Published in Optics Express 25, issue 14, 16527-16533, 2017
which should be used for any reference to this work

High-power amplification of a femtosecond vertical external-cavity surface-emitting laser in an Yb:YAG waveguide

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Abstract: We present the amplification of a mode-locked vertical external-cavity surface-emitting laser (VECSEL) using an Yb:YAG crystalline waveguide as gain medium. The VECSEL seed laser operates at a center wavelength of 1030 nm and generates 300-fs pulses at a repetition rate of 1.77 GHz. An average seed power of 60 mW was launched onto a 8.3 mm long fs-laser written Yb:YAG waveguide pumped by 7.7 W from a 969-nm continuous-wave VECSEL. The amplifier achieves an average output power of up to 2.9 W, corresponding to an amplification factor of 17 dB. Due to gain narrowing, the pulse duration increases to 629 fs. Our results show that crystalline waveguides are a promising technique for the realization of compact multi-watt ultrafast amplifier systems.

OCIS codes: (230.7380) Waveguides, channeled; (140.3280) Laser amplifiers; (140.4480) Optical amplifiers; (140.4050) Mode-locked lasers; (140.5960) Semiconductor lasers.

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1. Introduction

Ultrafast lasers have undergone rapid and important progress in the last decades, leading to higher output powers, shorter pulse durations and increased peak powers [1–3]. The improved performance of fiber and solid-state ultrafast lasers has revolutionized many fields in fundamental science as well as industrial applications. Ultrashort laser pulses are nowadays routinely implemented in numerous applications such as multiphoton microscopy in medicine and biology, material processing and precision metrology. Most commercial ultrafast systems rely on semiconductor saturable absorber mirrors (SESAMs) [4] for pulse formation. The simplicity and robustness of SESAM-mode locking was important for the commercial success of ultrafast sources in real world applications. Progressing to semiconductor gain materials has the potential to provide even simpler, more compact and less expensive solutions [5–7].

The most suitable semiconductor laser technology for the generation of ultrashort pulses with excellent beam quality and high power levels is based on semiconductor disk lasers (SDLs). They are also known as vertical external-cavity surface-emitting lasers (VECSELs) or optically pumped semiconductor lasers (OPSLs) [8]. The first demonstrated SESAM mode-locked VECSEL [9] was limited in output power to a few milliwatts and to 22-ps pulse duration. Since then, both output power and pulse duration have made huge progress and nowadays the average output power has surpassed 5 W in pulsed operation at sub-picosecond pulse duration [10]. However, the up-scaling of the pulse energy and peak power levels of VECSELs still remains a challenge. Today, mode-locked VECSELs in the fs-regime are limited to 5.1 W of average output power [10] or to 4.35 kW of peak power [11]. Until now, the combination of sub-100 fs pulses and watt-level average output power directly generated by a VECSEL is not achieved.

An alternative to direct power scaling of the mode-locked VECSEL is external amplification of the ultrashort pulses. With fiber amplifiers average power levels above 200 W were generated [12]. The amplified signal was employed for the generation of supercontinuum [13,14] as well as for the first carrier-envelope offset (CEO) frequency detection of a VECSEL [15]. However, the long fiber results in a relatively large footprint of the system. In order to preserve the simplicity of SDLs, an external amplification system should remain compact and easy to integrate.

Crystalline waveguide amplifiers are an attractive technology for this task. Similar to fiber amplifiers they offer high light confinement and a very good overlap between pump and laser mode. Due to an excellent thermal conductivity and high emission and absorption cross sections, multi-watt power levels have been obtained from waveguide lasers that are only few mm-long [16].

In this paper we present the first amplification of a femtosecond VECSEL using a crystalline waveguide. As gain material, we selected Ytterbium-doped $Y_3Al_5O_{12}$ (Yb:YAG), which is one of the best developed crystalline active materials for channel waveguides in terms of lasing properties, i.e. slope efficiencies and output powers [16–18]. The fabrication of low-loss YAG waveguides has been performed with different techniques such as ion implantation [19], proton beam writing [20] or femtosecond laser writing [21], which enables the direct inscription of refractive index changes in a wide range of dielectric materials. Since the first study of the influence of fs-laser radiation on dielectric material by Davis et al. in 1996 [22], fs-laser writing has shown to be a versatile and efficient method for the fabrication of various active and passive waveguiding optical devices in different materials [21]. For many laser crystals the inscription of two parallel tracks with distances in the order of 20 μm is the method of choice for single mode waveguides with small mode field diameter [23,24]. In this case the refractive index change is induced by stress resulting from the tracks and the waveguiding region is located in the center between the tracks. Recently, a novel writing scheme has been developed that adds a sinusoidal oscillation to the longitudinal translation during the inscription [25]. With this method the waveguide losses could be decreased and the stress induced by the tracks was increased. This results in a higher refractive index change and thus provides a stronger confinement of the guided modes. Typically, the gain provided by these waveguides is high enough to compensate for very high output-coupling losses and allows for laser oscillation only from the Fresnel-reflection of the waveguides end-facets. All these characteristics led to the demonstration of efficient waveguide lasers with high output powers and low laser thresholds [16,24]. Here, we reveal that such fs-written Yb:YAG waveguides are also very well suited as external amplifiers for ultrashort pulses, demonstrating a gain bandwidth large enough to support femtosecond pulse durations. We show that a femtosecond VECSEL seed source with sub-100 mW average seed power can be amplified to multi-watt output power in a compact Yb:YAG waveguide with only 8.3 mm length. Both femtosecond VECSEL and crystalline waveguide amplifier technologies can be integrated and their combination has a large potential for providing robust and compact multi-watt ultrafast gigahertz repetition rate sources for science and industry.

2. Experimental setup

2.1. SESAM mode-locked VECSEL oscillator

Our femtosecond seed oscillator is a SESAM mode-locked VECSEL prototype developed at ETH Zurich. The cavity is located in a closed housing for high stability and low noise operation. The design of the ultrafast VECSEL chip is similar to the one described in [26]. The cavity is V-shaped with the VECSEL-chip as folding mirror and the SESAM and output coupler (OC) (radius of curvature of 100 mm and transmission of 1.0% at the laser wavelength) as end mirrors. The VECSEL is pumped under an angle of 45° with a commercially available 808-nm multimode fiber coupled pump diode typically operated with 19 W of output power. Both the SESAM and the VECSEL are temperature controlled for more stable operation and for optimization of the pulse duration, operation wavelength, and output power.

The operation wavelength was adapted by tuning the temperature of the SESAM and VECSEL chips to be as close as possible to 1030 nm, the peak gain wavelength of Yb:YAG. In stable operation, the central emission wavelength of the seed laser was 1032.6 nm [Fig. 1(a)] with a pulse duration of 300 fs [Fig. 1(b)]. The radiofrequency (RF) spectrum [Fig. 1(c)] reveals stable mode locking with a repetition rate of 1.77 GHz. The average output power is 90 mW with a spectral bandwidth of 4.1 nm full width at half maximum (FWHM) and an M^2 factor of 1.05.

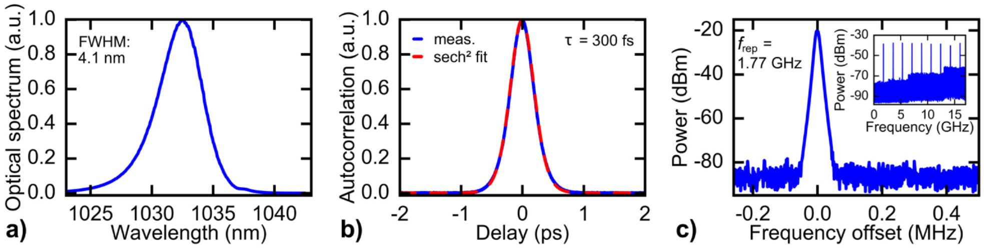

Fig. 1. Pulse characterization of the seed laser. a) Optical spectrum centered at 1032.6 nm with a FWHM of 4.1 nm. b) Autocorrelation trace (blue) and fit to the autocorrelation of sech^2 pulses (dashed red) corresponding to a pulse duration of 300 fs. c) Microwave spectrum centered at 1.77 GHz measured with a resolution band width (RBW) of 10 kHz. Inset: Wide span RF spectrum of the higher harmonics of the repetition rate measured with a RBW of 100 kHz.

2.2. Yb:YAG waveguide amplifier

The VECSEL seed beam is amplified in an 8.34 mm-long waveguide, which was fabricated by femtosecond laser inscription in a 7% Yb-doped YAG crystal. The waveguiding region is centered between two parallel tracks, separated by 29 µm. The tracks are inscribed by a linear translation with a velocity of 25 µm/s of the sample perpendicular to the incident fs-laser beam. To improve the confinement of the laser mode the translation is superimposed with a sine oscillation with an amplitude of 3.5 µm and an oscillation frequency of 70 Hz. In contrast to previous waveguides fabricated in Hamburg [16,24,27] a pinhole with 600 µm diameter was inserted in the beam path of the fs-laser to improve its beam quality by mode cleaning. Due to the large distance between the pinhole and the aspheric focusing lens (f = 3.1 mm, NA = 0.68) employed for the laser inscription, only the 0th order of the resulting diffraction pattern is transmitted through the aperture of this lens. The position of the pinhole was adjusted in such a way that the aperture of the lens was completely filled. After waveguide inscription, the output facet was wedged by approximately 24° to avoid parasitic laser oscillation due to the feedback from the Fresnel-reflections. Afterwards both end-facets were polished.

The amplification setup is shown in Fig. 2. The waveguide was longitudinally pumped by a continuous-wave (CW) VECSEL providing up to ≈ 9 W of output power at a central wavelength of 969 nm. A diode laser emitting 30 W at 814 nm was used to optically pump the CW gain chip. Seed and pump beam are combined with a dichroic mirror and are co-propagating through the waveguide. A lens with a focal length of 30 mm was used for coupling of the pump and the seed beam into the waveguide. The waveguide mode field diameter for the pump and seed wavelength is approximately 18 µm. After amplification, a dichroic mirror is used as a filter to separate the residual pump and amplified laser light and the nearly collimated beam is split with wedged glass plates. The near field of the waveguide mode is imaged on the chip of a CCD camera (WinCamD-UCD15) with a microscope objective to analyze the mode profile. Simultaneously, we recorded pulse characteristics on an autocorrelator (Femtochrome FR-103), spectral characteristics with an optical spectrum analyzer (Yokogawa AQ6370C), and used an ultrafast photodiode (New Focus Model 1014) and a radiofrequency analyzer (HP8562A) for detecting the repetition rate. The seed and pump power were measured before the focusing lens and are then corrected by the transmission of the lens (97.5%) and the Fresnel reflection losses on the crystal-air interface (8.4%) in the following. The resulting VECSEL seed power amounted to 60 mW.

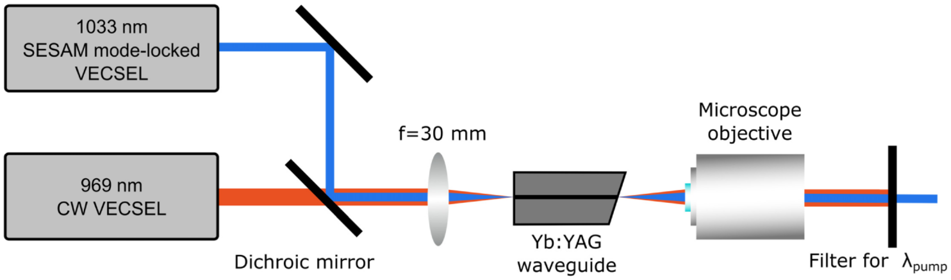

Fig. 2. Schematic setup for amplification of the mode-locked VECSEL seed beam in the wedged Yb:YAG waveguide.

As a first step, we evaluated the waveguide amplification in the CW-regime. Our seed source was a fiber coupled distributed feedback laser (Eagleyard Photonics EYP-DFB-1030-00500-1500-BFY02-0010). The laser provided a seed power of 42 mW at a wavelength of 1029.6 nm. In this configuration, the maximum amplified output power reached 4.14 W for a pump power of 7.64 W. This corresponds to an amplification factor of 99, i.e. 20 dB.

3. Results and discussion

The characteristics of the amplification of the mode-locked VECSEL are presented in Fig. 3. A maximum amplified output power of 2.89 W was achieved with a pump power of 7.68 W and a seed power of 60 mW. The corresponding amplification factor is 48 (17 dB), which is two times lower than for the CW seed source. The coupling efficiency η_c of the VECSEL was roughly estimated to 60% by measuring the transmission of the unpumped amplifier for the seed and considering the scattering losses of ≈ 0.5 dB/cm, the Fresnel reflection at both end facets as well as the small-signal absorption at 1032.6 nm. This estimation neglects bleaching effects and thus overestimates η_c, which could be as low as 40% assuming total bleaching. However, as the coupling efficiency for the CW seed should be in the same order, the lower amplification for the fs-seed beam is not only attributed to a different η_c. In addition the CW-seed laser exhibits a narrow spectrum close to the gain maximum of Yb:YAG at 1030 nm [28]. In contrast, the fs-VECSEL seed beam is centered at 1032.6 nm and broader than the gain of our Yb:YAG waveguide [see Fig. 3(b)]. Consequently, only a part of the 300-fs-seed spectrum is successfully amplified and the central wavelength is shifted to 1030.4 nm. This shift is accompanied by a narrowing of the optical bandwidth from the initial

4.1 nm of the fs-seed to 2.1 nm (FWHM) at the output, still supporting 520 fs pulses. The measured pulse duration of 629 fs thus indicates a low effect of self-phase modulation or dispersion during the amplification and the resulting time-bandwidth product of 0.381 is only slightly above the value of 0.315 for ideal sech^2-pulses [see Fig. 3(c), (d)].

A slope efficiency of 50% was achieved for pump powers below 3 W [see Fig. 3(a)]. The right axis presents the extraction efficiency, calculated as the ratio of amplified output power minus seed power to pump power. The maximum extraction efficiency is 46% at 1.3 W of amplified power and decreases to 37% at maximum output power. This decrease in efficiency results from an increase in the unabsorbed pump that reaches 1.7 W at the maximum amplification and indicates gain saturation. An improved performance can be expected by operating the amplifier in a counterpropagating scheme, improving the spatial overlap of high excitation densities and high signal intensities. The mode profile remains nearly circular even at maximum amplified output power [inset of Fig. 3(a)] as expected for fs-written waveguides [24].

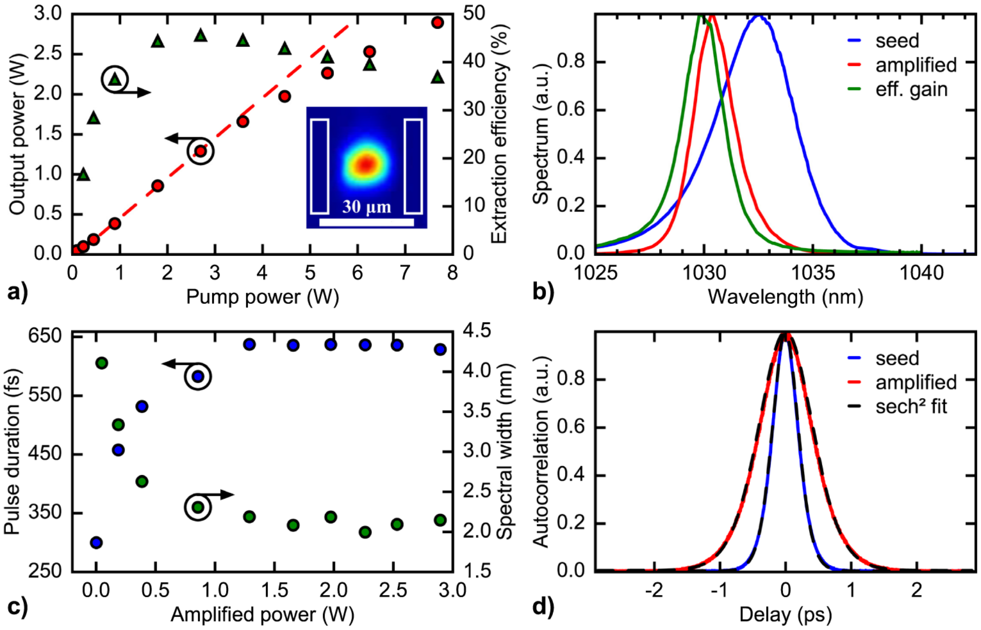

Fig. 3. Characterization of the amplified signal. a) Amplified signal power as a function of the pump power in red, slope efficiency for pump powers below 3 W (dashed red) and extraction efficiency in green. Inset: beam profile of the amplified seed with a pump power of 7.7 W. The two rectangles represent the inscribed tracks of the waveguide. b) Normalized optical spectrum of the seed in blue with a central wavelength of 1032.6 nm and FWHM of 4.1 nm, of the amplified signal in red with a central wavelength of 1030.4 nm and FWHM of 2.1 nm and the normalized effective gain spectrum of our waveguide amplifier in green (computed from the ratio between amplified and seed spectrum). c) Pulse duration in blue and spectral bandwidth in green as a function of the amplified output power. d) Autocorrelation trace before amplification in blue and with maximum amplified power in red and fit to the autocorrelation of sech^2 pulses corresponding to an amplified signal pulse duration of 629 fs.

In this proof-of-principle demonstration, the achieved amplification factor and efficiency for the fs-seed do not yet reach the values of typical Yb^{3+}-doped fiber amplifiers. As an example, the amplification of a VECSEL provides 72% of efficiency and 21 dB of amplification in a 12 m-long fiber [12], corresponding to 0.175 dB/cm. However, our waveguide amplifier is only 8.34 mm long with a corresponding gain per length of 20 dB/cm and has the potential of a very compact setup and much higher efficiency at better spectral match of seed and amplifier as well as optimized coupling efficiency.

When compared to previous experiments with a low-doped transversally single-sided pumped Yb:YAG planar waveguide amplifier, where 5 passes through a 13 mm long amplifier were necessary to obtain 12 dB of gain [29], the higher doping concentration and the better laser mode confinement in our fs-written waveguide permit an improved efficiency and amplification factor.

4. Conclusion

We have demonstrated the amplification of femtosecond pulses from a semiconductor disk laser in a crystalline waveguide. The forward-pumping amplifier configuration provided 2.89 W average output power pulses with a duration of 629 fs and a repetition rate of 1.77 GHz. This encouraging result promises an elegant way of combining the advantages of ultrafast semiconductor lasers and crystalline waveguides with respect to simplicity and integration. In this experiment, the pump power is not fully absorbed in the waveguide. As a next step, an optimization of the waveguide length, pump scheme and coupling efficiency should lead to higher amplified power. The efficiency and pulse duration are also limited by the offset between the VECSEL emission peak wavelength at 1033 nm and the waveguide gain maximum at 1030 nm. This can be improved by using a femtosecond VECSEL with a better matching center wavelength. Even shorter pulses should be supported by using gain materials with broader emission bandwidth. Particularly promising is Yb:CALGO [27], which exhibits a significantly broader spectral gain bandwidth than Yb:YAG allowing the amplification of the full VECSEL seed spectrum. Finally, an even more compact system could be realized with a mode-locked integrated external-cavity surface emitting laser (MIXSEL) [30] as seed source, which integrates the semiconductor saturable absorber and the gain chip.

Funding

Deutsche Forschungsgemeinschaft (DFG) (EXC 1074, CA 1380/1-1); Swiss National Science Foundation (SNSF) (146738); Nano-Tera.ch MIXSEL II (20NA21_145932).