Generation of octave-spanning intense supercontinuum from Yb:doped solid-state lasers in multiple thin plates

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Abstract—**We demonstrate generation of intense octave-spanning supercontinuum, covering from 550 nm to 1250 nm at the -20 dB level, in a double-stage multiple thin plate system driven by 1030 nm, 170 fs pulses. The output pulses have good beam quality and long-term stability. Such supercontinuum can support 4 fs single-cycle pulses for applications in bright isolated attosecond pulses generation and time-resolved spectroscopy.**

Keywords-component; supercontinuum; single-cycle pulse

Intense single-cycle femtosecond pulses are ideal light source for generating bright isolated attosecond pulses via high order harmonic generation (HHG) for attosecond science, e.g., investigating the dynamics of atomic and molecular, nano-materials and bio-molecular systems, achieving unprecedented temporal and spatial resolution.

Most few-cycle pulses are formed by compression of an ultrabroadband light source obtained in meter-long hollow-core fiber filled with noble gas [1,2]. However, the hollow-core fiber scheme requires a careful alignment and is extremely sensitive to the beam-pointing direction, limiting its long-term stability. The alternative of generation in bulk media has been marred by multi-filamentation and low optical damage threshold that have limited the input pulse energy to a few microjoules, making solids unattractive for high power applications. Recently we reported a novel approach of using a set of plates for continuum generation (MPCs) using 800 nm 28 fs pulses [3], that enables the generation of 0.22 TW few-cycle pulses and isolated circularly polarized attosecond pulses [4,5].

In this paper, we present a two-stage MPC generation scheme for driving with 1030 nm lasers that have pulse duration of as long as 170 fs. We demonstrate a spectrum spanning from 550 nm to 1250 nm, (bandwidth at -20 dB intensity) that is capable of supporting single-cycle pulses while maintaining good output beam quality. This dual-stage pulse shortening scheme can be very important for Yb-based lasers, since the main disadvantage for all diode-pumped Yb-doped laser is that these lasers have a bandwidth of ≈15 nm, which limits the pulse duration to ≈ 200 fs, thus hindering their application in attosecond science and extreme nonlinear optics.

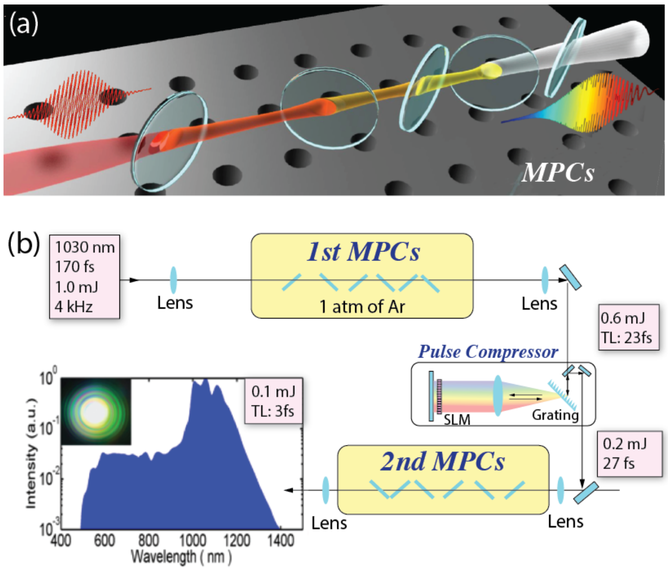

Figure 1. (a) Schematic of MPCs (b)The experimental setup of two-stage MPCs, together with the output spectrum and beam profile at the visible part of the spectrum. SLM represents spatial light modulator. TL represents the transform-limited pulse duration.

Fig. 1(b) shows our two-stage cascaded MPC system, which is driven by a 1.0 mJ, 170 fs, 1030 nm Yb-based laser (Light Conversion, PHAROS). Pulses are focused in the first MPC system of six 200 µm thick quartz plates) held in a chamber filled with 1 atm of argon. An incident peak intensity of 8.6×10^{12} W/cm^2 is estimated for the first thin plate, initializing the nonlinear broadening process. Subsequent plates are inserted by following the proceduredescribed in reference 3. After inserting 6 plates and optimizing their positions for maximum bandwidth while keeping good output beam quality, we broadened the bandwidth by > 5 times, resulting in a spectrum ranging from 940 nm to 1100 nm at -20 dB intensity, Fig. 2(a). The output energy of the broadened pulse is 575 µJ. The conversion efficiency of this stage of MPC is > 55%.

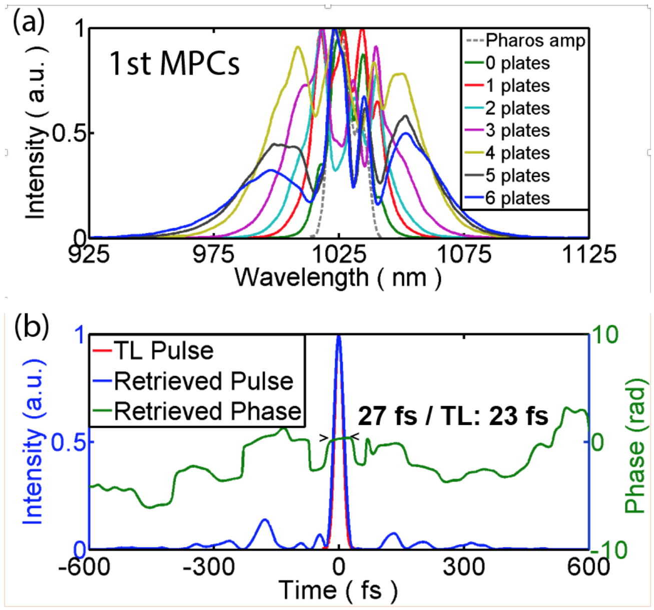

Figure 2. (a) Spectrum generated with different number of quartz thin plates in the first MPCs. The input pulse is 170 fs, 1.0 mJ pulses running at 4 kHz. The transform-limited (TL) pulse duration possible after the first MPCs (6 plates) is 23 fs, while the pulses are compressed to 27 fs as measured by PG-XFROG (b). It is worth mentioning that without any plates, we also observed a little spectrum broadening because of self-phase modulation (SPM) induced by argon.

To compress the pulses from the first MPC, we use a shaper-assisted 4-f compressor consisting of a grating, a spatial light modulator (SLM, JenOptik SLM640d) and cylindrical lens to compensate the nonlinear dispersions induced by the first MPC. Fig. 2(b) shows the compressed pulse, characterized by polarization-gating cross-correlation frequency-resolved-optical-gating (PG-XFROG). The figure shows that the pulses are successfully compressed to 27 fs (8-cycles) when its transform limit is 23 fs. Currently, the pulse energy after the compressor is only 195 µJ, due to the low transmission of spatial light modulator. Eventually by using custom chirped mirrors, we expect an efficiency of > 50%, when converting 170 fs pulses to 23 fs. Then the peak intensity of output pulses would be ≈ 3 times higher than that of the input pulses.

We next send the compressed pulses through a second set of quartz plates for further spectral broadening. Fig. 3 presents the spectrum with different number of plates. After six 100 µm thick plates, the bandwidth spans from 550 nm to 1250 nm at the -20 dB level, while the quality of the output beam is as shown in the inset in Fig. 1. The conversion efficiency to the supercontinuum in the second stage is 55 %, resulting in an output pulse energy of 107.5 µJ. It is clear that adding more plates in this stage introduces a stronger blue shifting of the spectrum than in the first stage. This is because the pulse duration of the input pulses at the second stage is short enough to induce a strong contribution from pulse steepening effect to spectral broadening than in the previous stage [6]. The final supercontinuum thus generated can support a pulse duration down to 3 fs (sub-cycle) as shown in Fig. 3(b).

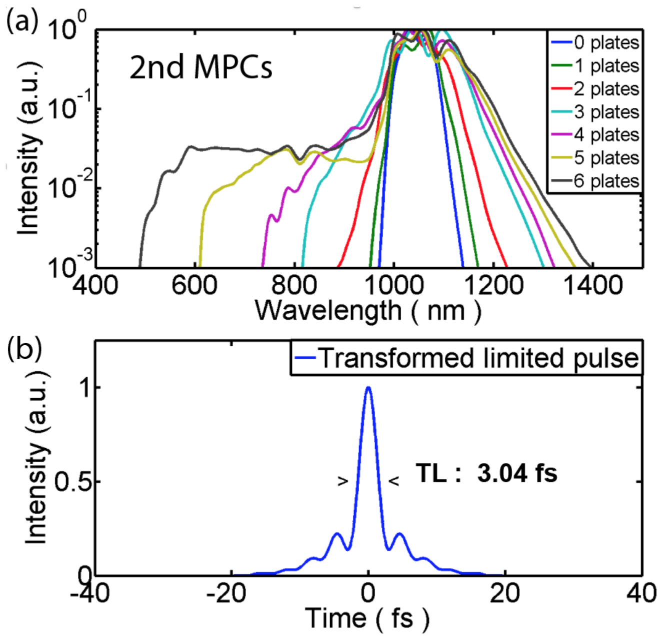

Figure 3. (a) Spectrum generated with different number of quartz thin plates in the second MPCs.. The figure is in log scale. (b) The transform-limited pulse shape of output spectrum two MPCs system. The T-L pulse duration is 3.04 fs (single cycle pulse).

In summary, we have demonstrated two-stage MPCs system driven by 1 mJ, 170 fs Yb-based pulses running at a repetition rate of 4 kHz that expands the bandwidth of 1µm Yb:CaF_2 laser by > 50 times for the first time, covering more than one octave at -20 dB level while keeping a good output beam quality. After phase compensation, the peak power of these pulses could reach several gigawatts. Such intense, stable diode-pumped single-cycle laser pulses will make isolated attosecond pulses accessible to a broad user community.

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