1030 nm to 0.7 % at a wavelength of 1060 nm, the relaxation time of the absorber is less than 10 ps, and the saturation energy density is 120 μJ cm^{-2}. The group velocity dispersion was compensated by using two special mirrors, each of them providing the negative group velocity dispersion of about 450 fs^2 in the region 1040 – 1070 nm after one reflection of radiation from the mirror. These mirrors, together with the mirror with the saturable absorber, provided the stable mode locking of the laser and pulse duration between 250 and 300 fs depending on the radiation wavelength. Figure 2 presents the typical autocorrelation function of pulses and their spectrum. The pulses were not close to transform-limited ones, thereby demonstrating that the group velocity dispersion has not been completely compensated in the laser resonator. The maximum average output power of the laser pumped by a 4-W beam was 130 mW at a wavelength of 1045 nm.

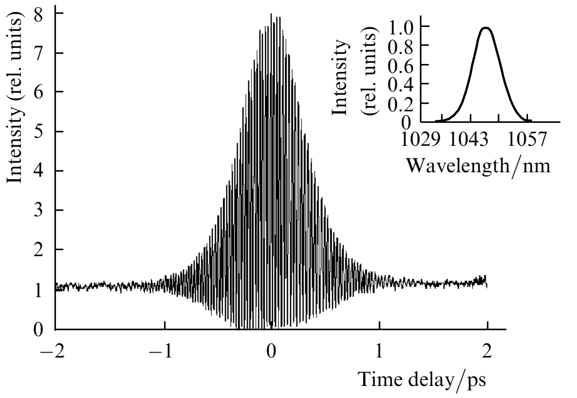

Figure 2. Autocorrelation function of pulses from the Yb : KYW laser. The insert shows the pulse spectrum.

The laser was tuned in the mode-locked and cw regimes with the help of a prism mounted in front of the output mirror of the resonator. The laser could be tuned in the pulsed regime from 1038 to 1053 nm, and in the cw regime – from 1030 to 1070 nm.

The output radiation of the Yb : KYW laser was coupled into a Yb-doped fibre amplifier (the fibre core diameter was 15 μm) with the help of two mirrors, microobjective, and a SMF-28 fibre of length 1 m, which was spliced with the Yb fibre. The optical feedback between the laser and amplifier was eliminated by using a Faraday isolator. Due to radiation losses in the Faraday isolator and microobjective, the radiation power at the input of the fibre amplifier was 100 mW.

The amplifier was pumped by a 8-W, 90-nm ML500-SP linear diode laser array. The output fibre of the diode array was spliced with the input fibre for pumping the GTWave amplifier; the external diameter of both fibres was 125 μm. A small part of the pump radiation (~ 10 %) emerging from the 'pumped' fibre was reflected by a mirror (PM3 mirror in Fig. 1). The output power of the amplifier was 4 W both for cw and pulsed lasing. Figure 3 presents the amplified emission spectra for both operating regimes of the Yb : KYW laser. The amplified cw emission spectrum exhibits an additional band in the region of maximum amplification at 1070 nm. The amplified pulsed emission spectrum exhibits only one band of width ~ 10 nm. The duration of amplified pulses measured with a scanning autocorrelator did not exceed 0.9 ps (Fig. 4). The duration of pulses at the amplifier output increases due to their phase modulation produced after propagation through a comparatively long (4 m) fibre amplifier. If necessary, the duration of amplified pulses can be reduced to their initial duration (250 – 300 fs) and less with the help of standard compression methods by using two diffraction gratings or a microstructure fibre [8]. The energy of amplified pulses was 40 nJ at a pulse repetition rate of 100 MHz. The incident radiation was linearly polarised at the amplifier input, while the polarisation of output radiation did not exceed 63 %.

Note that the GTWave fibre amplifier efficiently operated at wavelengths near 1045 nm, and the power of amplified emission was about 50 % of the pump power

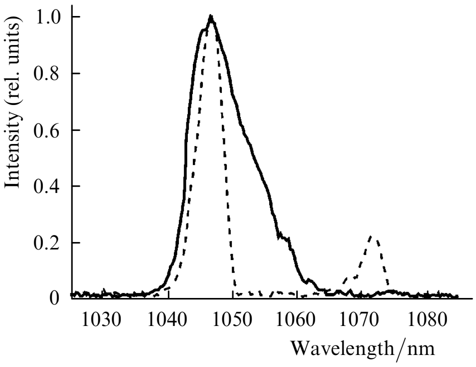

Figure 3. Amplified emission spectrum: the dashed curve is cw emission, the solid curve is pulsed emission.

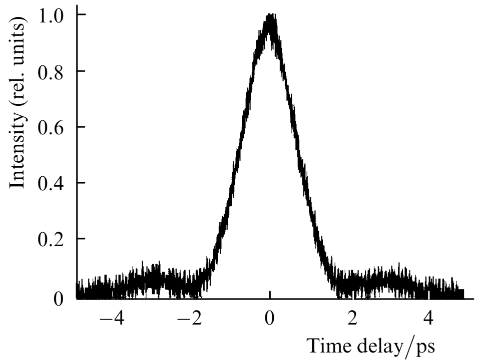

Figure 4. Autocorrelation function of amplified pulses (noncollinear detection scheme).

(Fig. 5). The wavelength 1045 nm corresponds to the maximum output power of the Yb : KYW laser but significantly differs from the wavelength ~ 1070 nm corresponding to the maximum amplification of the Yb fibre amplifier. Figure 6 presents the dependence of the gain of the GTWave fibre amplifier on the wavelength of incident cw radiation for a pump power of 0.9 W. This pump power corresponds to the maximum pump power at which the amplified emission spectrum repeats the spectrum of incident cw radiation. Upon pumping the amplifier by radiation power exceeding 0.9 W at wavelengths below 1065 nm, the amplified cw emission spectrum exhibits an additional band at 1070 nm, corresponding to amplified spontaneous emission. By performing measurements at a pump power of 0.9 W and cw incident radiation, we estimated the gain near its maximum at a wavelength of 1065 nm (14.8 dB) and at a wavelength of 1040 nm (10 dB) corresponding to the maximum output power of the Yb : KYW laser.

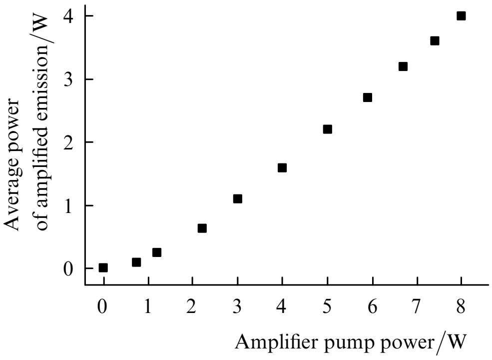

Figure 5. Dependence of the averaged power of amplified emission on the amplifier pump power.

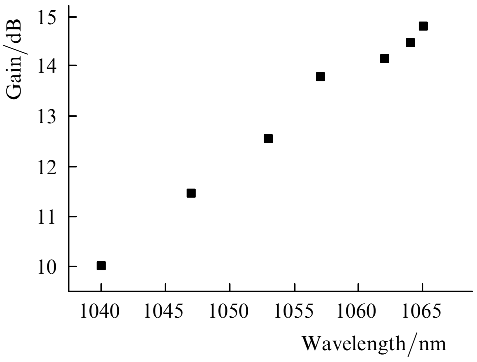

Figure 6. Wavelength dependence of the GTWave Yb-amplifier gain.

The efficiency of the CTWave Yb fibre amplifier is somewhat lower than that of double-clad Yb fibre amplifiers used in hybrid systems [6, 9], however the ease of operation conditions of the GTWave amplifier and its rather high efficiency provide, in our opinion, its advantage in oscillator – amplifier systems.

3. Conclusions

The recent tendency for increasing applications of hybrid bulk – fibre laser systems is explained by the fact that such systems combine the advantages of fibre technologies and technologies of discrete laser – optical devices. An advantage of the bulk mode-locked Yb : KYW laser used in our system is the possibility of tuning subpicosecond pulses, while the GTWave Yb fibre amplifier has the high efficiency and is simple in operation. Thus, the hybrid system proposed in the paper has advantages over all-bulk or all-fibre laser systems.

The GTWave Yb fibre studied in the paper can provide a high gain not only in systems with solid-state Yb : KYW/KGW lasers but also in systems with many other lasers based on Yb-doped active media such as Yb : $CaGdAlO_4$, Yb : glass, Yb : $Sr_3Y(BO_3)$, Yb : CaF_2, Yb : $SrY_4(SiO_4)$, Yb : CaGdO(BO), and Yb : YVO_4.

References

1. Brunner F., Spuhler G.J., Au J., Krainer L., Morier-Genoud F., Paschotta R., Lichtenstein N., Weiss S., Harder C., Lagatsky A.A., Abdolvand A., Kuleshov N.V., Keller U. *Opt. Lett.*, **25**, 1119 (2000).
2. Klopp P., Griebner U., Petrov V., Mateos X., Bursukova M.A., Pujol M.C., Sole R., Gavalda J., Aguilo M., Guell F., Massons J., Kirilov T., Diaz F. *Appl. Phys. B*, **74**, 185 (2002).
3. Kisel' V.E., Troshin A.E., Shcherbitskii V.G., Kuleshov N.V., Pavlyuk A.A., Brunner F., Paschotta R., Morier-Genoud F., Keller U. *Kvantovaya Elektron.*, **36**, 319 (2006) [*Quantum Electron.*, **36**, 319 (2006)].
4. Lagatsky A.A., Rafailov E.U., Leburn S.G., Brown S.T.A., Xiang N., Okhotnikov O.G., Sibbett W. *Electron. Lett.*, **39**, 1108 (2003).
5. Liu H., Nees J., Mourou G. *Opt. Lett.*, **26**, 1723 (2001).
6. Roser F., Rothhard J., Ortac B., Liem A., Schmidt O., Schreiber T., Limpert J., Tunnermann A. *Opt. Lett.*, **30**, 2754 (2005).
7. Grudinin A.B., Payne D.N., Turner P.W., Nilsson L.J.A., Zervas M.N., Ibsen M., Durkin M.K. *Multi-Fibre Arrangements for High Power Fibre Lasers and Amplifiers*. Patent USA No. 6826335, 30.11.2004.
8. Limpert J., Schreiber T., Nolte S., Zellmer H., Tunnermann A. *Opt. Express*, **11**, 3332 (2003).
9. Limpert J., Schreiber T., Clausnitze T., Zollner K., Fuchs H.-J., Kley E.-B., Zellmer H., Tunnermann A. *Opt. Express*, **10**, 628 (2002).