Gigahertz femtosecond Cr:ZnS laser

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Abstract: We demonstrate the first Cr:ZnS laser with a gigahertz pulse repetition rate. The passively mode-locked by the graphene-based mirror laser provides 105 mW output power with 180 fs pulse duration and 110 pJ pulse energy.

OCIS codes: 140.4050 Modelocked Lasers; 140.3070 Infrared and far-infrared lasers, 140.3580 Lasers, solid-state

1. Introduction

Femtosecond laser sources with high pulse repetition rate and good optical quality pulses (frequency combs) are desirable for a number of potential applications, most notably in spectroscopy and frequency metrology. A high-repetition rate frequency comb is distinguished by a large distance between the comb lines, resulting in higher power per line, better line resolution, and simplified line selection. This improves the signal-to-noise ratio and simplifies comb manipulation in applications. In Ti:sapphire mode-locked oscillators, which are the most advanced few-cycle solid-state lasers, serving as an industry benchmark, repetition rates up to 10 GHz have been demonstrated [1]. At the same time, increasing the repetition rate leads to decreasing the pulse energy, which affects the nonlinear-optical effects that critically depend on the pulse peak power. For example, the self-phase modulation is required for both, the pulse shortening inside the laser source and spectrum broadening – examples of two nonlinear optical effects, which are important for carrier-envelope offset stabilization techniques. For this reason, self-referenced Ti:sapphire lasers are typically demonstrated at about 0.5-1 GHz repetition rate, with the highest rates around 2 GHz [2].

The Cr:ZnS femtosecond laser [3] is in many respects analogous to Ti:sapphire with a 3 times longer wavelength centered at 2300-2400 nm, and has been shown to deliver high average power, high-energy pulses [4] of only 5 optical cycles in duration [5], with typical repetition rates of 90-270 MHz [6,7]. Cr:ZnS laser has also shown good performance in combination with a semiconductor saturable absorber mirror [8] and graphene saturable absorber [6]. Operating in the mid-infrared, this laser is especially interesting for applications in molecular spectroscopy and sensing, and demonstration of high repetition-rate comb would be an important step in bringing this laser source to practical use. For all these reasons the goal of the present work was to achieve a next significant milestone in the femtosecond Cr:ZnS laser technology – development of a GHz repetition rate mode-locked laser.

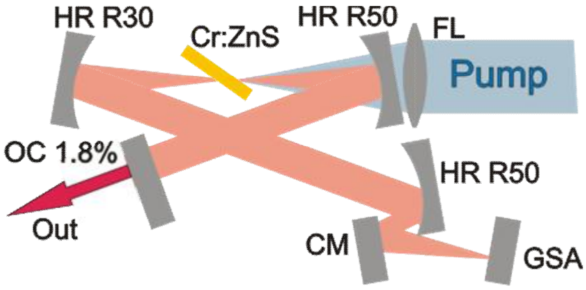

Fig. 1: Experimental setup of the graphene mode-locked Cr:ZnS laser. FL is the pump focusing lens (f = 50 mm), HR are the highly-reflective concave mirrors, CM is the plan chirped mirror, OC is the output coupler with 1.8% transmittance, GSA is the graphene-based saturable absorber mirror.

2. Experimental setup

The experimental setup is shown in Fig. 1. The pump beam of the Er-fiber laser at 1.61 μm was focused by the 50-mm AR-coated lens. The X-folded astigmatically compensated four-mirror cavity with round-trip length of 300 mm was implemented. Active element (2.4 mm thick Cr:ZnS single crystalline sample) was positioned at Brewster angle between the concave mirrors having 30 and 50 mm ROC. Graphene saturable absorber was deposited on the surface of the flat high-reflector mirror thus forming a graphene-based saturable absorber mirror. The cavity mode was additionally focused to the graphene saturable absorber by an ROC=50 mm concave mirror resulting in cavity mode diameter of about 80 µm on graphene. The cavity mode diameter in the active element was kept around 50 µm. Active cooling was applied neither to active crystal, nor to saturable absorber. The output coupler with transmittance of 1.8% was used in the experiments. Compensation of the group-delay dispersion was achieved by the chirped mirror (CM in Fig. 1) providing the net intracavity dispersion of -500 fs^2 at 2350 nm.

All measurements were performed in the open air, with relative humidity ~30%. The spectrum was analyzed by a commercial FTIR spectrometer at 1 cm^{-1} resolution. The pulse duration was measured using a self-made autocorrelator based on a two-photon absorption in an amplified Ge photodetector. The pulse train was recorded by a 60-MHz extended InGaAs photodetector coupled to a 1.5 GHz oscilloscope.

3. Results and discussion

Though output powers up to 1 W have been demonstrated in mode-locked Cr:ZnS laser [3,4,7,9], operation in the gigahertz regime results in a reduced pulse energies and, thus, requires decreasing of output coupling to keep the intracavity pulse energy at the desirable level. We used an output coupler of 1.8% in this experiment, and the average output power was therefore limited at a 100-mW level.

The mode-locking threshold was measured to be around 0.9 W of pump power. Mode-locking could be supported up to 2.7 W when thermal effects caused mode degradation. Stable and reliable single-pulse mode-locking was achieved in the output power range of 35-100 mW (Fig. 2, left). Beginning with 60 mW of output power (3.3 W intracavity power), corresponding to 63 pJ (3.5 nJ intracavity) pulse energy, the laser operated in self-starting regime. The output power scales approximately linear with increasing pump in the whole mode-locking power range (Fig. 2, left). Below 2.2 W of pump power the pulse spectral width (red dots in Fig. 2, right) also maintain the linear dependence, while the spectral shape keeps very close to sech^2, with only slight red-shift of the central wavelength from 2340 to 2350 nm. Simultaneously, the pulse duration shortens from 850 down to 180 fs with time-bandwidth product of 0.32±0.03 as expected for a passively mode-locked laser operating well in the soliton regime. Fig. 3 shows the autocorrelation and spectrum of the output pulse, as well as the RF spectrum of the pulse train, recorded at 102 mW of output power. The repetition rate, as derived from the RF spectrum, is 0.952 GHz (Fig. 3, right).

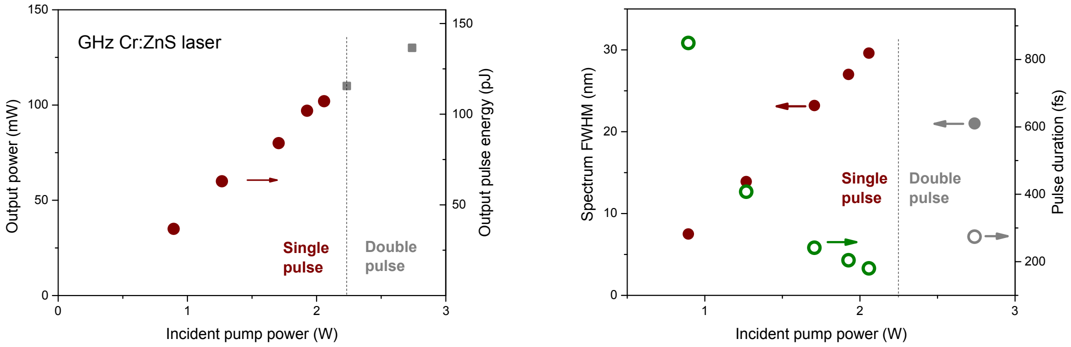

Fig. 2: *(Left graph)* Output power and pulse energy of a high-repetition rate Cr:ZnS laser. *(Right graph)* The pulse spectral width (closed circles) and duration (open circles, sech^2 assumed). Double-pulse regime is shown in grey.

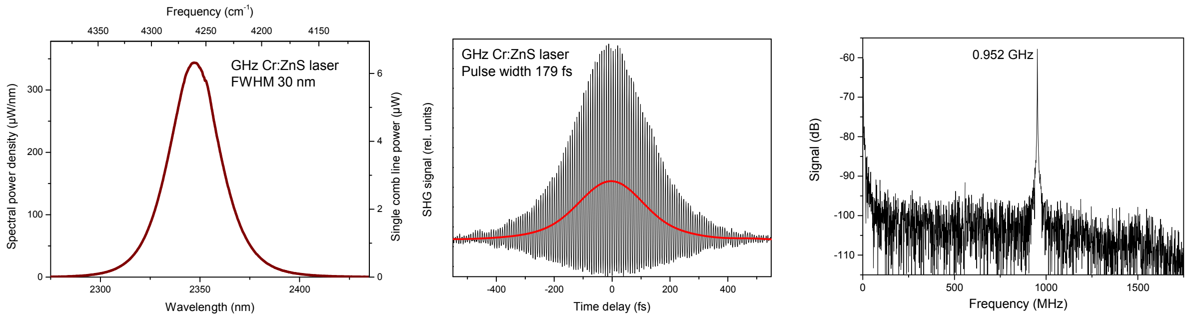

Fig. 3: The laser output spectrum *(left)*, pulse autocorrelation trace *(center)* and RF power spectrum *(right)* of a GHz mode-locked Cr:ZnS laser at 102 mW of output power (107 pJ pulse energy).

At pump power above 2.2 W (~110 mW of output power) the mode-locking stability starts degrading and the output acquires narrowband components in the spectrum. With further increase of the pump power above 2.5 W the stable mode-locked operation restores, with a sech^2 spectrum and 20-21 nm bandwidth. At 130 mW of output power (grey points in Fig. 2), the bandwidth of 21 nm and pulse duration of 275 fs correspond to those, that are obtained by interpolation at twice lower output power of about 60-70 mW. We therefore interpret this regime as a double pulse, most probably an evidence of harmonic mode-locking at 2 GHz frequency, which remains to be reliably confirmed by using the sufficiently fast detection system.

4. Conclusion

Summarizing, we report the first mode-locked Cr^{2+}:ZnS laser with a gigahertz-level pulse repetition frequency. The laser generated pulses of about 180 fs duration at 2.35 μm wavelength with the average output power exceeding 100 mW. To the best of our knowledge, this is the highest pulse repetition rate generated by a laser oscillator in the mid-IR. Evidence of the double-pulse operation suggests that even higher repetition rates are feasible in this system.

Acknowledgements

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