

Tunable 30-fs light pulses at 1-W power level from an Yb-pumped optical parametric oscillator

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We report on an Yb-pumped optical parametric oscillator (OPO) that delivers 30-fs pulses with spectral coverage from 680 to 910 nm and an average output power up to 1.1 W. The resulting peak power is ~0.5 MW, which is, to the best of our knowledge, the highest ever demonstrated in a femtosecond OPO. The intensity noise remains at a level of 0.2 % rms and rapid wavelength tuning is obtained by simply scanning the resonator length. The performances of the OPO are promising for a variety of applications in nonlinear microscopy and ultrafast spectroscopy. © 2017 Optical Society of America

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The generation of broadly tunable ultrashort light pulses is one of the frontiers of ultrafast optics, with applications that range from ultrafast spectroscopy [1] to biomedical imaging [2], from precision metrology [3] to high-field science [4]. Ti:sapphire lasers can generate femtosecond pulses tunable in the 680-1040 nm region and with duration down to 4 fs [5]; however, due to the short excited state lifetime of the gain medium, they typically require green pump lasers, which make their optical setup complex and expensive. In addition, the power scalability of Ti:sapphire lasers is limited, with maximum output power of the order of 3-4 W. Yb-based gain media, on the other hand, have long excited state lifetimes, which allow direct laser diode pumping, and low quantum defect, enabling the extraction of very high average powers with limited heat deposition and thermal loading. Yb-based femtosecond oscillators, both in bulk and fiber format, are compact, rugged and low-cost laser

sources, which are revolutionizing ultrafast laser technology and generating unprecedented levels of average and peak power [6, 7]. However, due to their narrow gain bandwidths, Yb-doped gain media suffer from two major drawbacks: (i) they produce comparatively longer pulses, with transform-limited (TL) durations of the order of 100-300 fs; (ii) their central wavelength is virtually untunable, peaking around 1040 nm.

Frequency tunability of ultrashort pulses can be achieved exploiting parametric second-order nonlinear processes [8], in which energy is transferred from a high intensity and high frequency beam (the pump), to a lower intensity and lower frequency beam (the signal), thereby generating a third beam (the idler) to fulfill energy conservation. Besides providing frequency tunability, parametric processes can achieve a very broad gain bandwidth, by a properly designed phase-matching configuration with group velocity matching between signal and idler waves [9]. In this way, one obtains a broadband optical amplifier based on virtual transitions, which is able to transfer power from a narrowband pump to a broadband signal pulse. This property is especially important in combination with Yb-based laser systems, since it allows to considerably shorten their pulse duration and to overcome their limited gain bandwidth.

Broadband phase matching has been extensively exploited in travelling-wave optical parametric amplifiers (OPAs), which amplify a seed pulse, typically obtained by self-phase-modulation, in one or multiple stages. A wide range of ultra-broadband OPAs, generating few-optical-cycle pulses across the visible and infrared ranges, has been designed and experimentally demonstrated, with numerous scientific applications [10]. However, implementing OPAs starting from mode-locked oscillators is not trivial, due to the difficulty of generating a broadband coherent seed from low-energy, high repetition rate pulses [11]. This limitation is circumvented in optical parametric oscillators (OPOs), where the nonlinear crystal is enclosed in a resonant cavity and parametric amplification repeats itself at each cavity round-trip, eventually leading to the formation of a stationary broadband signal pulse train out of quantum noise. OPOs are strictly analogous to laser

oscillators and, as such, they offer the advantage of a very high repetition rate. Remarkably, much less activity has been devoted to the development of broadband OPOs as compared to OPAs; this is due to the added complication that, like in a laser oscillator, the bandwidth of the pulses produced by an OPO depends not only on the available gain bandwidth, but also on the pulse formation dynamics, which is ruled by intra-cavity dispersion. Using a Ti:sapphire pump laser, already in 1995, Cavallari *et al.* managed to generate pulses with duration down to 15 fs and average power <100 mW using a second-harmonic (SH) pumped non-collinear OPO (NOPO) [12, 13], but a similar performance level has never been replicated since then. Using collinear phase-matching, Hebling *et al.* generated 34 fs pulses with 50-mW average power at 1200 nm from a KTP-based OPO pumped by the fundamental wavelength of Ti:sapphire [14]. On the other hand, Yb-pumped OPOs have so far generated comparably longer pulses. Lang *et al.* [15] reported on a β -barium borate (BBO)-based NOPO pumped by the SH of a 22-W thin-disk Yb: KLu(WO₄)₂ oscillator, delivering >3W average power in pulses that were not compressed but with a potential TL duration of 70-80 fs. More recent studies reported on a 0.3-W LiB₃O₅(LBO)-based OPO delivering ~150-fs-long pulses [16] and, more recently, a 1-W BiB₃O₆-based OPO with near-TL duration as short as 71 fs [17].

In this paper we demonstrate the generation of broadly tunable 30-fs pulses from an Yb-pumped OPO. The system is pumped at 520 nm and uses BBO as a nonlinear crystal in a linear prismless cavity. It produces a highly stable output power of about 1 W with a 0.2 % rms intensity noise and a spectrum tunable in the 680-910 nm wavelength range. Pulses are extra-cavity compressed and fully characterized with a ~30 fs duration, resulting in a state-of-the-art peak power level of ~0.5 MW.

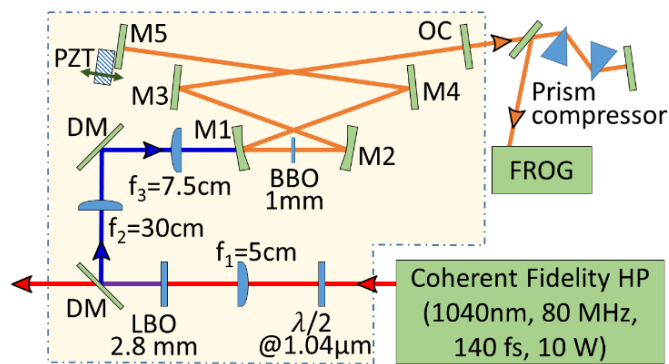


Fig. 1. Optical lay-out of the OPO. HWP: half-wave plate at 1040 nm. DM: dichroic mirror with high reflectivity at 520 nm and high transmission at 1040 nm; PZT: piezotransducer.

Figure 1 shows a sketch of the experimental setup. It starts from a commercial femtosecond fiber-based Yb-fiber laser (Coherent Fidelity HP) producing pulses with 80-MHz repetition rate, 140-fs duration and up to 10 W average power at 1040 nm. The laser output is frequency doubled in a LBO crystal (2.8-mm thickness, type-I phase matching, $\theta = 13.8^\circ$), anti-reflection (AR) coated at 520 and 1040 nm, to generate the 520-nm pulses needed to pump the OPO. As it is shown in Fig. 2(a), an increase of the pump diode current of the Yb laser results in an almost linear increase of the SH generation efficiency, till a value of about 68 % that corresponds to a SH power of 6 W in typical operating conditions. The SH spectrum,

displayed in the inset of Fig. 2(b), has a width of 4 nm, which corresponds to a 100-fs TL pulse duration. The green pump beam, which displays excellent spatial quality due to the low spatial walk-off angle of LBO, is focused inside the 1-mm-thick BBO crystal used as a parametric gain medium with a spot-size diameter of ~17 μm , closely matching the 15- μm OPO resonator mode. The BBO crystal is cut for type-I phase matching ($\theta = 22.7^\circ$) and has AR coating in the 750-950 nm range. The OPO employs a linear cavity with X-type folding, which includes a pair of spherical mirrors with a radius of curvature of 75 mm in the BBO arm of the cavity (M1 and M2), a pair of flat folding mirrors (M3 and M4), a metallic end mirror (M5) and an output coupler (OC) with 5 % transmission. Mirror M5 is mounted on a piezotranslator for fine tuning of the cavity length. Mirrors M1 and M2 have AR coatings at 532 nm, and high reflectivity (HR, reflectivity > 99.8%) coatings in the 700-900 nm range, thus effectively limiting the tuning range of the OPO. Their group delay dispersion (GDD) is nearly zero, whereas mirrors M3 and M4 have HR chirped coatings (mirror pair with compensation of the GDD oscillations), each introducing an average GDD of $-50 \pm 20 \text{ fs}^2$ (650-1000 nm). The OC has a GDD of $+120 \pm 50 \text{ fs}^2$ in the 700-900 nm range, and a substrate thickness of 1 mm, which is beneficial to avoid excessive dispersion of the out-coupled pulses that would result from thicker substrates. The GDD of the metallic mirror M5 is negligible. Finally, the BBO crystal introduces a positive GDD of $+36 \text{ fs}^2$. The overall average GDD of the OPO cavity is therefore positive; however, precise evaluation of the cavity dispersion profile reveals the presence of residual wavelength-dependent ripples, mainly ascribed to the higher order dispersion of the chirped mirror pair M3 and M4 and of the OC.

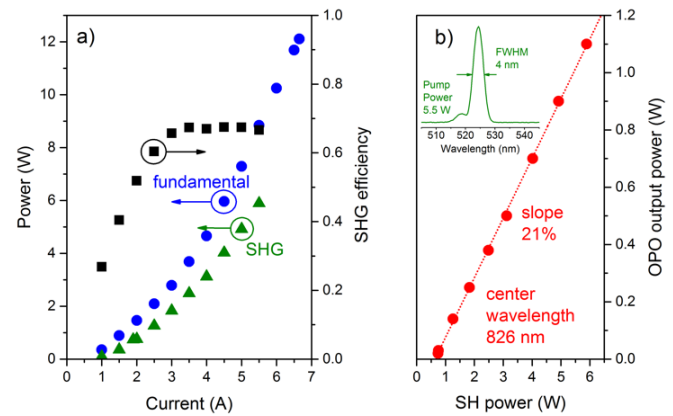


Fig. 2. (a) Yb laser output power (blue circles), second harmonic (SH) power after the LBO crystal (green triangles) and corresponding second-harmonic-generation efficiency (black squares) as a function of the pump diode current of the Yb laser. (c) Power scaling of the OPO output as a function of the input pump power. The inset shows the 4-nm-wide optical spectrum of the pump pulses.

The BBO crystal, thanks to a thickness of only 1 mm and to a favorably low group-velocity mismatch between signal and idler (20-60 fs/mm, depending on the wavelength), exhibits a broad parametric gain bandwidth without the need to recur to non-collinear phase-matching. At the calculated pumping fluence of > 100 GW/cm² [9], in the long-wavelength part of the tuning range towards 900 nm, i.e. close to degeneracy, the bandwidth exceeds 50 THz, which corresponds to a virtual transform-limited duration below 10 fs. The effective

oscillation bandwidth was actually kept below such a maximum value by operating the cavity in a slightly positive dispersion regime, which resulted to be highly beneficial for the OPO stability. Notwithstanding the small BBO thickness, the parametric gain is remarkably high because the group-delay mismatch between pump and signal/idler pulses remains below 100 fs in the whole tuning range, i.e. within the envelope of the 100-fs-long pump pulses.

Figure 2(b) reports the OPO output power at a signal wavelength around 830 nm as a function of the pump power. The curve is highly linear with a threshold at only 700 mW, which is comparable to [16] or even better than [15] threshold values reported for 2- and 2.5-mm-long BBO crystals. This is the consequence of a highly circular pump beam delivered by the fiber-based Yb oscillator and of a carefully optimized spatial overlap between pump and signal beams in the nonlinear crystal. Another benefit comes from the nearly perfect matching between pump pulse duration and group-delay-mismatch between pump and signal/idler pulses (100 fs, see above), which ensures simultaneously high pump intensity and an exponential parametric gain along the entire crystal length. Figure 3(a) shows the OPO output power as a function of wavelength, with values around 1 W and a slight decrease approaching the blue edge of the tuning range. The spatial mode of the OPO, reported in the inset of Fig. 3(c), is also remarkably round.

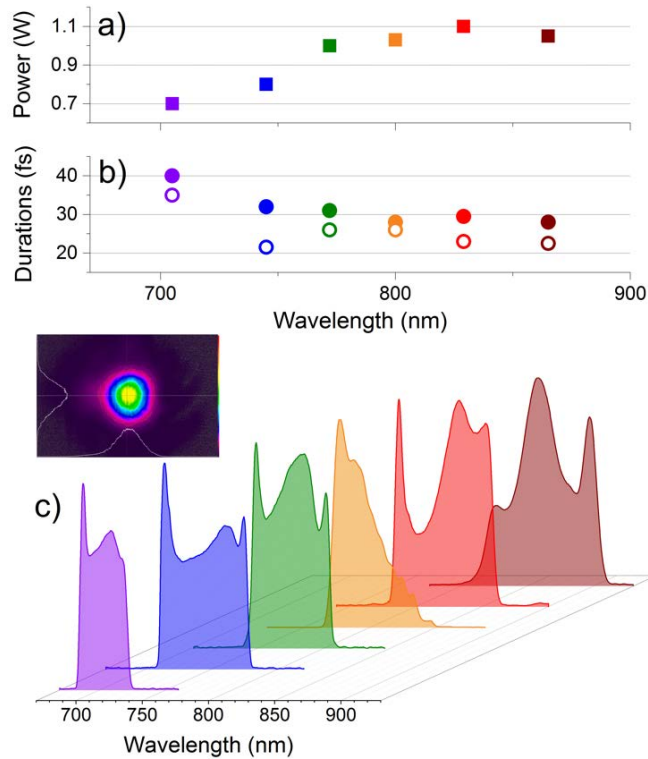


Fig. 3. (a) Output power of the OPO as a function of central wavelength. (b) Calculated TL pulse durations (empty circles) and corresponding experimentally determined durations (filled circles) as a function of central wavelength. (c) Optical spectra of signal pulses while detuning the cavity length, showing tunability from 680 to 910 nm. Inset: spatial beam profile of the OPO output.

Figure 3(c) reports the OPO output spectra obtained by step-tuning the cavity length, without any adjustment of the

BBO phase-matching angle, with a 10-millisecond switching time (given by the piezo-electric transducer acting on mirror M5). Remarkably, thanks to the broad parametric gain bandwidth, the spectra entirely cover the 680-910 nm range and, except for the shortest signal wavelength around 700 nm, they all support a sub-30 fs TL duration (empty circles in Fig. 3(b)).

The spectral shape reveals the typical steep edges due to a net positive intra-cavity GDD, whereas the presence of spectral peaks close to the edges is ascribed to residual GDD ripples [18]. The OPO pulses are sent to an extra-cavity compressor, which compensates for the residual intra-cavity GDD and for the dispersion introduced by the substrate of the output coupler. The compressor consists of a double pass in a pair of Brewster-cut LaFN28 prisms at a distance of 36 cm. LaFN28 was chosen because of its combination of high GDD, allowing for a compact footprint, and low third-order dispersion, which minimizes the uncompensated spectral phase [19]. The compressed pulses are characterized by second-harmonic generation frequency-resolved optical gating (SHG-FROG) [20] employing a 10- μm -thick BBO crystal. Figures 4(a) and 4(b) show the experimental and retrieved SHG-FROG maps for the pulses centered at 800 nm, while Figures 4(c) and 4(d) report the retrieved temporal and spectral intensity and phase profiles (rms retrieval error 0.68%). The measured 28.2-fs pulsewidth is very close to the TL value (26 fs), demonstrating nearly perfect correction of the spectral phase, as also shown in Fig. 4(d). Similar pulsewidths of the order of 30 fs were retrieved across most part of the OPO tuning range (see filled circles in Fig. 3(b)), with the longer 40-fs pulses measured around 700 nm attributed to a bandwidth limitation induced by the cutoff of the cavity mirrors reflectivity. These are the second shortest pulses ever demonstrated at the output of an OPO, and the shortest obtained in a collinear phase-matching configuration and from an Yb-pumped OPO. Remarkably – see Fig. 3(a) – such short pulse durations are combined with an average optical power in excess of 1 W, which translates in a nearly 0.5-MW peak power.

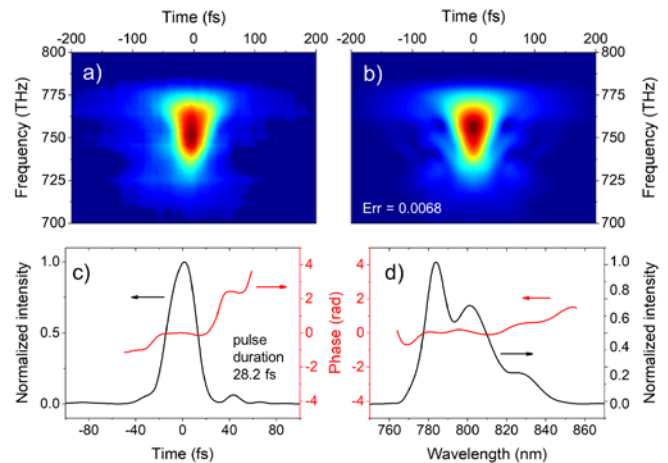


Fig. 4. SHG-FROG measurement of the OPO pulses at a signal wavelength around 800 nm. (a) measured FROG trace; (b) retrieved FROG trace; (c) intensity and phase profile as a function of time; (d) intensity and phase profile as a function of the wavelength.

To complete the OPO characterization, we measured its intensity noise, which is a particularly relevant parameter for

applications. The measurements were done by keeping the OPO within a plastic enclosure to minimize environmental noise. In these conditions the OPO output power remains highly stable, with rms noise level (see Fig. 5(a)) of 2×10^{-3} , which is in excellent agreement with the noise specifications of the Yb-laser source. This is confirmed in Fig. 5(b), where the relative-intensity-noise (RIN) spectrum of the OPO (red), measured with an electronic spectrum analyzer, is compared to that of the green pump pulse train (green) obtained after SH generation of the Yb-source. The two traces closely resemble each other over the whole range, apart from the Fourier frequencies above 4 MHz, where the OPO has lower amplitude noise than the SH pump, ascribed to the filtering action of the OPO cavity.

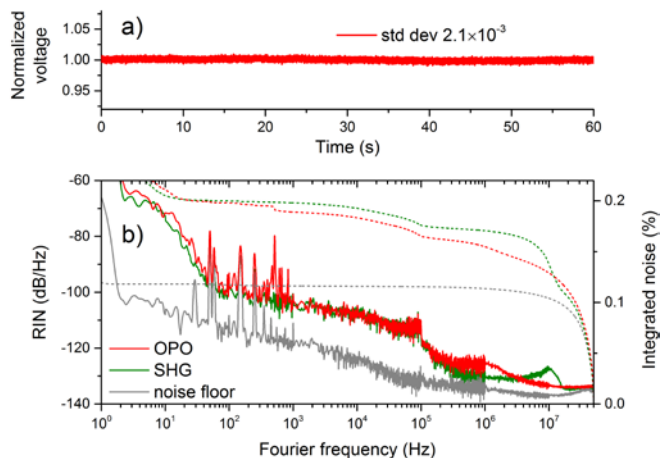


Fig. 5. (a) Temporal trace of the OPO output power, showing a normalized rms deviation of 2.1 parts over 10^3 . (b) Solid lines: relative intensity noise (RIN) spectrum of the OPO (red trace), of the green pump pulse train (green trace) and of the detector noise floor (grey). Dashed lined represents the integrated intensity noise from the Nyquist frequency (40 MHz) down to 10 Hz.

A satisfactorily low minimum noise value of -135 dBc/Hz occurs at the 40-MHz Nyquist frequency: it is nearly 15 dB above the shot-noise-limit but, in this respect, the OPO is somehow limited by the well-known relatively high noise floor of fiber-based oscillators [21]. This low noise figure is especially important for nonlinear spectroscopy applications, which often require the measurement of very low differential signals.

In conclusions, we have presented a femtosecond OPO with tunability from 680 to 910 nm pumped by a frequency-doubled fiber-based Yb oscillator. The OPO operates with a linear cavity and in a collinear phase-matching regime with a thin 1-mm-long BBO crystal. Among competing alternatives, the proposed OPO stands out due to a unique combination of average output power, which is in excess of 1 W in most part of the tuning range, short pulse duration, which has been measured at the 30-fs level above 740 nm, and low intensity noise, down to 2×10^{-3} rms, which is the lowest value demonstrated so far for a sub-100-fs OPO. This makes the system of major interest for a number of applications, among which nonlinear microscopy, ultrafast pump-probe spectroscopy at very high signal-to-noise ratio and also label-free broadband Stimulated-Raman-Scattering microscopy [22].

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