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100-fs diode-pumped Yb:KGW mode-locked laser

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ABSTRACT We have developed a mode-locked diode-pumped Yb:KGW laser generating 100-fs pulses with an output power of 126 mW. The corresponding optical spectrum has a 13.4-nm FWHM bandwidth and is centered at 1037.4 nm. In the multiple-pulsing regime, bound states of solitons with rotating phase difference and separated by 917.5 fs were observed. We compare the performance of the Yb:KGW crystal to that of an Yb:KYW crystal with the same thickness and Yb concentration.

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1 Introduction

For high-power laser systems which use chirped pulse amplification, stable, maintenance-free seed oscillators are required. For the development of the POLARIS system, a diode-pumped laser in the petawatt class [1], 100-fs pulses with 1-nJ energy are required. The goal of this work was to develop a suitable seed laser for this system.

Yb-doped materials have been recognized in recent years as very attractive active media for diode-pumped femtosecond laser oscillators and for regenerative amplifiers [2]. First, the simple electronic structure of Yb^{3+} and the broad absorption bands, well matched to the high-power infrared diode lasers emitting in the 940–980-nm spectral range, made possible the development of efficient and compact continuous-wave (cw) lasers. Furthermore, the broad emission spectra made these materials very suitable for ultra-short pulse generation.

Both Yb-doped potassium tungstates, Yb:KGd$(WO_4)_2$ (Yb:KGW) and Yb:KY$(WO_4)_2$ (Yb:KYW) exhibit large emission and absorption cross sections, broad emission bandwidths and good thermal conductivities [3, 4]. These are very promising properties for constructing efficient femtosecond oscillators. Moreover, the position of the center wavelength makes the Yb:KGW and Yb:KYW lasers very suitable to seed Yb-doped glass amplifiers, as used in the POLARIS system, which show a higher gain at wavelengths shorter than in Yb:glass oscillators [2]. Operation of mode-locked Yb:KGW [5–7] and Yb:KYW [7–9] lasers was demonstrated previously. The Yb:KGW lasers were passively mode locked by a semiconductor saturable absorber mirror [5, 7] or a saturable Bragg reflector [6]. The shortest pulse duration was 112 fs in the former case and 169 fs in the latter. From an Yb:KYW laser, pulse durations of 71 fs for Kerr-lens mode locking [8] and of 101 fs for mode locking using saturable absorber mirrors [7] were demonstrated.

We report here the development of a diode-pumped mode-locked Yb:KGW laser delivering 100-fs pulses with an output power of 126 mW and a repetition rate of 108 MHz. The laser was pumped by a high-brightness fiber-coupled laser diode and passively mode locked with a semiconductor saturable absorber mirror. The laser shows a typically soliton mode locking behavior. In the multiple-pulsing regime, bound states of solitons with rotating phase difference were observed. The performance of the Yb:KGW laser was compared to that of Yb:KYW in the same arrangement.

2 Experimental set-up

The laser set-up (Fig. 1) consists of a delta-shaped cavity with one arm folded by the plane mirror M4, in order to achieve a more compact design. The experiment was performed with a 1-mm-thick Yb:KGW crystal doped with 5 at. % of Yb^{3+} ions and cut for pumping along the b axis. The crystal was placed in the cavity at the Brewster angle.

The laser was pumped by a high-brightness fiber-coupled laser diode, which provides an output power up to 5 W. The fiber has a core diameter of 50 μm and an effective numerical aperture (N.A.) of 0.15, which leads to a beam quality of $M^2 = 12$. The pump beam is focused with two antireflective-coated achromatic lenses, resulting in a measured pump spot diameter of 100 μm, which fits well to the designed laser mode in the crystal. The typical emission spectrum has a peak wavelength of 975 nm and a bandwidth of 2.4 nm. The Yb-doped KGW and KYW crystals show an absorption peak at 981 nm, with bandwidths of 3.7 nm and 3.4 nm, respectively. In order to tune the wavelength to 981 nm, we increased the operating temperature to 33.5 °C. At elevated temperatures, the diode was operated at a pump power of 4.15 W in front of the fiber tip. 3.35 W was incident on the crystal. The losses are mainly introduced by the folding mirror M1 due to the closeness of the pump and laser wavelengths.

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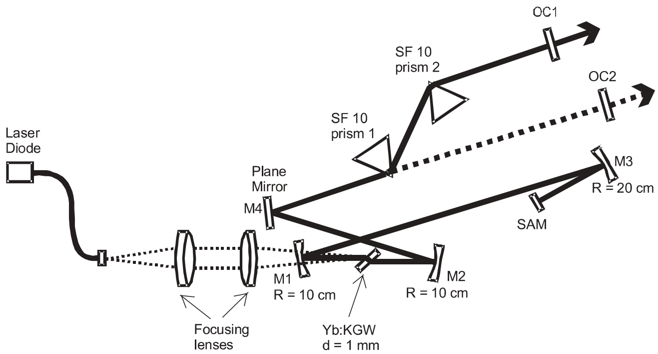

FIGURE 1 Experimental set-up for the mode-locked Yb:KGW laser. M1–M3, curved mirrors; *R*, radius of curvature; M4, high-reflective plane mirror; OC1, OC2, output couplers with different transmissions; SAM, saturable absorber mirror

The absorption length of the crystal at this pump wavelength is 0.4 mm for polarization parallel to the *a* axis and 2.2 mm for polarization parallel to the *c* axis. The pump radiation is not polarized; thus the measured absorption length was 1.45 mm. The folding mirrors M1 and M2 have a radius of curvature of 100 mm and a reflectivity $> 99.9\%$ in the range 1020–1070 nm.

To achieve mode locking we used two semiconductor saturable absorber mirrors (SAMs) with modulation depths of 2% and 0.6%, respectively. The SAMs have recovery time constants ≤ 10 ps and the introduced losses are less than 0.3% [10]. The 200-mm curved mirror M3 focuses the laser beam onto the SAM in order to achieve a beam radius of 65 μm. The energy fluences on the SAMs were $\approx 450\ \mu J/cm^2$ and $\approx 930\ \mu J/cm^2$, respectively. For several hours of continuous operation at these parameters, we did not observe any damage.

A pair of SF10 prisms separated by 34 cm were inserted in the arm with the output coupler (OC). They compensate for the group-velocity dispersion (GVD) introduced by the amplifying medium. In order to minimize the losses at the prism surfaces, the resonator was designed for a low divergence of the output beam.

3 Results

The first experiments were performed with the Yb:KGW crystal arranged in the set-up shown in Fig. 1. Using a 2% transmission output coupler and the SAM with 2% modulation depth, pulses as short as 100 fs were achieved. Figure 2a shows the intensity autocorrelation trace and the fit assuming a sech^2 pulse shape. The corresponding optical spectrum (Fig. 2b) is centered at 1037.4 nm and has a bandwidth of 13.4 nm. This results in a time–bandwidth product of 0.373, which is 18% more than the theoretical value of 0.315 for a sech^2 pulse shape. The shortest pulse duration achieved is somewhat less than reported previously [5, 7] for Yb:KGW lasers. As the time–bandwidth product is larger than the theoretical value, the pulses may be shortened further. The output power was 126 mW and the repetition rate 108 MHz. This corresponds to an energy per pulse of 1.17 nJ and to a peak power of 11.7 kW. The cw mode-locking regime was self-starting and stable.

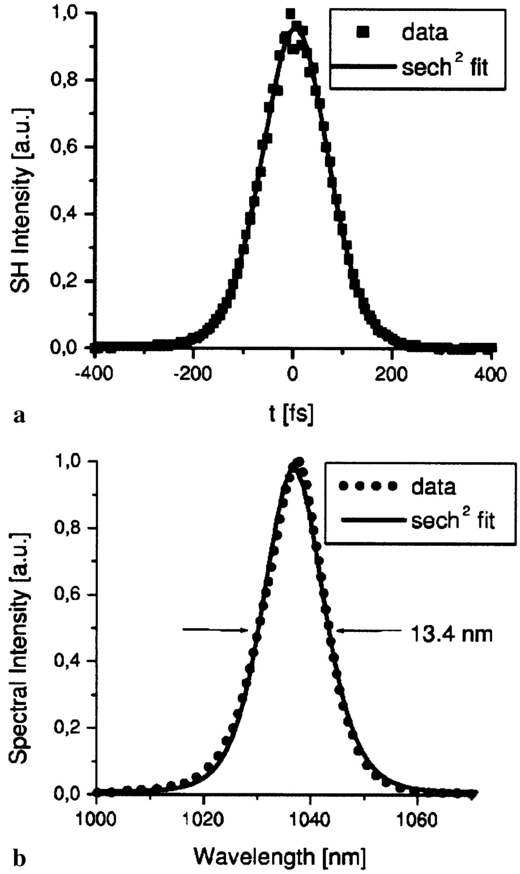

FIGURE 2 Intensity autocorrelation (**a**) and optical spectrum (**b**) of the 100-fs pulses obtained from the Yb:KGW laser with 126-mW output power. The *solid lines* show the theoretical curves assuming a sech^2 pulse shape

It was reported previously [11–14] that for soliton mode locking the pulse shortening is limited by the onset of multiple pulsing. Figure 3 shows the variation of the pulse length (a), output power (c) and center wavelength (b) with the intracavity group-velocity dispersion (GVD). In single-pulsing regime, the laser can be tuned between 1031 and 1037.4 nm (Fig. 3b). On decreasing the negative GVD, i.e. increasing the prism insertion, the pulse becomes shorter until it breaks into two longer pulses.

In the double-pulsing regime, the distance between pulses was less than 1 ps, which required autocorrelation measurements. Figure 4 shows the interferometric autocorrelation trace (Fig. 4a) and the corresponding optical spectrum (Fig. 4b). We measured a pulse separation of 917.5 fs, which remains constant once the multiple-pulsing regime is started, independent of the GVD. As the two lateral peaks in Fig. 3a corresponding to the overlap in time of consecutive pulses do not show interference structures, we can conclude that the phases of the two solitons are independent. The generation of soliton pairs with rotating phase difference in lasers passively mode locked with slow saturable absorbers was predicted in a stability analysis of the complex Ginzburg–Landau equation [15, 16] and experimentally observed in a Ti:sapphire laser [16]. The rotating phase difference is additionally confirmed by the shape of the optical spectrum, which shows no fringes that should appear in the spectra of the phase-locked soliton pairs.

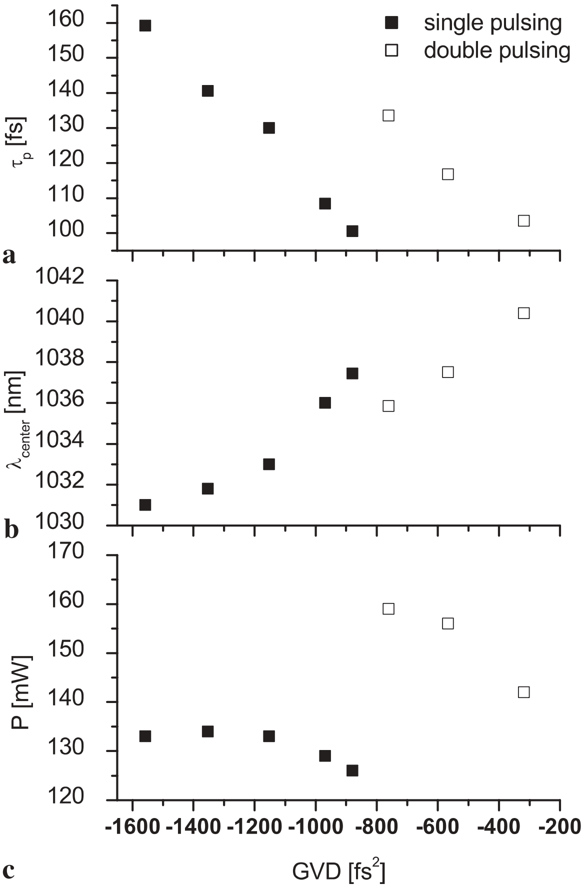

FIGURE 3 Variation with the negative GVD of the pulse duration assuming a sech^2 pulse shape (**a**), center wavelength (**b**) and output power (**c**) for the Yb:KGW laser

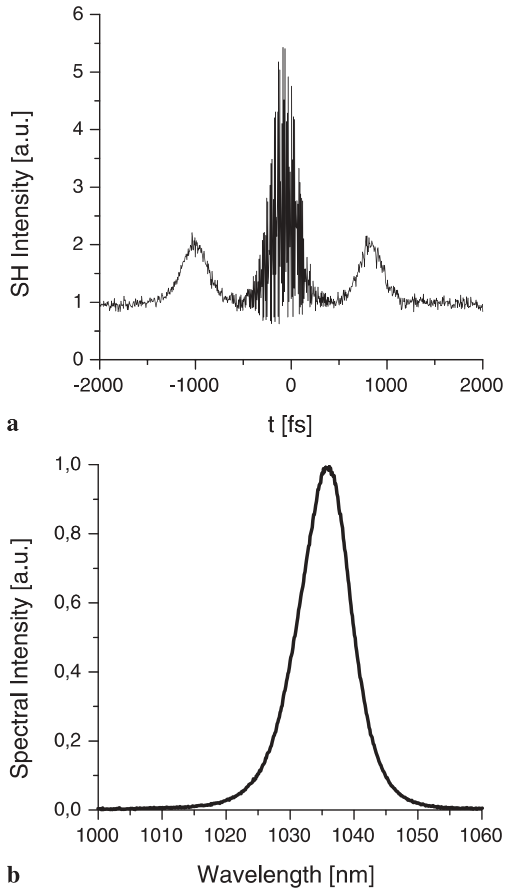

FIGURE 4 Interferometric autocorrelation on a 4-ps time range (**a**) and the corresponding optical spectrum (**b**) for double pulsing regime. The autocorrelation trace was recorded with a step larger than the optical cycle; consequently the contrast is smaller than the theoretical value of 1 : 8

On increasing the prism insertion further, more than two pulses were observed delayed up to the half-cavity round-trip time. In this regime, the oscillator was stable only for a few seconds.

We achieved an output power between 360 and 430 mW using a saturable absorber with 0.6% modulation depth and a 3% transmission output coupler. In this case the shortest pulse had a duration of 174 fs and a spectral bandwidth of 7.2 nm.

In the cw configuration, with a high-reflective mirror instead of the saturable absorber and with a 3% output coupler, the output power was 630 mW without the prisms and 520 mW after the prisms' insertion.

In order to compare Yb:KGW and Yb:KYW materials, we also performed experiments using an Yb:KYW crystal. It had the same thickness and Yb concentration as the Yb:KGW crystal and was tested using the same set-up. A comparison between the laser performances of the two crystals is given in Table 1. For both amplifying media, the shortest pulse length was achieved with a 2% modulation depht and a 2% transmission output coupler, and the highest output power was delivered for a 0.6% modulation depth and 3% and 4% transmission output couplers, respectively.

	τ_p [fs]	P_{output} [mW]	λ [nm]	$\tau_p \times \Delta\nu$	OC transmission	Modulation depth
Yb : KGW	100	126	1037.4	0.373	2%	2%
	218	430	1035	0.342	3%	0.6%
Yb : KYW	106.5	92	1039	0.380	2%	2%
	247	289	1032.2	0.343	4%	0.6%

TABLE 1 Comparison between Yb:KGW and Yb:KYW mode-locked lasers. The laser parameters are given for the shortest pulses and the highest output power, respectively

4 Conclusion

In conclusion, we have demonstrated the generation of 100-fs pulses from an Yb:KGW mode-locked laser. At 1.57-W absorbed power, the laser delivers 126 mW. Output power up to 430 mW was achieved for pulse durations longer than 174 fs. The laser works in the spectral range 1031–1037.4 nm and has a repetition rate of 108 MHz. In the multiple-pulsing regime, bound states of solitons with rotating phase difference and separated by 917.5 fs were observed. As the time–bandwidth product is about 18% larger than the calculated value of 0.315 for a sech^2 pulse shape, an external compression is likely to be capable of shortening the pulses further.

The achieved parameters show that the laser is suitable to seed the amplifiers of the POLARIS system.

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