Optics Communications 284 (2011) 4049–4051

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Efficient femtosecond Yb:YAG laser pumped by a single-mode laser diode

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ARTICLE INFO

Article history:
Received 10 February 2011
Received in revised form 30 March 2011
Accepted 17 April 2011
Available online 1 May 2011

Keywords:
70.020 (laser sources)
70.030 (ultrashort pulse generation)
70.050 (laser materials)

ABSTRACT

Single-mode diodes enable a particularly simple, compact and effective pumping of solid-state laser devices for many specialized applications. We investigated a single-mode, 300-mW laser diode for pumping at 935 nm a Yb:YAG laser passively mode-locked by a semiconductor saturable absorber. Relatively short pulse generation (156 fs), tunable across 1033–1059 nm has been demonstrated. An optical-to-optical efficiency of about 28% has been obtained with 320 fs long pulses. Therefore, contrarily to what previously believed, compact diode-pumped ultrafast Yb:YAG oscillators can reliably and efficiently deliver pulses in the range of ≈100–200 fs with few tens of mW, which are very appealing for bio-diagnostics and amplifier seeding applications.

1. Introduction

Near-infrared ultrafast, low-power solid-state lasers are used mainly for applications requiring only few tens of milliwatts in cw mode-locking regime, such as bio-diagnostics and amplifier seeding. In particular, 1-μm laser sources, based on either Nd^{3+} or Yb^{3+} active rare-earths ions, have been extensively investigated in the last 15 years [1,2]. More recently, a specific research effort was dedicated to the realization of efficient compact low-power ultrafast lasers employing single-mode low-power laser diode pumps. While Nd:glass lasers were demonstrated to be excellent performers with very low pump threshold owing to their four-level laser scheme, delivering sub-200-fs pulses [3,4] (and minimum pulse duration of 80 fs [5]) with good efficiency, it is nonetheless recognized that quasi-three levels ytterbium lasers are intrinsically more efficient, and that furthermore employ pump laser diodes at ≈940/980 nm which are generally more reliable as they evolved to comply with demanding telecom industry standards.

Earlier work on low-power single-mode pumping of ultrafast ytterbium lasers has been restricted to Yb:KYW [6] and Yb:YVO [4,7]. It has to be noted that relatively expensive single-mode fiber-coupled laser diodes were employed in those experiments. Output power as high as 227 mW and optical-to-optical efficiency up to 53% were reported in Ref. [6], whereas the shortest pulses of 61 fs were generated with Yb:YVO [4,7]. While the better developed and more broadly available Yb:YAG crystal was the subject of earlier investigations, leading to the shortest pulse width of 340 fs with Ti:sapphire pumping [2], Yb:YAG was ever since considered almost exclusively for multiwatt power scaling of sub-ps thin disk lasers [8]. Only recently, very likely owing to refinements of Semiconductor Saturable Absorber Mirror (SESAM) technology allowing more performing passive mode-lockers than those reported in Ref. [2], significantly shorter pulses have been achieved with Yb:YAG lasers. In particular, pulses as short as 136 fs [9] and, quite impressively, 35 fs [10] with SESAM and Kerr-lens mode-locking, respectively, have been reported. However, these laser systems employed multiwatt multimode pump lasers and were mainly optimized for generation of shortest pulses, with a rather low optical-to-optical efficiency of few percents. Higher optical-to-optical efficiency of ≈10% was reported in Ref. [11], where 170-fs pulses were achieved with SESAM mode-locking. In this article we report the results of optimization of a compact Yb:YAG laser, pumped by a single-mode 300-mW laser diode at 935 nm and mode-locked by a SESAM.

2. Experiments

The experimental setup is shown in Fig. 1. The pump diode was a single-mode 300-mW laser diode (FLC GmbH), emitting at 935 nm with a narrow single-longitudinal-mode 50-pm linewidth. Pumping at this wavelength offers the benefit of a broader absorption linewidth and therefore less critical temperature and wavelength control of the pump device. The maximum power delivered to the laser crystal was 270 mW. The elliptical pump beam was collimated with a 0.4 NA, 6.24-mm focal length aspheric lens and reshaped with a pair of anamorphic prisms. A 75-mm spherical singlet lens was used to eventually focus the circularized beam into the active medium. A CCD camera was employed to characterize the pump spot profile in the focal region of the optical system, yielding waist radii $w_{px} \times w_{py} \approx 20 \times 20\ \mu m^2$ in air and beam quality parameters of $M_x^2 \approx 1.2$ and $M_y^2 \approx 1.2$, respectively. By ABCD modeling, the resonator beam waist radius was calculated to be 15–20 μm within the stability region. The pump spot size was optimized in order to ensure both a reasonable mode-matching with the cavity beam, and a pump beam confocal parameter comparable with the length of the active medium. This is particularly important to minimize

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doi:10.1016/j.optcom.2011.04.046

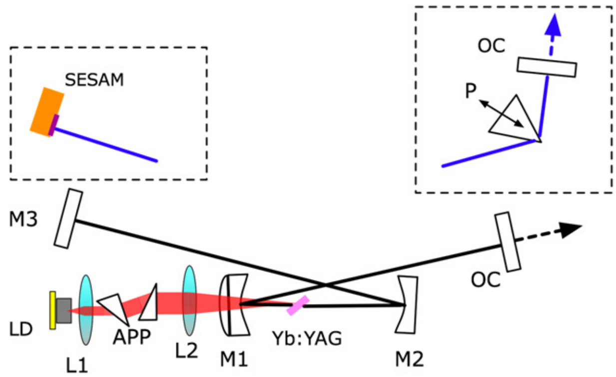

Fig. 1. Resonator layout. LD: pump laser diode; L1: aspheric lens (6.5-mm focal, NA 0.4); APP: anamorphic N-SF11 prisms pair; L2: spherical singlet lens (75-mm focal); M1: concave mirror, 50-mm curvature, high-reflectivity (HR) at 1000–1100 nm, high-transmittivity at 900–950 nm; M2: concave mirror, 100-mm curvature, HR; M3: flat mirror: HR; OC: output coupler, 30′ wedge. In the Insets: SESAM: $\Delta R_{tot}=1\%$ ($\Delta R_{sat}=0.6\%$); P: SF10 prism; OC: output coupler, 30′ wedge.

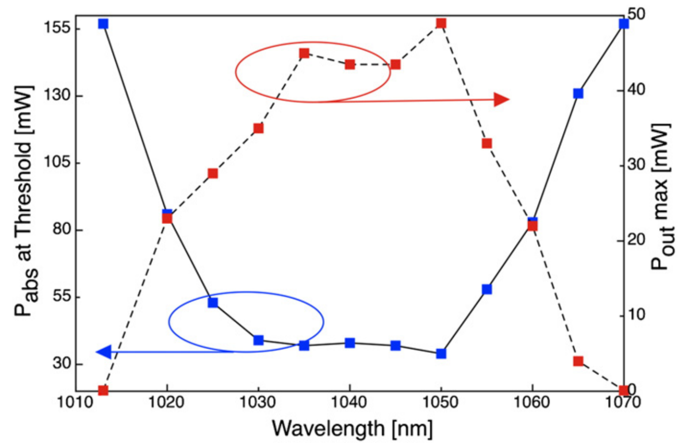

Fig. 2. Output wavelength tunability in cw regime with T = 2.4% output coupler. Both maximum output power (red points, right vertical axis) and absorbed pump power at threshold (blue points, left vertical axis) are shown.

the effect of the reabsorption losses of the quasi-three-level active medium. The Yb:YAG laser crystal was a 1-mm long, 10%-doped circular plate, with a diameter of 4 mm. The active medium was glued over a metallic plate without any active cooling, oriented at the Brewster angle in order to minimize insertion losses. Referring to Fig. 1, the separation between M1 and M2 was set at ≈ 87 mm for operation near the center of the resonator stability region; M2 − M3 and M1 − OC cavity arm lengths were about 260 and 350 mm respectively.

We carried out a preliminary cw laser characterization with several different output coupler transmittivities (T = 1.6%, 2.4%, 5% and 10%). The optimum performance was obtained with T = 1.6% output coupler transmittivity. A maximum output power of 60 mW at 155 mW absorbed pump power, with a slope efficiency of 50% and low (30 mW absorbed pump power) laser threshold was obtained, accounting for the good pump beam dimensioning inside the quasi-three level active medium. For comparison, under the same pumping and cavity arrangement, we characterized a 2-mm long, 10% doped Yb:YAG plate. With the same T = 1.6% output coupler, laser threshold was approximately doubled, going up to 55 mW.

In order to assess the tuning possibilities of our laser employing the 1-mm long Yb:YAG crystal, we inserted an SF10 dispersive prism (see Fig. 1) to measure the tuning range in cw operation. The results obtained with a T = 2.4% output coupler are shown in Fig. 2. The lasing wavelength was continuously tunable between 1012–1070 nm, with the lowest threshold and highest output power measured near the secondary emission peak of Yb:YAG near 1049 nm. Although the Yb:YAG emission cross-section peak around 1030 nm is almost seven times higher than that at 1049 nm [2], thermal population at the bottom of the ground-state manifold is higher, and the reabsorption loss at the shorter laser wavelength favors long-wavelength operation when using low-transmission output couplers [12]. The same measurement was carried out substituting the 2.4% with a 10% transmittivity output coupler. As expected, this resulted in both a reduction of the available tuning range (lasing was limited only between 1022–1031 nm and between 1046–1050 nm) and a lower laser threshold for the higher gain 1030 nm transition.

For cw-mode-locking experiments, we substituted the HR mirror M3 with a commercially available SESAM (Batop, GmbH) specified by the constructor to have a nominal loss of 1% (0.6% saturable + 0.4% non-saturable loss), a relaxation time of ≈ 1 ps and a saturation fluence of ≈ 60 μJ/cm^2. As shown in Fig. 1, we employed the SESAM as an end mirror in a classical X-folded resonator. Reducing the M2 − SESAM distance, and consequently increasing the distance M1 − M2 for cavity stability, allows to reduce the cavity mode size over the SESAM. We chose a beam waist radius of w_{sam} ≈ 30 μm by setting M2 − SESAM ≈ 175 mm and M1 − M2 ≈ 95 mm. The separation M1 − P ≈ 380 mm was chosen to provide the net negative Group Velocity Dispersion (GVD) required to stabilize the soliton mode-locking regime. In this single prism configuration, according to the ABCD modeling of the cavity carried out as in Ref. [13], the distance between "virtual" and real SF10 prism is approximately 30 cm.

Employing a T = 0.4% output coupler we readily observed stable and self-starting cw-mode-locked pulse trains with an average power of 18 mW. Adjusting the net intracavity dispersion and cavity alignment, nearly transform limited 177-fs-long pulses, with 6.5-nm wide spectra centered around 1039 nm were obtained.

We also investigated the optimum coupling for the maximum output average power in soliton mode-locking regime. With T = 1.6% we obtained 320-fs-long stable mode-locked pulses, with 43-mW average output power, corresponding to an optical-to-optical efficiency of ≈ 28% with respect to the absorbed pump power.

In order to explore the shortest pulse duration obtainable in our setup, we increased self-phase modulation by placing a 2-mm thick un-doped YAG plate in contact with the 1-mm-thick Yb:YAG crystal and chose again the lowest transmittivity output coupler (T = 0.4%) to maximize intracavity pulse energy. With this solution, we both obtained a shortening of the pulse duration and a broader wavelength tuning range. The results are reported in Fig. 3. 156-fs-long nearly

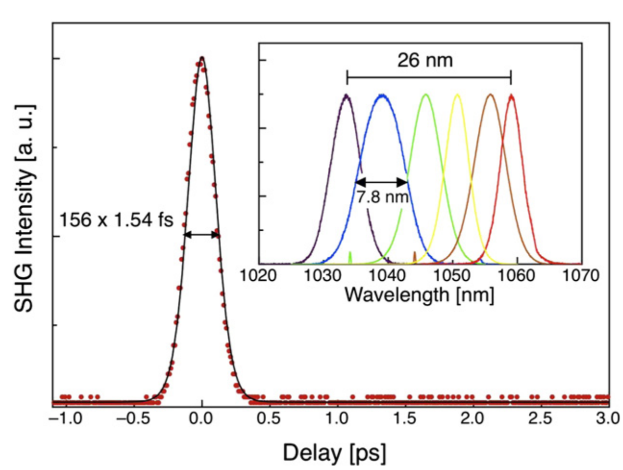

Fig. 3. Shortest pulse autocorrelation and best-fit corresponding to *sech*^{2} pulse shape. In the inset the output wavelength tunability and the 7.8-nm wide optical spectrum of the autocorrelated pulses are shown.

transform limited pulses with an average output power of 15 mW were obtained. Simply adjusting the horizontal tilt of the output coupler it was possible to move the central output wavelength continuously in the range 1033–1059 nm, with average output powers ranging between 14 and 20 mW and pulse durations between 156 and 275 fs.

3. Conclusions

In conclusion, efficient operation of femtosecond Yb:YAG laser pumped by a low-power single-mode laser diode was demonstrated for the first time to our knowledge. Optical-to-optical efficiency was as high as 28% with 320-fs pulses, whereas pulses as short as 156 fs were achieved with optimized self-phase modulation. The measured output power of 14–43 mW is more than sufficient for a large variety of applications. Relatively broad, continuous tuning range up to 26 nm ($\approx$50% of the cw tuning range) maintaining sub-300-fs operation is another interesting feature of this laser source. Overall, these results confirm the ability of broadly available Yb:YAG crystal to compete with other Yb^{3+} ion hosts for generation of $\approx$100 fs pulses with SESAM mode-locking, especially when the pump system is carefully optimized as it is readily done with low-power single-mode laser diodes.

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