Compact extreme ultraviolet source at megahertz pulse repetition rate with a low-noise ultrafast thin-disk laser oscillator: supplementary material

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This document provides supplementary information to “Compact extreme ultraviolet source at megahertz pulse repetition rate with a low-noise ultrafast thin-disk laser oscillator”, <http://dx.doi.org/10.1364/optica.2.000980>. We first describe in detail all the references used in the overview of the state-of-the-art of XUV sources with repetition rates > 100 kHz. In a second part, more details on the infrared laser source and compression set-up used in this work are given. © 2015 Optical Society of America

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1. Overview of XUV sources at high repetition rate

The photon energy and the reference of each point of the graph presented in Fig. 1 can be found in Fig. S1.

Fig. S1. Overview of the state-of-the-art of XUV sources with repetition rates > 100 kHz with the related reference and photon energy. The generated power on the strongest harmonic order is plotted versus the repetition rate of the source. Distinction can be made between intracavity generation, indicated by ▲ (within an enhancement cavity [1-6] or within a laser resonator [7]), and extracavity generation consisting of a single-pass into a gas jet, indicated by ■ [8-14]. In both cases, experiments can be driven by complex multi-stage amplifier systems (in blue) or with simple and compact laser oscillators (in red).

The photon energy of the associated strongest generated harmonics is indicated on the graph. The result presented in this letter is highlighted in red and represents the highest XUV power generated directly from an oscillator, opening the way towards compact XUV sources in the near future.

2. Laser driving source and compression

Figure S2 shows the set-up of the SESAM-modelocked diode-pumped Yb:YAG thin-disk laser oscillator and the single-pass Kagome hollow-core PCF compression stage. The laser cavity was built in a vacuum chamber operating at ≈ 100 mbar of Helium. Operating in a medium pressure Helium environment is beneficial to reduce the nonlinearity of the intracavity atmosphere in order to achieve stable soliton modelocking at high energy [15], but also relaxes thermal load on intracavity components compared to using lower air pressure. The use of a Herriott-type multipass cell (MPC) cavity extension inside the oscillator allowed us to reach an oscillator length of 63 m in a compact layout [16] (corresponding to a repetition rate of 2.4 MHz), while stable modelocking was started and stabilized by a high damage threshold SESAM [17] used as an end mirror in the laser cavity. Dispersive mirrors provided a total negative dispersion per roundtrip of $\approx 36\,000$ fs² to compensate for the nonlinear phase-shift of 150 mrad within the cavity and achieve soliton pulse formation [18]. In this configuration, we achieved up to 70 W of average power with reliable daily operation. The pulses had a duration of 870 fs at a repetition rate of 2.4 MHz, corresponding to a pulse energy of 29 μ J

and a peak power of 29 MW, and operated at a center wavelength of 1030 nm.

The compression set-up was similar as in Ref. [19]. The fiber was a 7-cell 3-ring hypocycloid-core Kagome-type HC-PCF with a mode-field diameter of $\approx 30 \mu\text{m}$ and an extremely low loss figure of 180 dB/km at 1030 nm. The 67-cm fiber was embedded in water-cooled gas cells in which 5 bar of Krypton were statically applied in order to generate sufficient spectral broadening in the anomalous dispersion regime with only $-5.4 \text{ fs}^2/\text{cm}$. At full launched power of 70 W, the spectrum was broadened from its initial 1.2 nm FWHM to more than 28 nm FWHM (see Fig. S2b). Using 22 bounces on dispersive mirrors, accounting for a total dispersion of $-12\,000 \text{ fs}^2$, the input pulses of 870 fs duration were compressed to a FWHM of 108 fs (Fig. S2c). Taking into account the pulse profile in the time domain, we estimate a percentage of 60% of the energy to be located in the main compressed peak, leading to an enhanced peak power of 105 MW for an average compressed power of 46 W.

Fig. S2. Laser and nonlinear compression set-up used in our experiments. a) The Yb:YAG SESAM-mode-locked thin-disk laser was set up to deliver 70 W with 870 fs pulse duration at 2.4 MHz repetition rate, i.e., 29 μJ of pulse energy [15]. Subsequently, nonlinear pulse compression using a 67 cm long Kagome fiber with a mode-field diameter of $30 \mu\text{m}$, filled statically with 5 bar of Krypton, leads to compressed pulse (b and c) reaching 108 fs with 60% of energy in the main peak, corresponding to 105 MW of peak power [19].

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