Femtosecond Yb:KGW MOPA driven broadband NOPA as a frontend for TW few-cycle pulse systems

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Abstract: White light continuum seeded noncollinear optical parametric amplifier driven by Yb:KGW master oscillator power amplifier (MOPA) system is reported. The demonstrated design provides amplification of broadband pulses at 800 nm up to 20 µJ energy at 1 kHz repetition rate and can be used as simple and reliable frontend source for systems producing high intensity few-cycle pulses. The amplified spectral bandwidth allows for <7 fs pulse durations and preliminary compression of partial spectrum yields sub-10 fs pulse.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (230.4480) Optical amplifiers; (320.7110) Ultrafast nonlinear optics.

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1. Introduction

Rapidly developing areas of high field physics, such as generation of mono-energetic electron beams or coherent X-ray pulses, require high energy few-cycle pulse sources with temporal contrast of the order 10^{-10} at least. Optical parametric chirped pulse amplification (OPCPA) [1] have shown potential to satisfy these requirements and at present OPCPA is the leading technology for high energy few-cycle pulse table-top systems [2–4]. Stable carrier-envelope phase (CEP) is also of great importance for single attosecond pulse generation and CEP control schemes for OPCPA employing electronic phase locking [5] or passive stabilization through parametric processes [6] have been demonstrated. The frontend of such system has to provide a compressible broadband clean seed pulse for further amplification. It has been shown, that in order to achieve high contrast and suppress parametric superfluorescence (PSF) higher intensities of seed pulse are preferred [4,7]. In majority of systems nanojoule pulse from broadband oscillator is stretched to picosecond or even nanosecond duration, therefore its intensity is reduced by several orders of magnitude, and then it is seeded directly to

OPCPA. Introducing short pulse amplifier to such system would increase seed intensity and improve output pulse contrast of the picosecond OPCPA stage.

Until recent time the main seed source for broadband non-collinear optical parametric amplifiers (NOPA) operated in vicinity of 800 nm were either output of broadband mode-locked Ti:Sapph oscillator or the white light continuum (WLC) generated by Ti:Sapph femtosecond regenerative amplifier pulses in bulk material [8]. However, in the latter case it is difficult to compress pulses to their transform limit due to structured intensity profile and strong nonlinear chirp of WLC in proximity of pump frequency [9]. Introducing hollow core fiber filled with noble gas under pressure for spectrum broadening of Ti:Sapph amplifier pulses on a microjoule energy level was of great improvement as it scaled up available broadband seed energies and compression of these pulses to sub-10 fs durations has been demonstrated [10,11]. But the non-uniform spectral intensity distribution typical for these setups usually results in additional satellites appearing after pulse compression. A different approach allowing to shift WLC pump wavelength away from 800 nm and achieve smooth seed spectrum by implementing of multiple NOPA and WLC generation stages pumped by Ti:Sapph laser was proposed recently [12]. However, the mentioned setups are quite complex and less robust. Furthermore, synchronizing with high energy, mostly Nd-doped pump sources for next OPCPA stages in pursuit for multi-millijoule few-cycle pulses would require nonlinear spectrum shifting to 1064 nm by means of photonic crystal fiber [13], or precise electronic synchronization on picosecond timescale [5].

With the introduction of femtosecond ytterbium-based laser systems a new opportunity emerged for WLC generation in bulk material by implementing the ~1030 nm femtosecond pump source. Differently from Ti:Sapph lasers, Yb-doped systems are directly diode-pumped that makes them more compact and efficient. In combination with broadband NOPA this allows for sub-10 fs pulses around 800 nm wavelength to be generated [14,15]. Employing frequency doubled output of the same ytterbium laser for NOPA pump allows to keep the whole system compact and robust. However, until now such systems produced relatively low energy pulses or longer pulses at higher energies [16,17]. As for several microjoule energies and pulse durations of sub-10 fs at 800 nm from Yb-doped laser pumped femtosecond NOPA, only Ti:Sapph oscillator seeded systems have been reported [18–20].

In this paper we demonstrate compact completely Yb:KGW MOPA based WLC seeded femtosecond NOPA which provides up to 20 µJ energy broadband pulses for seeding of high energy OPCPA system. Due to highly nonlinear nature of WLC generation such setup can provide better contrast and smooth spectrum seed pulses for further amplification as compared to the case of seed from Ti:Sapph oscillator. The system has potential for carrier-envelope phase control and CEP stable operation of similar Yb:KGW MOPA has been demonstrated recently [21]. Furthermore, mode-locked Yb-based oscillator allows for reliable direct optical synchronization with high energy Nd:YAG based systems for OPCPA pump without any additional nonlinear spectrum broadening [22,23].

2. Broadband NOPA setup and performance

I type phase-matching nonlinear crystal based OPA parametric amplifiers operating close to degeneracy in near collinear geometry allows to achieve > 2000 cm^{-1} amplification bandwidths [24]. But in this case undesired parametric cascading processes may appear [25,26]. An alternative is a non-collinear optical parametric amplifier that can be designed also for non-degenerate broadband pulse amplification using pump pulses at 515 nm [27].

In oscillator seeded systems the lower contrast limit is usually determined by initial oscillator contrast (noise-to-peak ratio) if no additional pulse cleaning is introduced. For Ti:Sapph mode-locked oscillators the typical contrast is around 10^{-7} on picosecond scale [28]. Further the contrast of compressed pulses can be degraded due to pump noise transfer to spectrum of amplified signal [29] or due to PSF arising in parametric amplifiers. In order to suppress the PSF and achieve high contrast at the output of the system, the use of higher energy seed pulse and several lower gain amplifier stages is preferable. Moreover, PSF generation occurs only in temporal window defined by pump duration. Accordingly, NOPA

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pumped by femtosecond pulses can improve the contrast on a picosecond scale by a factor equal to parametric gain [30]. Thus, starting from femtosecond NOPA and then gradually increasing from stage to stage the pulse duration to picosecond or even to nanosecond timescale in high energy multistage OPCPA system one can expect to improve the contrast of compressed output pulse. This is the main principle of stepwise increasing duration (SID) concept we are proposing for multistage OPCPA system, which combines the advantages of short pulse implementation together with high energies at longer durations. The choice of multistage setup also allows for distribution of overall gain, spatial signal filtering between stages, use of shorter crystals and better compensation of pump-signal group velocity mismatch (GVM) in each stage. It also provides possibility for signal spectrum shaping as slightly different part of the pulse may be amplified in each stage [31]. WLC generation in bulk material provides not only extremely stable broadband pulses, but also allows to achieve high pulse temporal contrast since the noise coming from pump laser is present only at the pump spectrum wavelengths.

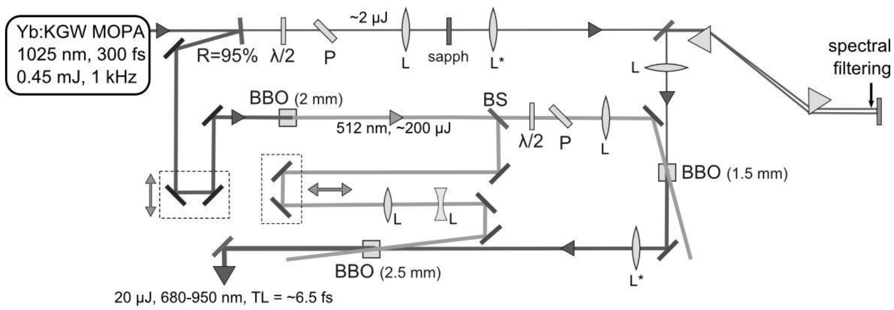

Fig. 1. Diagram of of two stage NOPA experimental setup. BS: beam splitter, P: thin film polarizer, λ/2: waveplate, L: lens, L*: concave Ag mirror (depicted as lens for simplicity).

In our setup (Fig. 1) Yb:KGW MOPA ("PHAROS", Light Conversion Ltd.) generating nearly transform limited pulses ($\Delta\nu\Delta\tau \le 1.3$) of high spatial quality ($M^2 < 1.1$) was used both for WLC generation and pumping of successive NOPA stages. Part of pump pulse was split into continuum generator channel and waveplate-polarizer attenuator was used to achieve optimum conditions for WLC generation. The 300 fs FWHM pulses was focused into 4 mm-thick sapphire plate by 80 mm focal length aspheric lens. This resulted in $1/e^2$ beam radius of ~50 µm at the input surface of sapphire which corresponds to ~180 GW/cm^2 peak intensity at the optimal 2,2 µJ pump pulse energy that was slightly below the threshold of continuum multi filamentation. As a result ~10 nJ of overall seed energy was produced in spectral region from 550 nm to 970 nm (Fig. 2a). The near field WLC beam profile is presented in Fig. 2b. M^2 parameter was measured at several wavelengths in the 700-900 nm range and its value did not exceed 1.5. The shape of WLC spectrum is highly stable and is well reproducible on a daily bases. WLC and second harmonic for NOPA pump were generated by the pulse of same duration and due to dispersion in sapphire crystal and focusing lens the signal pulse initially was longer than the pump. Also, it has been shown previously, that in order to avoid spectral narrowing in OPCPA the signal-to-pump duration ratio should be ~0.3 [32–34]. Therefore, the WLC pulse was pre-compressed by 67° apex angle BK7 prism compressor (distance between prisms apexes is ~40 cm). Additionally we cut off the pump pulse spectrum components by the knife placed in front of compressor folding mirror. The approximate signal pulse duration evaluated as group delay for 700 and 900 nm spectrum components is ~100 fs.

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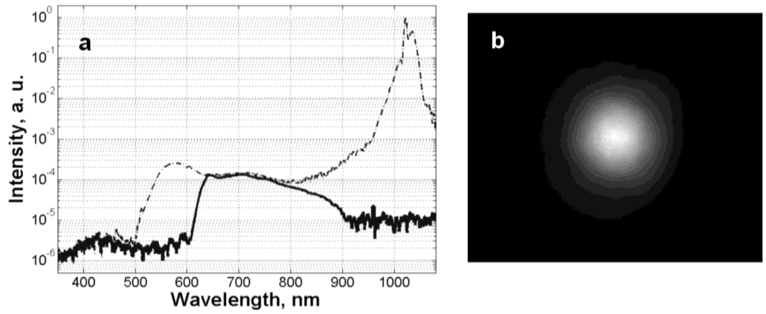

Fig. 2. (a) Spectrum of white light continuum at the output (dashed line) and after spectral filtering (solid line). (b) Near-field continuum beam profile.

The parametric amplification was carried out using type-I BBO crystals pumped by laser second harmonic pulses. The tangential phase-matching geometry at internal non-collinearity angle α close to 2.5° and phase-matching angle θ = 24.6° has been employed in both stages. In the first stage the seed and pump beams were both focused to a spot size of ~120 µm (at $1/e^2$ intensity level) onto 1.5 mm BBO crystal. In order to minimize the PSF, the first stage was operated in relatively low gain regime setting pump pulse energy to ~14 µJ.

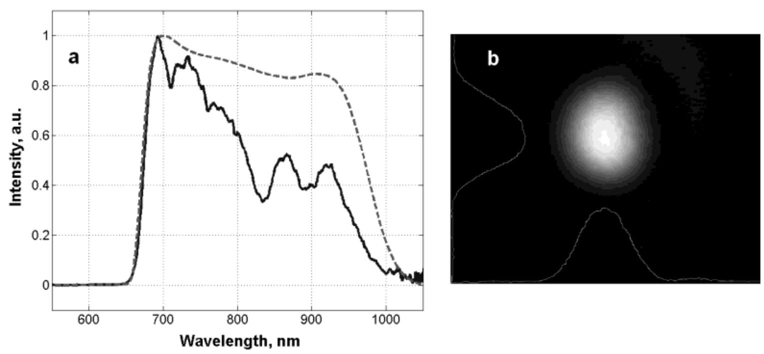

Fig. 3. (a) Amplified pulse spectrum (solid line) and calculated amplification bandwidth (dashed line) at θ = 24.6°, α = 2.52°. (b) Output beam profile at the focus of R = 2 m mirror.

Further the ~1 µJ energy signal was collimated to the second NOPA stage matching its beam size to pump beam diameter (1 mm, at $1/e^2$ intensity level). The BBO crystal (2.5 mm) is short enougth as compared to signal-pump temporal walk-off length (~3.5 mm). At pump peak intensity of ~40 GW/cm^2 the signal was amplified up to 20 µJ with good spatial quality. The NOPA output pulse spectrum is presented in Fig. 3a. The shape of spectrum modulation significantly depends on lateral position of knife edge placed in pre-compressor. So, we believe that this modulation is caused mainly by effects of seed diffraction on the sharp edge of knife. Different filtering setup for obtaining smooth output spectrum is under investigation. The measurements performed by using of imaging spectrometer have revealed the presence of slight spatial chirp at NOPA output that vanishes after several meter of propagation due to beam diffraction. The angular dispersion of output beam was negligible. The PSF level at the output of the NOPA with the blocked seed was undetectable in 3 orders of magnitude range. Output pulse energy RMS fluctuations of less than 1% have been measured. The far field beam profile is close to Gaussian one and exhibits only slight ellipticity (Fig. 3b).

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3. Pulse compression

The transform limit of the amplified pulse spectrum (Fig. 3a) corresponds to ~6.5 fs duration. Although this system is proposed as a frontend and the further pulse stretching and amplification is intended, a preliminary experiment on pulse compression was carried out.

The output pulse was compressed using double-pass prism compressor, comprising of 57° apex angle SF57 prisms separated by ~94 cm, and acousto-optic programmable dispersive filter (AOPDF "DAZZLER", Fastlite). Unfortunately, transmission range (at applied AOPDF phase load of D_1 ~4900 fs^2, D_3 ~640 fs^3 and D_4 ~162 × 10^3 fs^4) was restricted from 700 to 900 nm because of the limited (25 mm) length of currently available AOPDF crystals. A SHG FROG set-up employing 10 μm-thick I type phase-matching BBO crystal was used for compressed pulses characterization. Figure 4 presents compressed pulse temporal intensity, spectrum and phase profiles retrieved from 256x256 points FROG trace (FROG error was 0.008). The measured pulsewidth at FWHM is 9.8 fs, whereas the Fourier-limited duration is 9 fs. The spectrum of compressed pulse is somewhat different from the one at the NOPA output due to wavelength dependent efficiency of AOPDF at given higher order dispersion compensation values.

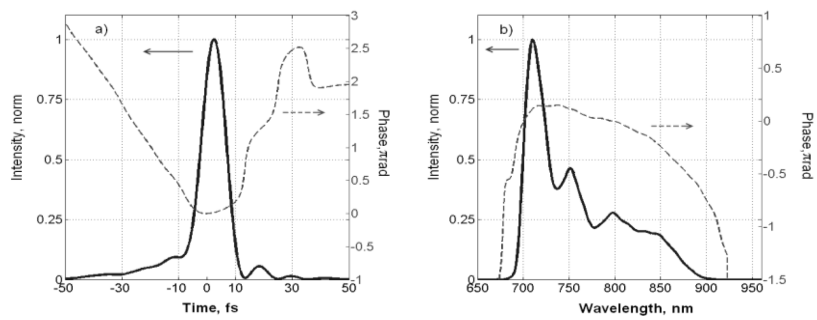

Fig. 4. Intensity profile (solid) and phase (dashed) of compressed pulse in temporal (a) and spectral (b) domains, retrieved by FROG measurement.

The system provides long term stability and turn-key operation. Only minor adjustments of phase compensation by AOPDF had to be introduced in several days of operation.

4. Conclusion

In conclusion, we have demonstrated broadband NOPA pumped by femtosecond Yb:KGW MOPA. High contrast of the system is anticipated due to femtosecond temporal pump window and relatively high intensity of initial seed. Pulse energies of up to 20 μJ were demonstrated and compression to sub-10 fs was performed. There is no fiber coupling involved, which makes it simple and less vibration sensitive. The system is based on diode pumped compact femtosecond Yb-doped MOPA operating at wavelength close to 1 μm, which allows for direct optical synchronization with Nd-doped high energy OPCPA pump systems. The employment of femtosecond NOPA as a frontend for TW-class OPCPA system can provide high intensity seed for picosecond parametric amplifiers and offers good prospects for output pulse energy contrast enhancement. The amplification in stepwise increasing duration concept based OPCPA system implementing femtosecond and picosecond NOPA stages is currently in progress and 30 mJ output pulse energy already has been achieved prior to compression [35].

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