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Ultrabroadband OPA in YCOB with a sub-ps Pump Source

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Abstract: We demonstrate the broadband optical parametric amplification of near-infrared laser pulses using a single yttrium calcium oxyborate (YCOB) crystal pumped in a noncollinear geometry by a sub-picosecond, milijoule-level source. The crystal uses an optimized orientation for phase matching outside of the principal planes, enabling ultrabroadband amplification (gain of ∼800) in the range of 750–950 nm and supporting down to 7 fs pulses.

Keywords: laser amplification; ultrashort pulses; parametric amplification; nonlinear materials

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1. Introduction

Over the last decade, there has been a growing interest in the applications enabled by high peak and high average power laser sources, in particular in the strong-field physics community. Progress in diode-pumped solid state sources coupled to nonlinear amplifiers based on optical parametric chirped pulse amplification (OPCPA) has enabled the development of state-of-the-art sources in the near- and mid-infrared spectral regions [1]. The OPCPA technique employs nonlinear crystals to mediate the energy transfer from a more readily available, long-pulse laser (the pump) into an ultrabroadband pulse (the signal), temporally stretched to match the pump duration, which can then be compressed to an ultrashort duration. The nature of parametric amplification allows overcoming the gain narrowing associated with inversion-based optical gain, while also allowing a tunable output. Driven by highly efficient and energetic diode-pumped, ytterbium-based sources, OPCPA has led to a new generation of advanced, high repetition rate ultrashort pulse systems [2].

Despite its huge potential for high-energy ultrashort pulse generation, the OPCPA technique still has intrinsic limits on the amplified bandwidth, maximum amplified energy and average power. These depend both on the properties of the nonlinear medium used and on the design, geometry and implementation of the amplifier.

Concerning the nonlinear medium, yttrium calcium oxyborate (YCOB) is a member of the borate crystal family that has attracted attention in recent years thanks to its excellent nonlinear properties, such as an effective nonlinear coefficient ($d_{\text{eff}} \geq 1.0$ pm/V) comparable to that of β-barium borate (BBO), high laser-induced damage threshold (25 GW/cm^2 @ 75 ps, ∼2.2 TW/cm^2 @ 100 fs pulse durations) and large growth capability (102 × 100 mm^2 aperture). This great potential for ultrabroadband amplification up to the kJ level makes YCOB a leading candidate for high repetition rate petawatt systems [3–6]. Typically used in a type I configuration for maximum nonlinear coefficient, YCOB has also been used for parametric amplification in type II operation [7] and even in quasi-phase matching (QPM) regimes [8]. Its broadband operation has also allowed its use as a down-conversion crystal to generate mid-infrared pulses driven by Yb-based laser systems [9].

Although the opto-electrical properties of YCOB compare favourably with competing media [10,11], the recognition of its potential was slow [12–14], partially motivated by issues with photodarkening. The crystal has been shown to exhibit the required qualities for joule-level [6], few-fs amplification based in OPCPA and has the potential to become an efficient alternative to current options such as BBO, lithium triborate (LBO) or (deuterated) potassium dihydrogen phosphate ((D)KDP) for high peak and high average power amplification [15,16]. More recently, the front end of a 5 PW LBO-based laser project [17] was used to test the high-energy scaling of YCOB amplification, yielding 20 fs pulses [18].

In the near-infrared range, YCOB has been shown to allow for ultrashort pulses in a nanosecond pumping scheme and with working angles along the principal plane of operation [18,19]. In fact, the use of operating angles outside the principal planes leads to a 40% higher nonlinear coefficient ($d_{\text{eff}}{\sim}1.4$ pm/V) [20], enabling a shorter crystal which, coupled with the use of an optimum noncollinear angle, allows for the broadest amplified bandwidth and shortest supported pulse duration. The nanosecond pumping scheme is well adapted for large high-power, low repetition rate (1–10 Hz, PW-level) laser facilities, where the larger stretching factor enables the use of well-established narrowband Nd-doped solid-state lasers to provide kJ pumping energies. However, for applications demanding kHz repetition rates and high average powers, such as for low cross-section studies, the use of a ps-level pump is more adequate.

In this work, we demonstrate for the first time a ps-pumped, optimized geometry YCOB-based OPA system. In our approach, the ultrashort seed for amplification is derived from the super-continuum generation of a portion of the pump beam, dispensing the requirement of an ultrashort oscillator, while ensuring jitter-free optical synchronization. The intrinsic chirp of the signal beam is ensured by a self-phase modulation (SPM) dominated supercontinuum generation process. The smaller stretch ratio of the amplified pulses allows for a smaller footprint prism compressor, resulting in an overall more compact approach.

2. Experimental Setup

Figure 1 shows the layout of the OPA system. A Ti:sapphire, Kerr-lens mode-locked oscillator (Coherent Mira 900F) delivers 4 nJ, 1030 nm, 76 MHz pulses with 150 fs duration (20 nm FWHM bandwidth), which go through a high-contrast pulse picker operating at 160 Hz, to match the top repetition rate of the pump laser. This is followed by a double-pass Offner grating stretcher providing a stretching factor of 47 ps/nm delivering ∼1 ns pulses. The stretched pulses are then sent to a diode-pumped Yb:CaF_2 regenerative amplifier delivering 2.25 mJ pulses at 160 Hz. About 76% of this pulse energy (1.7 mJ) is sent through a grating compressor which delivers ∼700 fs, 1.2 mJ pulses [21]. Both the pump and signal pulses used to drive the OPA are derived from these compressed pulses, by splitting them in a controlled fashion via a wave-plate coupled with a polarizer. Most of the pulse energy (0.8 mJ) is frequency doubled in a 1 mm thick BBO crystal with an efficiency conversion of 37.5%, delivering pump energy of 0.3 mJ at 515 nm to pump a single-stage ultrabroadband OPA based on YCOB. The remaining fraction of the compressed regenerative amplifier output is focused on a 4 mm thick sapphire plate, yielding a broadband white light continuum. This continuum is spectrally filtered (bandpass filter) to transmit only the 625–1000 nm spectral range (a separate region below 575 nm is also transmitted), see Figure 2, in order to remove the unconverted 1030 nm portion of the original spectrum, and seeds the OPA stage. An estimated ∼5 nJ is available after filtering, corresponding to a 1.25% efficiency. From previous measurements, roughly half of this energy spectrally corresponds to the amplifiable bandwidth, with ∼2.5 nJ being the seed energy for the amplifier.

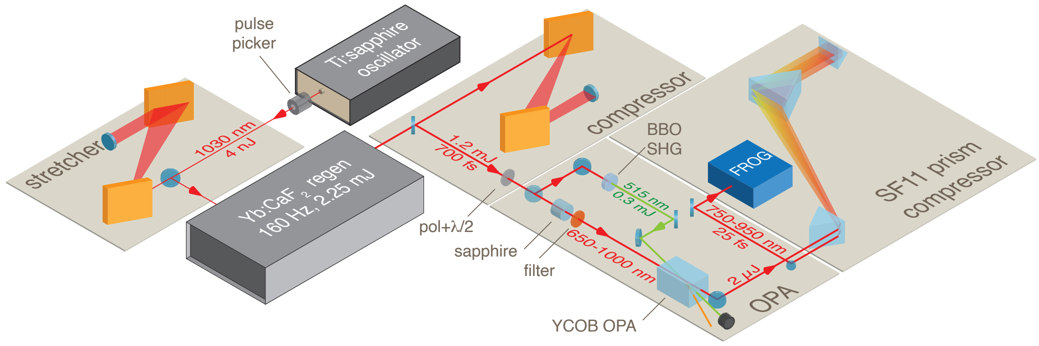


Figure 1. Schematic of the sub-picosecond pumped OPA experimental setup. pol+$\lambda/2$: half-wave plate and polarizer set; sapphire: supercontinuum generation stage; BBO SHG: second-harmonic generation stage; YCOB OPA: nonlinear amplification crystal; FROG: frequency-resolved optical gating diagnostic.

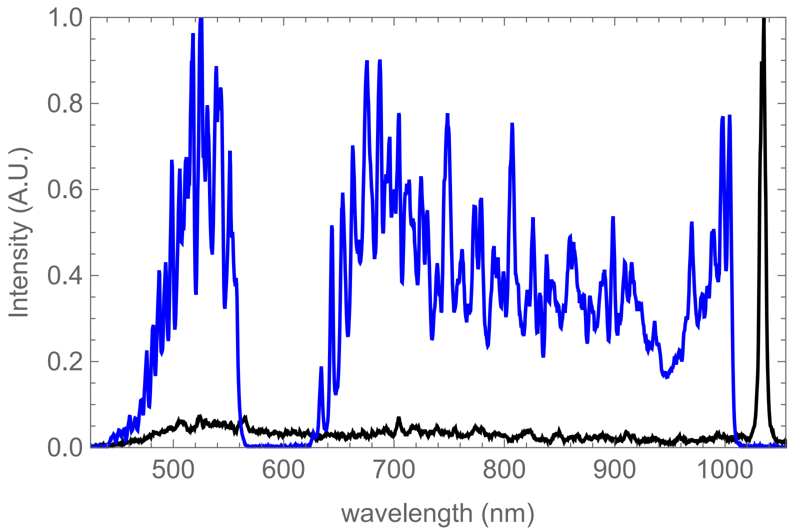


Figure 2. White-light continuum spectrum before (black) and after (blue) spectral filtering. The vertical scale is normalized separately for each measurement.

The nonlinear crystal is a 0.7 mm thick YCOB cut to operate outside of the principal planes and in a noncollinear geometry optimized for maximum aplified bandwidth at the central portion (i.e., 800–900 nm) of the available spectrum (θ_{NC} = 3.75°, θ = 65° and $\phi \approx 150°$ as in [20]). Different spectral ranges could be amplified (at 700 nm, for example, or closer to degeneracy ∼950 nm) by changing the crystal angles (and adjusting the noncollinear angle) in a manner similar to described in [20]. The pump and signal beams are imaged and focused with approximately the same diameter (∼300 µm FWHM) onto this crystal, corresponding to a pumping intensity of ∼400 GW/cm^2. Pulse synchronization and output optimization are ensured by an adjustable delay line on the pump beam optical path.

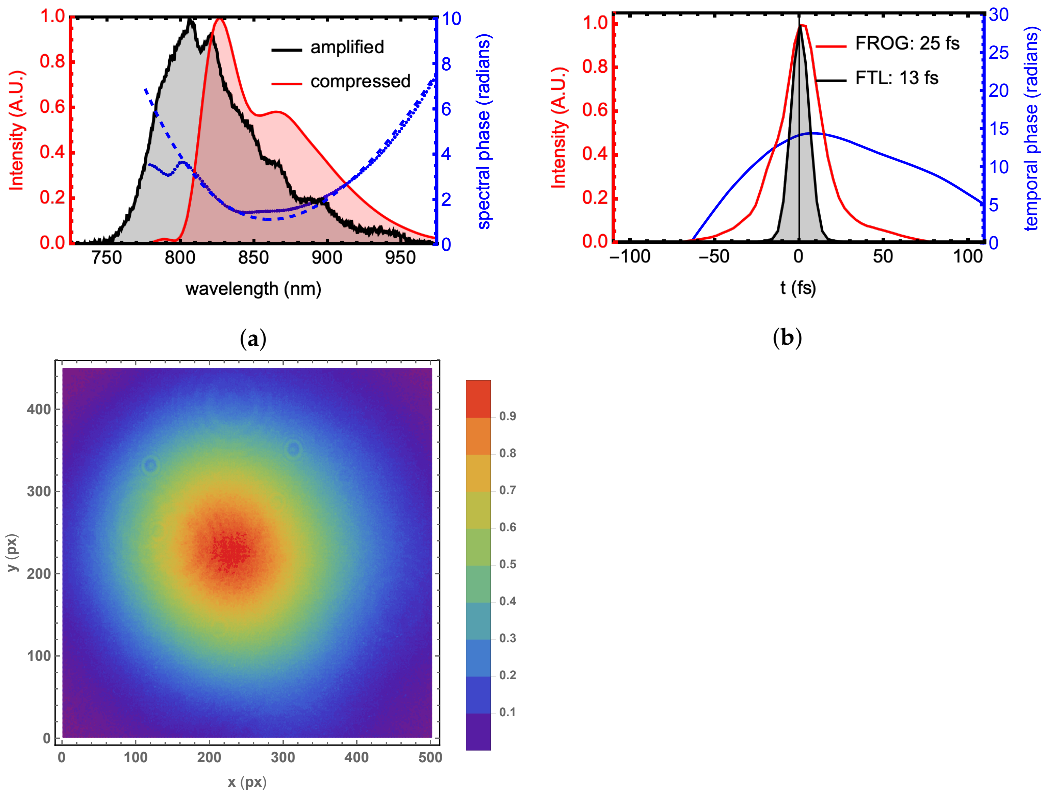
3. Results and Discussion

The amplified pulses have an energy of 2 µJ and a bandwidth of 70 nm FWHM (spanning from 750 to 950 nm) at a central wavelength of 815 nm, measured with a fiber-coupled array spectrometer (Figure 3a). The temporal duration of the OPA pulses was measured to be about a third of the pump pulse duration (FWHM) before compression using an SHG FROG.

It is worthwhile noting that the amplified spectral region is broad enough to support ∼7 fs pulses, the broadest to our knowledge using YCOB in the high gain regime, clearly demonstrating that the use of a ps pump pulse coupled with the outside of principal plane operation maximizes ultrashort pulse amplification with YCOB crystals to scale sub 10 fs pulses to high energies.

For the case of our pulse, the spectrum at the compressor exit was measured and corresponds to a calculated Fourier transform-limited (FTL) duration of 13 fs. This spectrum is comparable to the previously simulated amplified spectral range for a comparable pulse duration of 500 ps (with gain in the 750–875 nm region: see [20]), however, since the operation is in the high gain regime and does not reach saturation, the spectral shape also does not have a supergaussian/flat top profile.

In order to test the temporal quality of the amplified signal, we designed and implemented a straightforward two-prism, double-pass compressor, consisting of two SF11 (group velocity dispersion: 187.5 fs^2/mm at 800 nm) prisms with a 52.5 cm separation. The compressed pulses were characterized with a scanning second harmonic frequency-resolved optical gating (SHG-FROG) device, resulting in an optimized compressed pulse width of 25 fs FWHM, almost 30 times shorter than the input 700 fs pulses. The retrieved traces of the compressed pulses are shown in Figure 3, alongside the spectrum at the compressor input. The ptychographic [22] retrieval algorithm was used. The output beam retains a Gaussian-like spatial profile, as shown in Figure 3c (measured after 15 cm of free propagation after the compressor output).



(c)

Figure 3. Compressed pulse FROG retrieval: (**a**) retrieved spectral intensity, phase and quadratic phase fit (red, solid blue and dashed blue, respectively), and spectrum measured at compressor input (black); (**b**) retrieved temporal intensity and phase (red and blue, respectively), and corresponding Fourier Transform limit duration (black); (**c**) Compressed beam spatial profile.

In the nanosecond pumping regime and in the same spectral range YCOB was used to amplify laser pulses to the ∼100 mJ range and compress them down to 20 fs [18]. Following a similar strategy in the picosecond pumping regime to amplify these pulses to the multi-mJ range, together with further compression optimization (using grisms or tailored chirped mirrors), will allow for compact sub-20 fs laser systems.

The retrieved signal indicates a remaining 99 fs^2 of GDD and a negligible component of higher order phase, however further compression using a prism compressor was not possible. The underlying processes preventing optimized pulse compression are most likely spatio-temporal distortions occurring due to the relatively large noncollinear angle as previously reported for similar systems [23,24].

One of the reasons for these distortions is the walk-off between the pump and signal beams coupled with the pulse front tilt of such broadband pulses. These distortions are likely the limiting factor preventing full compression and leading to the loss of the shorter wavelength spectral region (∼30 nm of bandwidth). It should be noted that outside the principal plane of operation, the OPA process has a marginally higher walk-off per mm of crystal; despite this, the increase in the value of d_{eff} allows for a lower total walk-off [20].

In general, there is a rotation direction along which phase matching conditions are kept constant, leading to a parameter able to tune the walk-off. The two extremes of this tuning define the "walk-off compensating" and "tangential phase matching" (also referred as "non-walk-off compensating") [25]. In our particular case, the good quality of the beam spatial profile indicates walk-off not to be a major issue, as predicted by our simulations.

In conclusion, we have demonstrated a single-stage YCOB-based OPA system operating in the near-IR with sub-picosecond pumping and phase-matching angles outside the principle plane, with a compressed pulse duration of 25 fs. These results highlight the potential of YCOB for ultrashort OPA and OPCPA systems, and thanks to the large apertures available and good thermal properties [12] it makes this crystal an ideal nonlinear medium for both high average and high peak power laser systems.

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