Passively mode-locked Yb:$LuVO_4$ oscillator

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Abstract: Passive mode locking of the ytterbium doped orthovanadate crystal Yb:$LuVO_4$ is reported for the first time. We demonstrate what we believe to be the shortest pulses directly generated with an Yb-doped crystalline laser using a semiconductor saturable absorber. The pulses at 1036 nm have a duration as short as 58 fs for an average power of 85 mW.

OCIS codes: (140.5680) Rare earth and transition metal solid-state lasers; (140.4050) Mode-locked lasers.

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1. Introduction

The uniaxial orthovanadate crystals are recognized as attractive host materials for the development of efficient, compact, diode-pumped solid-state lasers. In comparison with YAG, their advantages are generally related to the high absorption and emission cross-sections of the dopant, and the broader absorption and emission bandwidths, while the thermal conductivity is very similar. Recent studies indicated that the ytterbium doped orthovanadates $GdVO_4$, YVO_4, and $LuVO_4$ are particularly promising laser materials for the 1 µm spectral range [1-4]. Subsequently, the output powers in the continuous-wave regime were substantially increased using diode pumping, exceeding 4 W for all three of them [5]. Nevertheless, due to the closer ionic radii and masses of Yb and Lu, it can be expected that lutetium vanadate, $LuVO_4$, whose growth technology is still in the development stage, will be the most suitable host for Yb, especially in the high-power regime, because higher doping (important for thin-disk laser configurations) should be possible without affecting the crystalline quality and the effect of the dopant on the thermal conductivity of the host should be minimized. The broad emission spectra of Yb-doped vanadates make them interesting not only for tunable laser operation in the 1 µm spectral range but also for reliable and efficient diode-pumped femtosecond lasers. Both mode locking with a semiconductor saturable absorber mirror (SESAM) and Kerr lens mode-locking have been demonstrated for $Yb:YVO_4$ [6,7]. The pulses obtained were as short as 120 fs and 61 fs for SESAM and Kerr lens mode-locked operation, respectively.

The broad and smooth emission spectrum and the somewhat higher emission cross sections of $Yb:LuVO_4$ make it very interesting to evaluate its potential for passive mode-locking in the sub-100 fs regime. This is due to the fact that the basic limitation of the present Yb-laser ultrafast technology which is based on diode pumping, in comparison to the widely spread Ti:sapphire laser technology which requires frequency doubled pump sources, is connected with the available bandwidths and the pulse durations that can be achieved. Here we report, for the first time to our knowledge, mode-locked operation of $Yb:LuVO_4$ with Ti:sapphire laser pumping using a SESAM.

2. Gain profile of ytterbium doped lutetium vanadate

The $Yb:LuVO_4$ crystal was grown along the ***a***-axis by the conventional Czochralski method with a doping concentration of 1.56 at. % (measured in the crystal [4]). The fluorescence lifetime of Yb in $LuVO_4$ amounts to 256 µs [4]. The absorption and emission cross-sections exhibit strong anisotropy and are higher for π-polarization (***E***//***c***) than for the σ-polarization. The main absorption band for π-polarization is centered at 985 nm with a peak cross section of 8.42×10^{-20} cm^2 [4]. In the wavelength range of 1020-1055 nm, where laser oscillation occurs, the emission cross-section ranges from 2×10^{-21} to 10.3×10^{-21} cm^2.

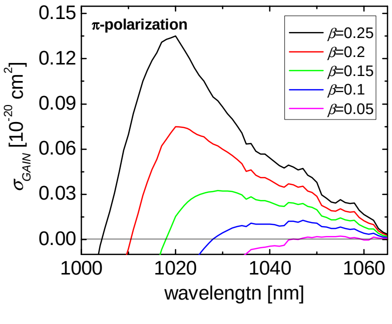

Fig. 1. Gain cross section σ_{GAIN} of $Yb:LuVO_4$ for π-polarization (***E***//***c***) and different population inversion rates β.

In order to estimate the potential gain bandwidth for mode-locked operation, the gain cross section for π-polarization and several values of the population inversion parameter β is calculated and presented in Fig 1. β is the ratio of the number of excited ions to the total number of Yb-ions. It can be seen that the amplification bandwidth depends on the oscillation wavelengths and hence on the net gain or cavity losses. The gain profile is also quite smooth.

3. Experimental set-up

We employed a Z-shaped astigmatically compensated resonator (see Fig. 2) similar to that used in [8]. The folding section was formed by two mirrors (M2 and M3) with radius of curvature RC=-10 cm, and the active element was pumped through one of them. The 2-mm thick sample was oriented for π-polarization ($\boldsymbol{E}//\boldsymbol{c}$) under Brewster angle. It was clamped in a Cu-block without active cooling. A Ti:sapphire laser which emitted up to 1.8 W at 985 nm was used as a pump source. The continuous-wave performance of such a Yb:LuVO$_4$ laser was described in more detail in a previous publication [4]. For the present work, an additional focusing mirror (M1, RC=-15 cm) was added into one of the cavity arms (see Fig. 2) in order to increase the pulse fluence on the SESAM which was used for passive mode-locking. The general advantages of using a SESAM are the self-starting femtosecond laser operation and the relatively uncritical alignment of the cavity in comparison with Kerr-Lens mode-locking.

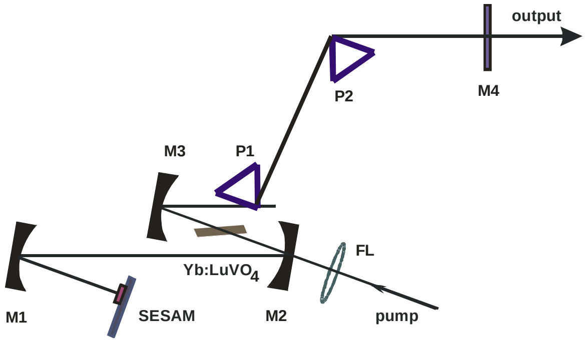

Fig. 2. Setup of the mode-locked Yb:LuVO$_4$ laser: M1 - focusing mirror; M2, M3 - folding mirrors, P1, P2 - Brewster prisms; M4 - output couplers, FL - an f=6.28 cm focusing lens.

The SESAM used for mode-locking was grown by metalorganic vapor phase epitaxy (MOVPE). The distributed Bragg mirror on a GaAs substrate contained 25-AlAs/GaAs quarterwave layer pairs. Its high reflection band with R>99% extended from 1000 to 1080 nm. The absorbing part on top of the Bragg mirror was a 10 nm thick single InGaAs quantum well (QW) embedded in a GaAs layer. To accelerate the saturable absorber relaxation the QW was implanted with As-ions. Its relaxation time was measured by the pump-probe technique to be less than 5 ps. The saturable absorption amounted to ~0.5% and the saturation fluence was 20 µJ/cm^2. The non-saturable losses were negligible.

Two SF10 prisms with a tip-to-tip separation of 37.5 cm, in the other cavity arm containing the output coupler, were used for dispersion compensation, Fig. 2. There was no tuning element in this cavity, so the wavelength changed slightly only when exchanging the output coupler, an effect well known for three-level laser systems like Yb. The incident power measured in front of the Yb:LuVO$_4$ crystal was 1.14 W and roughly 80% of it was absorbed.

4. Experimental results and discussion

After optimization of the cavity alignment for mode-locked operation, the shortest pulses were obtained with an output coupler of transmission T=1%. The intensity autocorrelation trace with the corresponding fit and the spectrum of the shortest pulses are shown in Fig. 3. The pulse FWHM assuming sech^2-pulse shape is 58 fs (Fig. 3a). This is what we believe to be the shortest pulse generated directly with a SESAM mode-locked crystalline Yb-laser. The

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corresponding output spectrum is centered at 1036 nm and has a bandwidth of 22 nm. This results in a time-bandwidth product of 0.357, which is only slightly above the Fourier limit for a sech^2-pulse (0.315). This indicates that there is only limited potential for additional pulse shortening by extracavity compression. The average output power was 85 mW for a repetition rate of 94 MHz. The output power level increased to 200 mW at a longer pulse duration of 129 fs when an output coupler with T=3% was used. In this case the oscillation wavelength was 1024 nm and the time-bandwidth product was 0.332. The observed transversal mode of the Yb:LuVO$_4$ laser remained in all cases essentially TEM$_{00}$. No tendencies for Q-switching instabilities were observed [9], and when decreasing the pump power the laser eventually switched to continuous-wave operation.

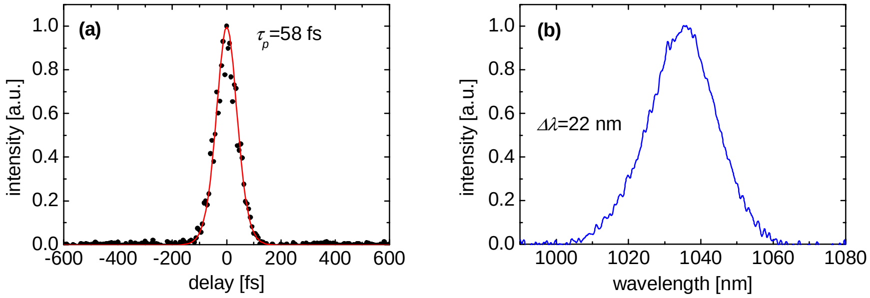

Fig. 3. Autocorrelation trace and the corresponding fit assuming sech^2-pulse shape (a), and spectrum (b) in the femtosecond regime of the Yb:LuVO$_4$ laser.

The achieved pulse duration of 58 fs is one of the shortest for ytterbium lasers. Similar pulse durations, 61 fs, were obtained only very recently with a Kerr-lens mode-locked Yb:YVO$_4$ laser [7]. Shorter pulses of 47 fs were reported only from a Yb:CaGdAlO$_4$ laser but with external compression [10]. In both cases the average output power was lower than in the present work. The same holds also for the mode-locked Yb:phosphate and Yb:silicate glass lasers which produced pulses as short as 58 and 61 fs, respectively [11]. Thus our Yb:LuVO$_4$ laser provided the shortest pulses directly from a SESAM mode-locked oscillator based on an Yb-doped crystalline material. It can be concluded that Yb-doped crystalline laser materials, and in particular the orthovanadates with their superior thermal properties, can provide the same bandwidths and smooth gain profiles as glasses.

5. Conclusion

In conclusion, we have demonstrated what we believe to be the first Yb:LuVO$_4$ mode-locked oscillator. The laser generated pulses as short as 58 fs with an average output power of 85 mW. This result is indicative of the very high potential of Yb:LuVO$_4$ for the future development of efficient high-power femtosecond laser sources. The present limit on the achievable pulse duration is likely related to the gain bandwidth. In the three-level Yb-laser system, it can be seen from Fig. 1, that slightly larger bandwidths and consequently yet shorter pulse durations could be expected at lower absorption levels or increasing the bleaching effect (e.g. through double side pumping). Power scaling can be expected with diode pumping: Very recently it was shown that this laser material can provide more than 8 W in the continuous-wave mode [12] – the highest output power demonstrated so far with an Yb-doped vanadate crystal.

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