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Nanosecond cryogenic Yb:YAG disk laser

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Abstract. **A cryogenic Yb:YAG disk laser is modernised to increase its average and peak power. The master oscillator unit of the laser is considerably modified so that the pulse duration decreases to several nanoseconds with the same pulse energy. A cryogenic disk laser head with a flow-through cooling system is developed. Based on two such laser heads, a new main amplifier is assembled according to an active multipass cell scheme. The total small-signal gain of cryogenic cascades is $\sim 10^8$.**

Keywords: *pulsed laser, disk laser, Yb:YAG, cryogenic cooling.*

1. Introduction

The limiting factors for creating laser systems with a high pulse repetition rate and a high peak pulse power are thermally induced distortions and self-focusing of radiation. Therefore, the disk geometry of active elements (AEs) is most optimal since it ensures a small length of interaction of radiation with the active medium at a high time-averaged laser power. A project on the creation of a cryogenic laser with a high average and peak power based on Yb:YAG disks is being realised at the Institute of Applied Physics, Russian Academy of Sciences. Cooling to cryogenic temperatures is used to increase the laser optical efficiency and the pulse repetition rate f. The laser consists of three units: a front-end system, a preamplifier (PA) and a main amplifier (MA). The master oscillator signal with an energy of 2–3 mJ is expected to be amplified in the PA to 30–40 mJ and then in the MA to ~500 mJ at $f = 1$ kHz.

One of the main functions of the proposed laser system is to pump parametric amplifiers of femtosecond lasers [1, 2]. To obtain a higher peak power, it is reasonable to use maximally short pulses, down to one field cycle. For a wavelength of ~1 μm, it is several femtoseconds. In the case of optical parametric chirped pulse amplification (OPCPA), short femtosecond pulses, as a rule, are stretched to several picoseconds [2]. Since this energy does not accumulate in a parametric amplifier, the signal and pump pulses must coincide in time. This means that the created laser must emit picosecond pulses, whose amplification occurs according to the chirped pulse amplification (CPA) principle with increasing duration to fractions or units of nanoseconds. Therefore, to test the amplifying unit of the laser, it is enough to use a nanosecond master oscillator (MO). In this case, for further compression of pulses to picosecond durations, it is important to have a broad gain band. In the previous laser scheme [3], we used a cryogenic disk laser with active Q-switching by a Pockels cell. The output pulse duration was ~70 ns, and, in addition, high-frequency intensity modulation took place, which led to an increase in the peak power and to breakdown of optical elements, because of which we developed a new front-end system with shorter output pulses and a smooth envelope. Considerable changes were also made in the design and optical scheme of the MA, which allowed us to solve some problems caused by various thermal effects (thermal lens, thermal wedge, etc.)

2. Nanosecond front-end system

To test a cryogenic disk laser in the regime of chirped nanosecond pulse amplification, we created a front-end system (Fig. 1) consisting of a MO and the first preamplifier (FPA), which amplified the pulse energy to several millijoules. The MO was an Yb:YAG disk laser operating at room temperature with water cooling. In the laser cavity, we used a Pockels cell based on a BBO crystal with a double voltage switch (EKSMA, Lithuania), which allowed generation of pulses with a duration of 7 ns and an energy of ~0.2 mJ (Fig. 2a). The coincidence of the lasing wavelength with the maximum of the gain spectrum of the cryogenic disk laser was achieved using a Wood filter, which allowed us to tune the laser wavelength within the range 1028.5–1032 nm. At the MO exit, we placed an additional Pockels cell, to which a half-wavelength voltage was applied. This makes it possible to decrease the pulse duration to 3 ns and increase the output pulse contrast by two orders of magnitude.

The signal from the MO is sent to the FPA designed to amplify nanosecond pulses stretched to a duration exceeding 1 ns. For amplification, we used a composite Yb:YAG/YAG AE cooled to cryogenic temperatures [4]. The active multipass cell scheme of the amplifier allows the beam to make up to 16 passes through the AE, which corresponds to the total small-signal gain up to 7×10^4 and makes it possible to amplify submicrojoule pulses to several millijoules at $f \sim 1$ kHz. In the first experiments, we achieved amplification of nanosecond MO pulses to an energy of 5 mJ with the output radiation bandwidth of 0.7 nm (Fig. 2b). In such parameters as output energy and total gain, the developed FPA scheme is close to regenerative amplifiers [3], but is free of their main drawback, i.e., low contrast. According to performed measurements, the

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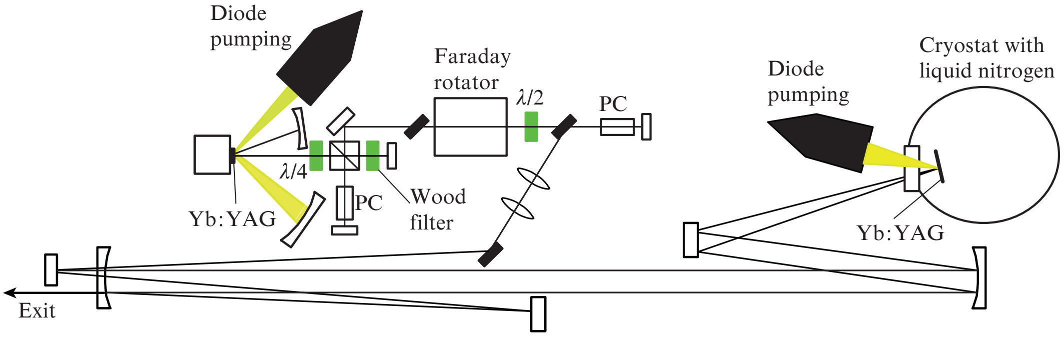


Figure 1. Principal scheme of the front-end system (PC is the Pockels cell).

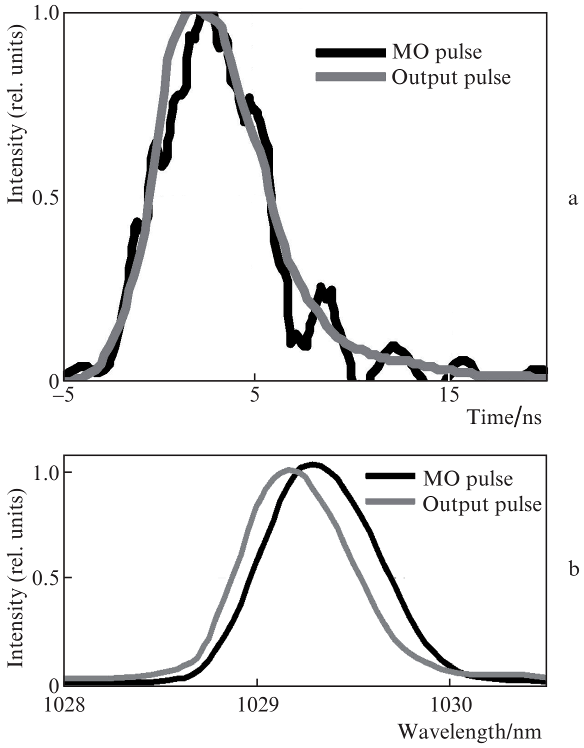
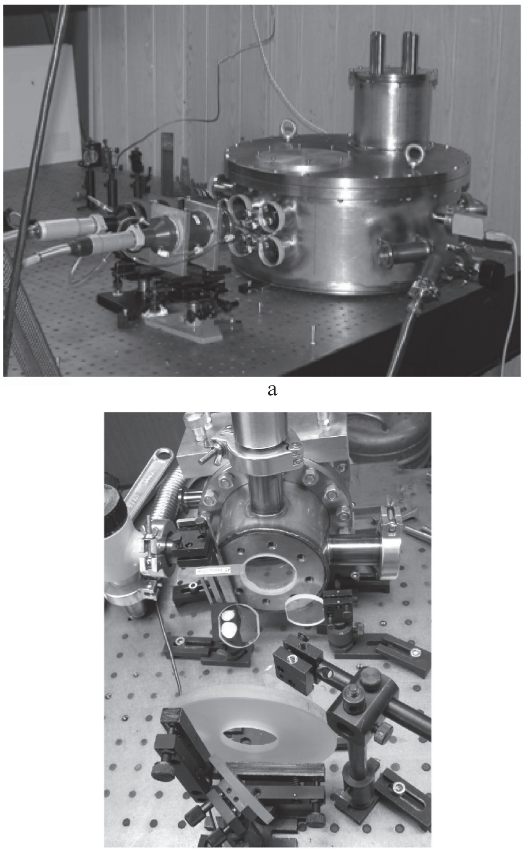


Figure 2. (a) Temporal and (b) spectral profiles of the MO and the first preamplifier output pulses.

pulse contrast in the nanosecond range exceeds 10^5. In addition, a regenerative amplifier always has a back mirror, and the signal must be amplified before the free-running mode development (in contrast to multipass amplifiers, which have no back mirrors). Correspondingly, the lasing threshold in a multipass amplifier is much higher, and this amplifier is more stable to self-excitation.

3. Main amplifier based on cryogenic disk laser heads with active cooling

The signal from the front-end system with an energy of 3–5 mJ is amplified in the PA up to an energy of ~30 mJ at $f \leqslant$ 1 kHz. The PA scheme is presented in [3]. However, while the PA cascade allowed us to obtain the desired results, the main two-cascade amplifier previously demonstrated amplification of pulses to 120 mJ with $f = 500$ Hz (the average power of amplified radiation in this case was 60 W [3]). Further increase in the average power in the previous MA scheme was limited by a thermal lens in the AE and by misalignment of the system with increasing pump power, when the pump and signal beams were mismatched in both size and position. To suppress these effects, one can use an active multipass cell scheme, which showed good results in previous amplifying cascades. Therefore, we developed and fabricated new laser heads, whose design was similar to the laser heads of disk lasers operating at room temperature [2], but cooling water was replaced by liquid nitrogen flow and the AE was placed in a vacuum chamber to avoid water vapour condensation (Fig. 3b) [5]. We performed first laser experiments with the new multipass MA scheme (Fig. 4). We managed to achieve up to six passes of the signal through the AE with a small-signal


a

b

Figure 3. Photographs of (a) the cryogenic chamber of the main amplifier and (b) the new cryogenic disk laser head with the optical pump system.

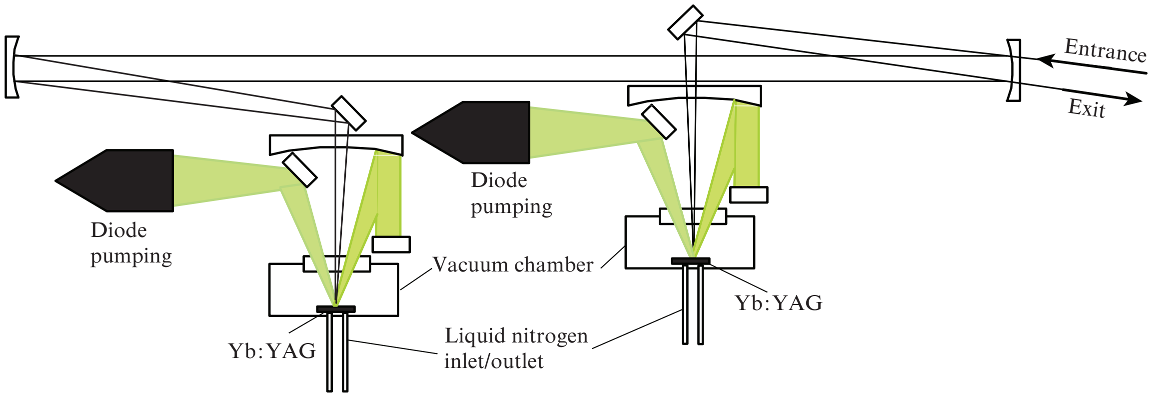


Figure 4. Principal scheme of the main amplifier.

gain no lower than 1.4 per pass at a pump beam diameter of 10 mm. An increase in the number of passes from one to four increased the pump efficiency. Stable laser operation was observed at a cw pump power up to 1.2 kW with a much better output beam quality.

According to calculations with the use of a program code developed by us [6], under the given conditions one can expect to achieve an output laser energy of 250 mJ. Unfortunately, we failed to demonstrate an increase in the pulse energy, which was related to high losses in the MA. Nevertheless, it is seen that the output energy does not depend on the thermal load (Fig. 5), which points to efficient heat removal from the AE as a result of cooling by liquid nitrogen flow with a rate up to 3 L min^{-1}. Further increase in the stored energy is limited by the appearance of parasitic lasing in the AE, which is confirmed by the measured temporal dependence of spontaneous emission intensity. At a peak pump pulse power exceeding 600 W and a pump pulse duration of 1.25 ms, the spontaneous emission intensity ceases to increase with time and, hence, with the stored energy (Fig. 6).

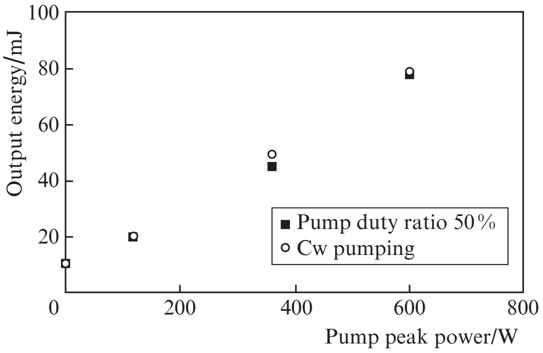


Figure 5. Dependence of the output laser energy on the peak pump power at a pump duty ratio of 50% and cw pumping.

Another important parameter for amplification of stretched pulses is the distortion of the temporal and spectral pulse profiles. According to our measurements, both profiles remain unchanged with the pulse propagation through the amplifying cascades (gray lines in Fig. 2). The spectral width is 0.7 nm as before, which corresponds to the bandwidth-limited pulse duration of ~2 ps. The small-signal gain of the entire scheme is 10^8.

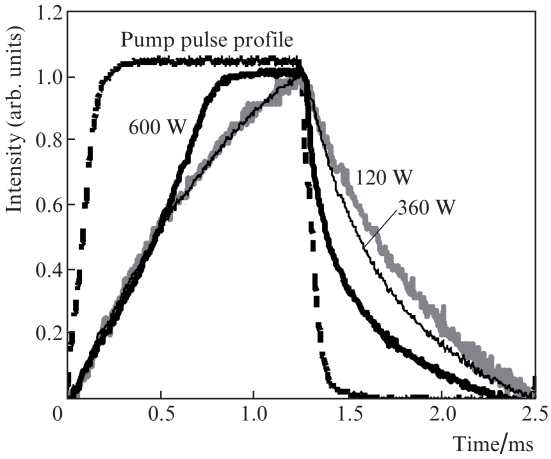


Figure 6. Temporal dependences of the spontaneous emission intensity at peak pump powers of 120, 360 and 600 W, as well as the pump pulse temporal profile.

4. Conclusions

The front-end system and the main amplifier of the laser are modernised. The cryogenic laser is replaced by a laser with an additional amplifying cascade, while the master oscillator is created based on the water-cooled laser head operating at room temperature. The MO pulse duration decreased from 70 to 3–7 ns, which made it possible to increase the output peak power to 27 MW.

A cryogenic disk laser head with the AE aperture of 20 mm was created to increase the average power of the MA, In combination with a telescopic amplification scheme, which was successfully used in the PA, the amplifier with two such laser heads allows one to considerably improve coupling of the signal and pump beams in the crystals, to compensate the thermal lens, and to achieve a required number of signal passes through the crystal. The firs experiments showed an improvement of the beam quality and a stable MA operation at a cw pump power up to 1.2 kW. The stored energy is limited by the appearance of parasitic lasing transversely to the AE. To solve this problem, we plan to make an AE with cladding of the perimeter. With the new laser heads, we managed to realise four pump beam passes through the AE, which allows us to more efficiently use the pump energy and apply AEs with a thinner doped part to decrease the effect of negative thermal effects. According to our calculations, after eliminating parasitic lasing, the output laser energy can reach 500 mJ. The first preamplifier, preamplifier, and main preamplifier can comprise an all-cryogenic laser amplifier capable to amplify stretched pulses of nanosecond duration.

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