EPJ Web of Conferences **41**, 10019 (2013)
DOI: 10.1051/epjconf/20134110019

Highly-efficient 1-GHz-repetition-frequency femtosecond Yb^{3+}:KY(WO_4)$_2$ laser for super-continuum generation

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Abstract. We present a 1.024-GHz-repetition-rate femtosecond Yb^{3+}:KY(WO_4)$_2$ laser with 61% optical-to-optical efficiency and 69% slope efficiency, generating a super-continuum of bandwidth 400 nm in silica photonic-crystal fibre. RIN measurements of the laser yielded values <0.1%.

1 Introduction

Efficient and robust diode-pumped femtosecond lasers with a pulse repetition frequency (PRF) exceeding 1 GHz have garnered a great amount of interest in recent years for their applicability to frequency comb systems [1]. Sources with high PRF are important because of the increased ability to resolve individual comb lines and the optical power per comb line increases proportionally with increasing PRF. Increased PRF also leads to shorter cavity lengths and the associated benefit of better robustness due to improved mechanical stability. Due to the increasing importance of laser frequency combs as components within larger systems (e.g. telescopes), practical sources exhibiting improved efficiency, compactness, and robustness are particularly timely.

Initial development in high-PRF solid-state laser sources revolved around Ti:sapphire [2], but only Yb:tungstate lasers have shown great efficiency in the GHz range [3]. In this work we report a Yb^{3+}:KY(WO_4)$_2$ (Yb:KYW) laser with a PRF of 1.024 GHz capable of generating 278 fs pulses with an optical-to-optical efficiency of 61% and a slope efficiency of 69%, motivated by the application of the laser in a simplified femtosecond optical frequency comb. To ensure that the source would be suitable for low-noise super-continuum generation we tested the relative intensity noise (RIN) characteristics of the overall system. The laser output launched into a photonic crystal fibre (PCF) displayed broadening to a spectral width of 400 nm.

2 System description

A schematic of the laser can be seen in Figure 1. The 10-at.%-doped Brewster-angled Yb:KYW crystal was 720-μm thick and orientated in the cavity for propagation along the b (N_p) axis so that the polarisation state of the intracavity beam was parallel to the N_m axis.

Two polarisation-maintaining, fibre-pigtailed laser diodes were used to pump the crystal at its absorption peak at 981 nm. The diodes were stabilised with fibre-Bragg gratings and produced average powers of 674 mW and 679 mW. The pump light was focussed to a spot radius of 17 μm ($1/e^2$ intensity) in the crystal. The resonator was designed as an asymmetric astigmatically-compensated Z-fold configuration. The two folding mirrors, M1 and M2, had a high-reflectivity

(HR) coating at wavelengths from 1020-1100 nm and a transmission of <0.06% about 1040 nm, while the transmission of all of the mirrors was >95% at the pump wavelength. The Gires-Tournois interferometer (GTI) mirror, included for dispersion management, had a double-pass group delay dispersion (GDD) of -2600 fs^2. The SESAM, used to ensure self-starting modelocking, was obtained from *BATOP GmbH*, and had a saturation fluence of 90 μJ cm^{-2}, an absorbance of 1%, and a modulation depth of 0.5%.

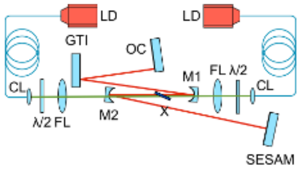

Fig. 1. Yb:KYW configuration. M1 and M2 are plano-concave HR mirrors with radii of curvature of 20 mm and 30 mm respectively. All other mirrors are plane. GTI, Gires-Tournois interferometer; FL, 30 and 40 mm pump focussing lenses; λ/2, half-wave plate; OC, 5-% output coupler; X, Yb:KYW crystal; CL, collimating lenses; LD, fibre-pigtailed laser diodes.

3 Results and discussion

An incident power of 1274 mW on the Yb:KYW crystal yielded 770 mW under stable modelocking conditions, indicating an optical-to-optical conversion efficiency of 61% and a slope efficiency of 69%, as shown in Figure 2. This was achieved by using high beam quality pump diodes, which offered excellent overlap with the tight 17 μm radius intracavity mode. The output pulses had a spectral bandwidth of 3.8 nm with a pulse duration of 278 fs (determined from a fringe-resolved interferometric autocorrelation). A radio-frequency spectrum confirmed a PRF of 1.024 GHz.

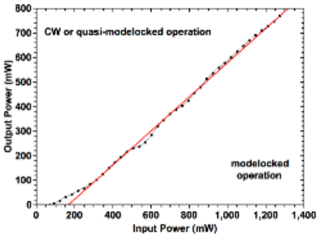

Fig. 2. Average power from the Yb:KYW laser. Modelocked operation was observed to the right of the dashed line. The line of best fit is represented by the solid line.

Due to differences in the pump sources and the upper-state lifetime of Yb:KYW, the noise characteristics were expected to differ from more common systems used for optical frequency combs. We measured the RIN of the Yb:KYW system and one of the identical diode pumps to investigate the impact of environmental noise by recording the power-spectral density of the RIN simultaneously with two silicon photodiodes using a 12-bit data acquisition card, seen in Figure 3. Below 1 kHz (i.e. an observation time of 1 ms) the Yb:KYW laser noise exceeded the pump diode RIN, while at higher frequencies the inverse was true. This is explained by the upper-state lifetime of Yb:KYW (0.3 ms), which damps any modulations faster than this timescale. As a result, modulations higher than 1 kHz are not strongly coupled into fluctuations in the Yb:KYW system. Below 1 kHz the noise of the laser exceeded that of the diodes, implying the coupling of external sources such as acoustic noise into the optomechanics of the cavity. At an observation time of 1 second we found that the RIN of the pump and the Yb:KYW lasers was similar, at <0.1%, a comparable value to Ti:sapphire laser systems [4].

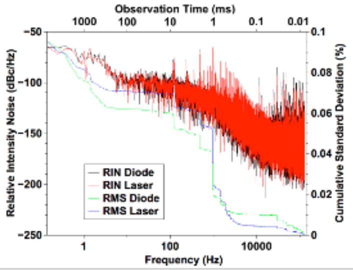

Fig. 3. RIN data and integrated root-mean-squared noise of the Yb:KYW laser for an observation time of 8 s. Lines referred to as "Diode" represent data from one of the two identical pump diodes; those referred to as "Laser" apply to the Yb:KYW output.

360 mW of the light was launched into a 3-metre photonic crystal fibre (*NKT Photonics*) to test the viability of octave-spanning super-continuum generation. Figure 4(a) illustrates how the spectrum of the Yb:KYW laser was broadened by ~400 nm, and Figure 4(b) presents a simulation of the experimental conditions. The super-continuum is characterised by the presence of multiple soliton generation, as expected for the pulse durations used. Pre-compression prior to launching the pulses into the PCF is expected to provide a greater bandwidth dominated by first-order soliton generation.

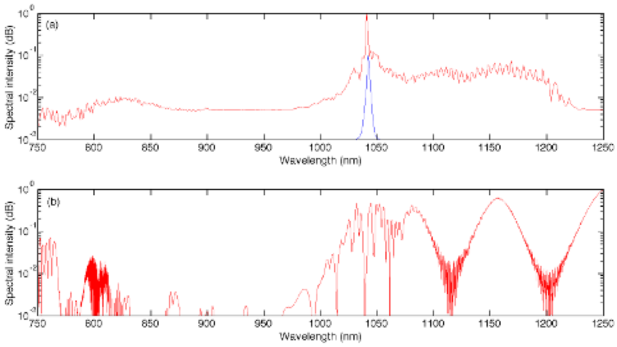

Fig. 4. (a) The spectra of the laser both before and after the PCF; (b) Modelled output of spectrum assuming 360 mW passing through a 3 m length of fibre with an initial pulse duration of 280 fs.

4 Conclusions

The highly efficient sub-300 fs pulse generation at a PRF of over 1 GHz provides an excellent laser source for femtosecond optical frequency comb systems, especially when taken in tandem with the laser's low noise and high efficiency. Preliminary spectral broadening results presented here show the potential of the system to achieve a super-continuum bandwidth sufficient for f-2f or 2f-3f carrier-envelope-offset stabilisation.

References

1. S.A. Diddams, J. Opt. Soc. Am. B **27**, B51-B62 (2010)
2. T.M. Fortier, A. Bartels, S.A. Diddams, Opt. Lett. **31**, 1011-1013 (2006)
3. S. Pekarek, C. Fiebig, M. Stumpf, A. Oehler, K. Paschke, G. Erbert, T Südmeyer, U. Keller, Opt. Express **18**, 16320-16326 (2010)
4. T. Ferreiro, J. Sun, D.T. Reid, Opt. Lett. **35**, 1668-1670 (2010)