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Active mode locking of picosecond $Ti^{3+}:Al_2O_3$ and $Cr^{4+}:Mg_2SiO_4$ lasers pumped by 0.5 – 5-µs laser pulses

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***Abstract*.** **Picosecond pulses are generated in actively mode-locked Ti : sapphire and Cr : forsterite lasers pumped by 0.5 – 5-µs pulses from a Nd : YAG laser.**

Keywords: *mode locking, Ti:sapphire laser, Cr : forsterite laser.*

1. Introduction

Crystals of sapphire doped with Ti^{3+} ions and forsterite doped with Cr^{4+} ions are widely used for generation of ultrashort pulses. A unique property of these crystals is that, along with a broadband gain spectrum, which provides the generation of femtosecond pulses, they have a comparatively high stimulated emission cross section. Both these crystals have been actively studied recently in a variety of laser schemes using both active [1, 2] and passive [3, 4] mode locking. The minimal duration of pulses achieved in an actively mode-locked Ti : sapphire laser was 150 fs [1] and 60 fs for a Cr : forsterite laser [2]. The use of Kerr-lens passive mode locking provides even shorter pulses with duration down to 6 fs for a Ti:sapphire laser [3] and 20 fs for a Cr : forsterite laser [4]. A disadvantage of these laser media is a comparatively short lifetime of laser levels (2 – 3 µs), which prevents obtaining a high gain, resulting in a rather high lasing threshold upon continuous pumping.

The generation of ultrashort pulses in these crystals upon pulsed pumping has not been obtained so far, although this regime is of considerable interest because it allows the generation of more powerful pulses. The problem is the absence of an appropriate pump source, which would generate pulses of duration comparable with the lifetime of the laser levels.

Pumping by a free-running Nd : YAG laser proves to be inefficient because the duration of pump pulses exceeds the lifetime of the laser level by two orders of magnitude and the lasing threshold is too high. On the other hand, *Q*-switched lasers generate too short pulses and do not allow to maintain the required population inversion in crystals during the entire period of formation of ultrashort pulses, which is usually no less than a hundred of round-trip transit times for a circulating pulse in the cavity upon active mode locking. For typical cavity lengths $L = 100$ cm, the required pulse duration should be no less than 700 ns. To form laser pulses from noise with a broad spectrum for a subsequent generation of ultrashort pulses in the case of passive self-mode locking, even a greater number of round-trips for pulses in the cavity are required, i.e., the pump-pulse duration should be even greater, namely, several hundreds of microseconds.

In this paper, we studied active mode locking in $Ti^{3+}:Al_2O_3$ and $Cr^{4+}:Mg_2SiO_4$ crystals pumped by 0.5 – 5-µs pulses from a specially designed Nd : YAG laser (and by its second-harmonic pulses in the case of $Cr^{4+}:Mg_2SiO_4$). The pump pulse duration was close to the lifetime of excited states in the crystals under study.

2. A Nd^{3+} : YAG pump laser emitting 0.5 – 5-µs pulses

Pump pulses of duration corresponding to the lifetime of laser levels in $Ti:Al_2O_3$ (2.7 µs) and $Cr:Mg_2SiO_4$ (2.7 µs) were obtained from a laser with an intracavity fibreoptic delay line . The principal scheme of the Nd^{3+} : YAG laser is shown in Fig. 1. The laser cavity is formed by a pair of plane dielectric mirrors (*1*) and (*7*), a all – silica fibre (*2*) with a core of diameter 300 µm, and a pair of coupling lenses (*3*) and (*5*). A Cr^{4+} : YAG crystal was used as a passive *Q* switch (*6*). The initial transmission of the *Q* switch and the reflectivity of the output mirror at 1064 nm were chosen experimentally for each length of the fibre to provide the maximum energy in a single output pulse. The pulse energy was measured with an IMO-2N power meter and achieved 100 mJ. Due to the mixing of transverse modes in the fibre, a high energy stability was achieved (better than 1 %), as well as the spatial homogeneity of the laser beam and the absence of speckles. The temporal

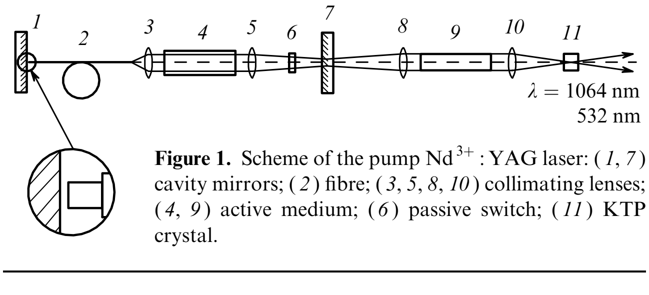

Figure 1. Scheme of the pump Nd^{3+} : YAG laser: (*1*, *7*) cavity mirrors; (*2*) fibre; (*3*, *5*, *8*, *10*) collimating lenses; (*4*, *9*) active medium; (*6*) passive switch; (*11*) KTP crystal.

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profile of the pump pulse for a fibre of length 50 m shown in Fig. 2 was controlled by a signal from an avalanche photodiode using a S9-8 oscilloscope. By changing the fibre length, the position of the passive Q switch and its density, we could vary the laser-pulse duration from 0.5 to 5 µs (using fibres of length from 10 to 70 m).

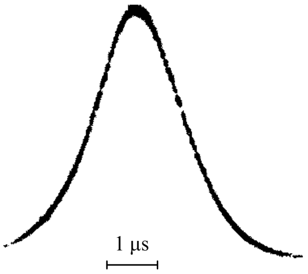

Figure 2. Temporal profile of the pump pulse for the fibre of length 50 m.

The Ti : sapphire laser was pumped by the second harmonic from a $\mathrm{Nd^{3+}:YAG}$ laser, which was generated by focusing the laser beam with lens (*10*) into a KTP crystal (*11*) of length 7 mm. The SHG efficiency achieved 20 % for 0.5-µs pulses. For longer pulses, the SHG efficiency drastically decreased because a comparatively high divergence of the laser beam did not allow us to use sharp focusing by retaining angular phase matching. To increase the second-harmonic energy at long pulse durations, we used an additional amplification stage, which provided the generation of 400-mJ pulses and the SHG efficiency up to 10 % for 5-µs pulses. The basic parameters of the pump laser are listed below. The data in parentheses correspond to a wavelength of 532 nm.

Wavelength/nm	1064 (532)
Pulse duration/µs	0.5 – 5 (0.3 – 3)
Maximum energy/mJ	400 (40 – 80)
Beam diameter/mm	6
Divergence/mrad	10
Pulse energy instability (%)	< 1 (< 3)
Pulse repetition rate/Hz	1 – 30

3. Picosecond $\mathrm{Ti^{3+}:Al_2O_3}$ and $\mathrm{Cr^{4+}:Mg_2SiO_4}$ lasers

The Ti:sapphire and Cr : forsterite lasers had identical cavities (Fig. 3) except the reflectivity of cavity mirrors. We used the Z-type cavity, which was close to a symmetrical astigmatism-compensated cavity. The cavity consisted of a pair of concave mirrors with the radius of curvature 200 mm, a plane highly reflecting mirror, and a plane mirror. The cavity length was 117 cm for the Ti : sapphire laser and 123 cm for the Cr : forsterite laser. A plane output mirror (*8*) had a high reflectivity in a broad spectral range with a maximum at the centre of the gain band of the laser crystal; the reflectivity was $R = 80$ % and 75 % for the Ti : sapphire and Cr : forsterite laser, respectively. The pump beam was focused with lens (*2*) to a spot of diameter 0.7 mm.

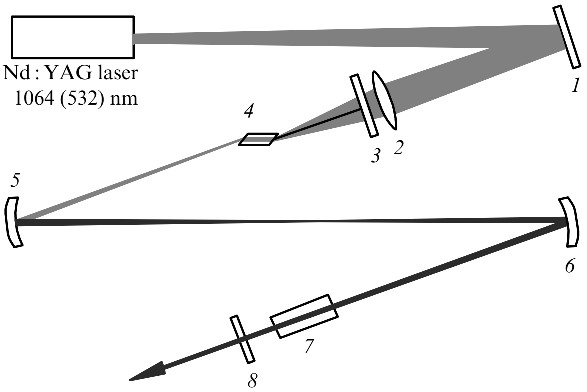

Figure 3. Scheme of $\mathrm{Ti^{3+}:Al_2O_3}$ and $\mathrm{Cr^{4+}:Mg_2SiO_4}$ lasers; (*1*) highly reflecting mirror; (*2*) focusing lens; (*3*, *5*, *6*, *8*) cavity mirrors; (*4*) active laser medium; (*7*) modulator.

The temporal profile of the output power was detected with an LFD-24 avalanche photodiode with the time response of 0.5 ns and a S7-19 oscilloscope. The duration of individual pulses in the train of ultrashort pulses was measured more accurately with an Imacon-500 streak camera with a resolution of 2 ps. The accurate calibration of the streak camera was performed by the double reflection of the laser pulse at an angle of 45° from a plane – parallel KV silica glass plate of thickness 10 mm. The total energy of laser pulses was measured with an IMO-2N power meter, and the energy instability was estimated using a pyroelectric power meter.

The free-running Ti:sapphire laser pumped by 0.6-µs second-harmonic pulses from the Nd : YAG laser generated several (1 – 3) pulses of duration 100 – 150 ns, which were modulated with a period equal to the round-trip transit time in the cavity (8 ns). The pulse duration depended on the pump power and remained constant when the pump power was not changed, whereas the degree of modulation varied within 20 % – 30% from pulse to pulse. When the lasing threshold (3 mJ) was slightly exceeded, a single pulse was generated. As the pump energy was increased, the second pulsed appeared and then, after ~ 0.5 µs, the third pulse was generated. The pulses merged when the pump energy substantially exceeded the lasing threshold.

The differential lasing efficiency of the Ti : sapphire laser was 25 %, and the output energy achieved 1.2 mJ when the absorbed pump energy was 8 mJ.

The active Q-switching was obtained by using an acoustooptic modulator placed near the output cavity mirror. The modulation period corresponded to the round-trip transit time in the cavity and was 8 ns. The minimum FWHM duration of pulses was 100 ps. The parameters of the Ti : sapphire laser are listed below.

Wavelength/nm	800
Minimal pulse duration/ps	100
Pulse train duration/ns	50 – 70
Pulse repetition rate/ns	8
Maximum energy/mJ	0.15
Radiation mode	$\mathrm{TEM_{00}}$

The free-running Cr : forsterite laser pumped by 2.0-µs pulses from the Nd : YAG laser emitted a similar train of modulated pulses of duration 150 – 300 ns. The differential efficiency of this laser was 16% and the output energy achieved 16 mJ for the absorbed pump energy equal to 120 mJ. The active Q-switching was obtained by using a piezoelectrostriction optical modulator operating in the

Raman–Nath diffraction regime, which provides a more efficient modulation compared to usual acoustooptic switches. The modulator was made of a $LiNbO_3$ crystal, whose side faces were covered by aluminium and served as electrodes to which a high-frequency voltage was applied. The crystal was a part of the resonance circuit excited by a G4-143 high-frequency generator with a frequency feedback. The resonance frequency of the modulator equal to 58.2 MHz was stabilised with an accuracy of 10^{-6}.

The control circuit of the modulator provided the supply of the high-frequency generator power in the pulsed regime using a G5-63 rectangular pulse generator. The pulsed regime (the round-trip transit time in the cavity was 8 ns) provided an increase in the modulation efficiency due to a decrease in the average acoustic power in the modulator crystal. The duration of the high-frequency pulse train was 200 μs for the peak power below 1 W.

The typical oscillograms of trains of picosecond pulses emitted by the actively mode-locked Cr : forsterite laser are shown in Fig. 4. When the pump energy was close to the lasing threshold, the laser emission consisted of a train of picosecond pulses of duration $\sim$ 300 ns. The train duration decreased with increasing pump energy, and the second maximum appeared in the temporal distribution of the output power when the pump energy was further increased. The maximum total energy of the pulse train was 8 mJ. This energy was achieved for the absorbed pump energy of about 120 mJ, when the gain saturation was observed. The minimum FWHM pulse duration was 75 ps. The parameters of the Cr : forsterite laser are presented below.

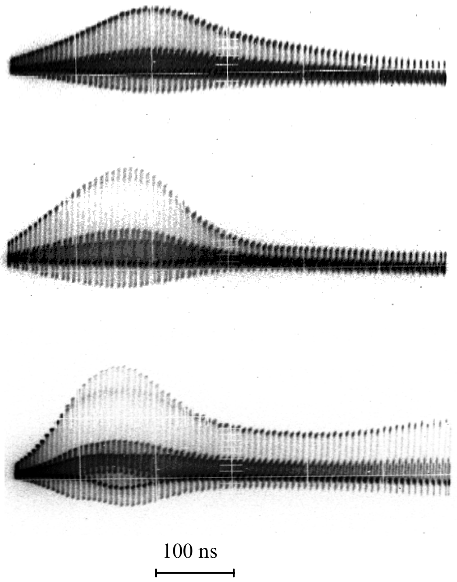

Figure 4. Temporal profile of the pulse train for the Cr : forsterite laser.

Wavelength/nm	1240
Minimal pulse duration/ps	75
Pulse train duration/ns	150–300
Pulse repetition rate/ns	8.6
Maximum energy/mJ	8
Radiation mode	TEM_{00}

4. Conclusions

We have obtained for the first time active mode locking in Ti : sapphire and Cr : forsterite lasers pumped by pulses from a Nd : YAG laser of duration 0.5–5 μs corresponding to the lifetime of laser levels in these laser crystals. The minimum duration of output ultrashort pulses was 75 ps. The further optimisation of the lasers and the use of additional passive intracavity nonlinear elements should result in a substantial shortening of the laser pulses.

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