Pushing the NOPA to New Frontiers: Output to below 400 nm, MHz Operation and ps Pump Duration

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Abstract: Two sub-ps MHz range Yb-based lasers are used to pump NOPAs at 343 nm. A SHG driven supercontinuum allows tuning down to 395 nm. For a 1-ps pump, supercontinuum seeding is applicable, the pulses are compressed to the 20-fs regime with a potential for sub-10 fs.
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1. Noncollinear optical parametric amplifiers pumped by Yb-based lasers

For many years the generation of powerful ultrashort pulses was dominated by Ti:sapphire oscillators and amplifiers. Optical parametric amplifiers (OPA) were developed to provide full spectral tunability. The introduction of noncollinear phase matching (NOPA) and chirped parametric amplification (OPCPA) enables to generate some of the most intense, shortest and most widely tunable pulses available today. NOPAs were originally pumped by the SHG of kHz Ti:sapphire systems with a pulse duration around 100 fs. This allows efficient continuum generation to be used as seed light and provides a high intensity in the amplifier.

Recently, the development of femtosecond lasers has turned to Yb-based active media, because higher average powers are achievable with diode laser pumping. The consequences are a central wavelength around 1030 nm and pulse durations not significantly below one picosecond. Pumping a NOPA with the SHG at 515 nm [1] and BBO as active material resulted in a shortest output wavelength of 600 nm. With THG pumping [2] 387 nm should be reachable, but was not yet demonstrated due to the lack of suited seed light.

We now show in two setups employing newly available Yb-based systems at up to 1 MHz as pump that the sub-400 nm rang can be reached if a SHG-pumped continuum is used as seed. We generate fully tunable blue pulses with Fourier limits in the 10 fs range. With a 1 ps, 300 kHz pump system we generate a stable continuum and subsequently amplify major spectral parts into powerful pulses with the potential of sub-10 fs duration.

2. Fully utilizing the tuning possibility of a 343 nm pumped NOPA

In our first series of experiments we use a 20 W fiber-based system (Tangerine fs, Amplitude Systemes) delivering 1030 nm pulses with 20 µJ pulse energy and 300 fs pulse duration. The system is operated at 200 kHz for development and 1 MHz for full output. To generate 343 nm pump pulses (see Fig. 1 a) we frequency-triple the major part of the pulses in a sequential arrangement of a type I doubling BBO and a type II BBO [2] to obtain 3 µJ UV pulses.

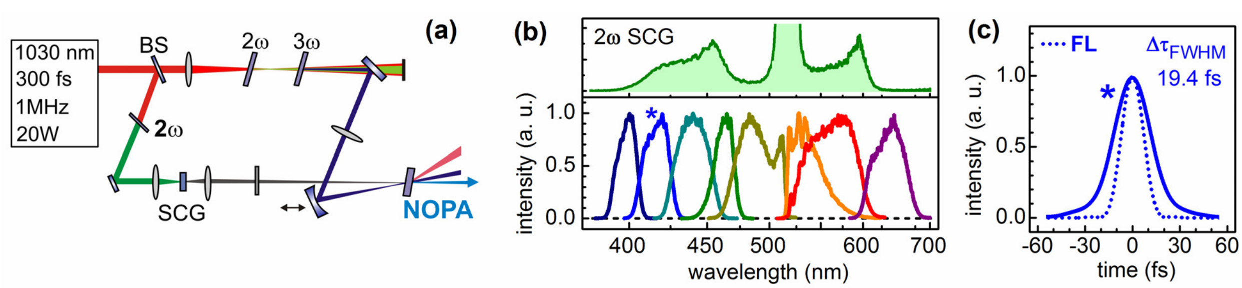

Fig. 1. a) NOPA pumped by 343 nm pulses. b) Supercontinuum (SCG) generated by pumping with 515 nm pulses. Spectra of pulses tunable from 395 to 630 nm with Fourier limits below and close to 10 fs. c) Autocorrelation of 425 nm pulses.

For the seed light generation, part of the 1030 nm pump is frequency doubled in a 0.8 mm BBO crystal. The SHG pulses with an energy of 750 nJ are spectrally filtered with dielectric mirrors and focused onto a 4 mm thick YAG crystal [3]. The observed continuum (Fig. 1 b) contains spectral components well below 400 nm and with a thicker crystal down to 350 nm. The high-wavelength cutoff is above 650 nm. Significant parts of this extremely wide spectrum are amplified in a NOPA employing a 3 mm BBO crystal cut at 32.5°. Typical output spectra are shown in Fig. 1 b with Fourier limits between 10 and 20 fs for the entire range. The shortest central wavelength reached is 395 nm, limited by idler absorption at around 3 µm. When optimized for output power, the pulse energy exceeds 1 μJ, corresponding to a 40 % quantum efficiency in the nonlinear conversion of the pump light.

The pulses are compressed with fused silica prisms. A typical autocorrelation at 425 nm is shown in Fig. 1 c, showing a sub-20 fs duration that is limited by higher-order chirp, but still highly competitive with alternative methods for generating tunable blue pulses at high repetition rate. We also frequency double the NOPA output and generate pulses down to 210 nm in a single additional conversion stage. The observed spectral width is only limited by the acceptance bandwidth of the BBO crystal, providing possible pulse durations of below 20 fs. Altogether, the system now provides fully tunable 10-20-fs pulses from the deep UV all the way up to 630 nm without any wavelength gaps. The additional range up to 950 nm can be reached with a NOPA pumped by the residual 515 nm light, which is already integrated in the actual amplifier layout.

3. Continuum-seeded NOPA with 1 ps pump pulses from a 130 W disk laser

The second pump system is a diode-pumped regenerative Yb:YAG disk amplifier based on a previous design [4], but operating at 50-300 kHz. The output power is up to 130 W at a central wavelength of 1032 nm and the pulses have 1 ps duration. The main challenge with these long pulses is the seed light generation. Here, we report on a stable supercontinuum generated with 7 μJ at 1032 nm in a 4 mm YAG crystal. This is the basis for the subsequent amplification in the NOPA, without resorting to external seed sources such as a synchronized Ti:sapphire oscillator. The continuum extends from below 500 nm up to the pump wavelength (Fig. 2 a). Using frequency-tripled 6.7-μJ pulses for NOPA pumping, we are able to generate tunable pulses in the green spectral range with up to 1 μJ output energy and Fourier limits close to 10 fs (Fig. 2 c). At specific phase matching conditions, pulses with a Fourier limit of 6 fs can also be obtained as a consequence of the long pump pulse length.

With a compressor made of two SF10 prisms at less than 1 m of separation, the pulses were compressed to the 20 fs regime (Fig. 2 b). This represents a pulse shortening by a factor of 50.

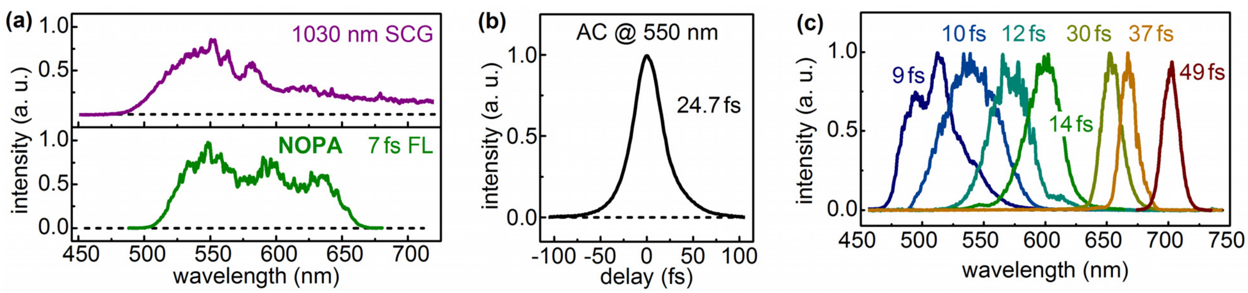

Fig. 2. a) Supercontinuum generated from 1-ps 1030 nm pulses and broadband NOPA output. b) Autocorrelation of 550 nm pulses. c) Tuning range of the 344-nm-pumped NOPA with Fourier limits.

In a first application, we produced narrow-band tunable pulses with a slit in the prism compressor and studied the performance of a femtosecond electron gun in dependence on the photoemission wavelength. We found that the two-photon photoemission regime with visible pulses reproduces earlier results with ultraviolet pulses [5]. The duration of the electron pulses decreases and the coherence increases as the photon energy approaches half of the work function. This result proves the applicability of a powerful picosecond laser at 50-300 kHz, which is powerful enough for providing tunable pump pulses for femtosecond electron diffraction and microscopy.

3. Towards new applications of wavelength-selectable MHz 10 fs pulses

The presented experimental results show that the presently evolving Yb-based ultrashort pulse sources operating at up to MHz repetition rate and with pulse durations close to 1 ps can be efficiently used to generate pulses tunable from 210 to 950 nm. Pulse durations below 20 fs are demonstrated and sub-10-fs capability is found. With both pump lasers, a supercontinuum generated in a YAG crystal is used as seed and avoids the need for elaborate temporal synchronization. Due to the high repetition rates, many new applications that need extensive scanning or a high degree of averaging together with a resonant excitation now become feasible.

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