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# Solid-state Yb:YAG amplifier pumped by a single-mode laser at 920 nm

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***Abstract.*** **An optical amplifier scheme for ultrashort 1030-nm pulses is proposed based on an Yb:YAG crystal with axial pumping by a transverse single-mode laser at a wavelength of 920 nm. A small-signal gain up to 40 dB per pass with a high output beam quality is demonstrated. The maximum average power is 14 W with a slope efficiency exceeding 50 %.**

***Keywords:*** *Yb:YAG, crystal rod, ultrashort pulses, single-mode pumping, neodymium fibre laser, CPA.*

## 1. Introduction

Ultrashort pulses are required for precision treatment of materials, including transparent ones, owing to the facts that the interaction of optical ultrashort pulses with matter is accompanied by nonlinear processes (for example, multiphoton absorption) and that the pulse duration is shorter than the electron–phonon interaction time [1, 2].

Hybrid lasers are the most reliable and cheap sources for high-power ultrashort optical pulses. Seed lasers in these schemes are passively mode-locked fibre lasers, whose radiation is amplified in a fibre stage. Bulk crystal amplifiers as an output amplifying stage allow one to considerably increase the pulse peak power and energy compared to fibre stages. Such schemes often use single- and two-pass crystal rod amplifiers. Amplifiers of this type provide a pulse energy higher than 20 μJ at a pulse duration of 800 fs and an average power up to 160 W [3]. The main problems of such amplifiers are low efficiency and considerable heating of the active medium.

In this work, we present a scheme of ultrashort laser pulse amplification in a cylindrical Yb:YAG crystal under transverse single-mode pumping by a neodymium fibre laser at a wavelength of 920 nm [4]. Single-mode laser pumping allows one to achieve both a high gain in the Yb:YAG crystal and a high output beam quality. In addition, this type of pumping makes it possible to achieve a high efficiency of the crystal amplifier in question.

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## 2. Experimental results

Figure 1 shows the optical scheme of the experimental setup. We used a chirped-pulse amplification (CPA) method to achieve high laser radiation energies. Ultrashort laser pulses with a wavelength of 1030 nm were amplified in an Yb:YAG crystal rod (5 mol % of $Yb^{3+}$) 17 mm long and 1 mm in diameter, which was placed in a water-cooled copper heat sink. The crystal rod was pumped by a neodymium fibre laser with a power of 35 W. After amplification, the optical pulse was compressed using a volume Bragg grating (VBG) compressor.

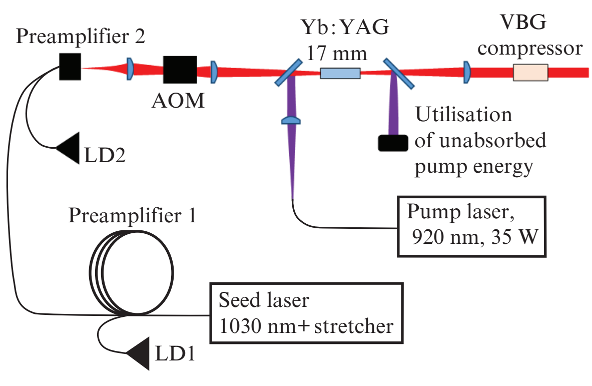


**Figure 1.** Scheme of the experimental setup.

As a seed laser, we used a mode-locked fibre laser emitting 5-ps pulses with a repetition rate of 14 MHz. The seed laser pulses were stretched to 40 ps using an optical fibre 120 m long, then amplified in a two-cascade ytterbium fibre amplifier with optical pumping by laser diodes LD1 and LD2, and focused into the Yb:YAG crystal. An acousto-optic modulator (AOM) in front of the crystal amplifier was used to decrease the seed laser pulse repetition rate to 2 MHz. The parameters of signal pulses incident on the Yb:YAG crystal are presented below.

Average power/mW . . . . . . . . . . . . . . . . . . .0.5–1350
Wavelength/nm . . . . . . . . . . . . . . . . . . . . . . . 1030
Repetition rate/MHz . . . . . . . . . . . . . . . . . . . . . . 2
Spectral width/nm . . . . . . . . . . . . . . . . . . . . . . . . 3
Duration/ps . . . . . . . . . . . . . . . . . . . . . . . . . . .40

In our experiments, we obtained laser pulses at a wavelength of 1030 nm with an average output power higher than 14 W under an average input signal power of 1.4 with slope efficiency $\eta$ with respect to the absorbed pump power exceeding 50 %. The output power was limited by the available pump power. In the small-signal gain regime with the input power $P_{in}$ = 0.5 mW, the average output power was 5 W (Fig. 2) with a gain up to 40 dB (Fig. 3), which, according to the literature data, is record-high for the single-pass scheme of amplifiers based on Yb : YAG crystal rods. The pulse compression after amplification was measured using a VBG compressor. The compressed pulse duration was 980 fs, which is rather close to theoretical estimates for a transform limited pulse.

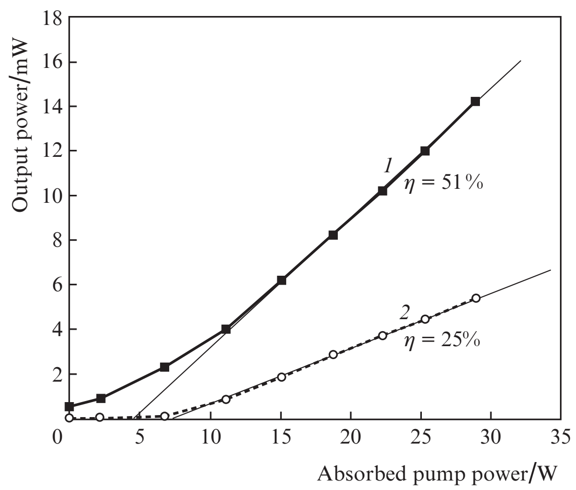


**Figure 2.** Measured dependences of the average output power on the absorbed pomp power at average input power $P_{in}$ = (*1*) 1350 and (*2*) 0.5 mW.

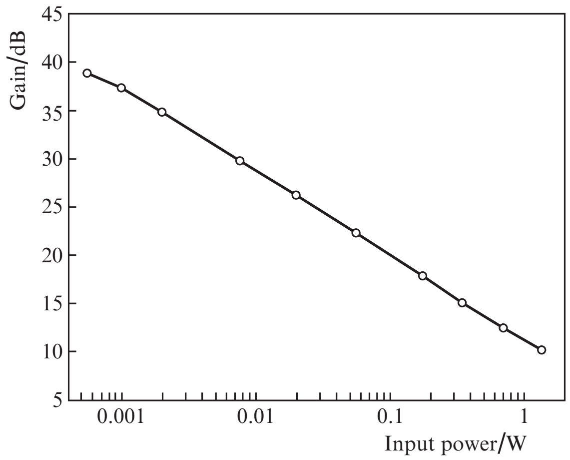


**Figure 3.** Dependence of the gain in an Yb : YAG crystal on the average input power.

The beam quality factor $M^2$ was 1.01 at the maximum output average power and 1.3 in the small-signal gain regime. A deterioration of the output beam quality in the large-signal gain regime can be caused by an inversion lens, whose role increases with increasing gain. The inversion lens effect is related to a change in the refractive index of the crystal with a change in the concentration of $Yb^{3+}$ ions in the excited state. This effect was studied theoretically and experimentally in [5]. For the crystal rod with 5 mol % of active $Yb^{3+}$ ions and at a population inversion of the upper laser level (term $^2F_{5/2}$) of about 60 %, the nonlinear additive to the intrinsic refractive index of the medium is approximately $10^{-4}$ [5]. On the other hand, a change in the refractive index caused by a thermal lens can be estimated as follows. It is known that the thermooptical coefficient in the Yb : YAG crystal is $8.4 \times 10^{-6}\,°C^{-1}$ [6]. We calculated the temperature gradient in the crystal to be about 15 °C, and, therefore, the additive to the refractive index due to the inversion lens will be comparable with the additive due to the thermal lens, which may distort the output optical characteristics of the amplifier.

The beam quality parameter was estimated using a DataRay BeamMap2 beam profiler, in which the laser beam waist was formed by an optical lens with a focal length of 100 mm placed at a distance of 150 mm from the output face of the crystal. In addition, we measured the waist shift at different powers of the input signal. Of much interest for application of the crystal amplifier in optical schemes is to measure the shift of the laser beam waist depending on the gain in the crystal. The dependence of the shift of the 1030-nm laser beam waist measured by us (Fig. 4) exhibits a pronounced extremum. We believe that the beam waist shift is caused by the dominance of the inversion lens at high (exceeding 25 dB) gains in the Yb : YAG crystal and by the dominance of the thermal lens at lower gains.

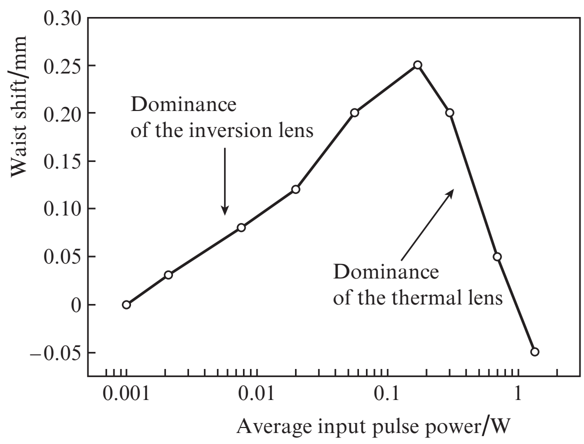


**Figure 4.** Experimental dependence of the amplified beam waist position on the average input pulse power after focusing by a lens. The pump laser power is 35 W.

Thus, we presented for the first time a scheme of single-mode 920-nm pumping of Yb : YAG rod amplifiers. The maximum average output pulse power at a wavelength of 1030 nm was 14 W with a slope efficiency exceeding 50 %. It is demonstrated that this scheme can be used as a small-signal amplifier with a maximum single-pass small-signal gain up to 40 dB.

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