MTW Optical Chirped-Pulse Amplification Stages

Optical parametric chirped-pulse amplification (OPCPA) is a key aspect of the MTW laser in its broadband mode, where it amplifies stretched pulses with more gain and bandwidth for higher temporal contrast than would be possible using Nd-doped amplifiers alone. OPCPA was chosen for the main amplifier stages due to its ability to provide broadband amplification with extremely high gain and very good contrast. It was built in two stages: a two-crystal preamplifier (PreAmp) provides high gain, while a single-crystal power amplifier (PowAmp) yields high energy-extraction efficiency. Operating the preamplifier stage with some OPCPA reconversion and the power amplifier in saturation balances the effect of pump-energy variations while maximizing energy extraction.

LBO crystals were selected for PreAmp and PowAmp because of their broad angular acceptance and low pump-to-signal walk-off compared to other bulk nonlinear crystals, such as BBO and KDP, commonly used in degenerate OPCPA systems at 1053 nm. The broad angular acceptance of LBO reduces the OPCPA system sensitivity to pump-laser wavefront errors, which can lead to reduced efficiency and undesirable beam modulation. Minimizing pump-to-signal walk-off also improves overall efficiency and beam quality, especially in a preamplifier that utilizes long crystals and small beams.

The OPCPA amplifier setup is shown in Fig. 1. The pump beam from the crystal large-aperture ring amplifier is converted into the green light in second-harmonic generation (SHG). The Pellin–Broca prism (PB) separates the second-harmonic beam from the fundamental beam, then two dichroic mirrors (DMs) dump the residual IR beam to block its propagation into OPCPA where it can ignite a regenerative regime of OPCPA. The half-wave plate (λ/2 #1) with the polarizer P1 distribute pump energy at 527 nm between the PreAmp and PowAmp in a proportion of about 1:10, respectively. That ratio can be adjusted, while λ/2 #2 with P2 and λ/2 #3 with P3 independently vary the pump energy in the preamplifier and power-amplifier stages. The vacuum image relays VIR1 and VIR2 put an image of the SHG crystal at OPCPA crystals and set pump beam size as 3 mm (FWHM) on the preamplifier and 6 mm (FWHM) on the power amplifier. Calorimeters K1 and K2 measure pump beam energies in the PreAmp and PowAmp stages, K3 and K4 measure the residual pump energies, and K5 measures the output signal energy.

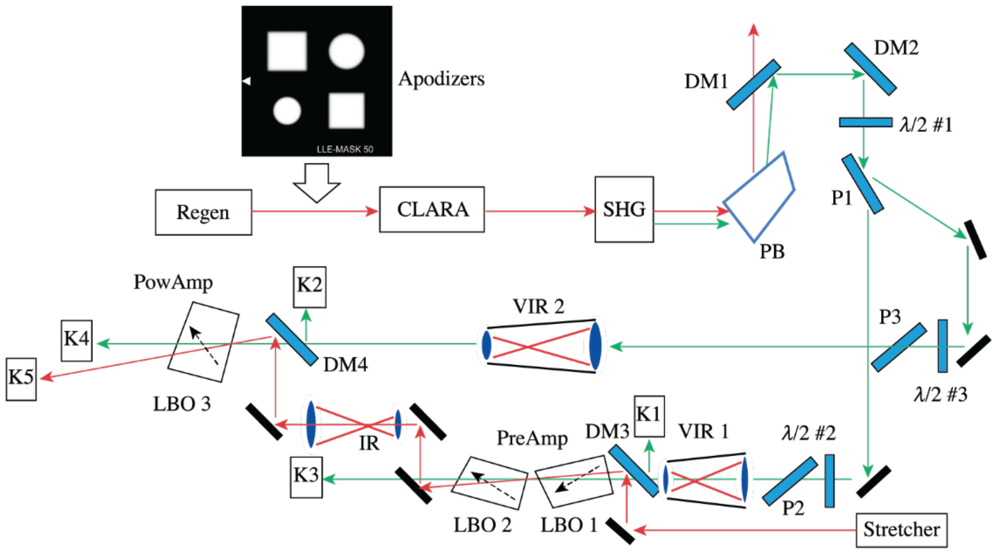

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Fig. 1. OPCPA layout. P: polarizers, LBO: lithium triborate crystals. Inset: a plate with four apodizers.

The seed beam is injected into the PreAmp under a slight noncollinear angle (8-mrad external) to the pump beam. A noncollinear regime between the pump and the seed beams in the phase-matching plane prevents self-doubling of the intense amplified signal and reduces pump–signal walk-off effects. That also simplifies separating the amplified signal beam from the residual pump and idler beams. The 15-ps (rms) temporal jitter between the pump and the seed lasers yields exceptional wavelength stability of the amplified OPCPA signal. The PreAmp uses two 5 × 5-mm aperture LBO crystals, 29.75-mm and 36-mm long. The crystals are critically phase matched in a walk-off–compensated arrangement when the main optical axes of crystals are antiparallel.

Orientation of the crystals is extremely important to prevent parasitic SHG, which reduces the output signal beam energy and shapes spectrum of the output signal. It is critical to set the axis of the second crystal of the preamplifier at a larger angle with seed beam propagation than in the first crystal. In this case, the parasitic SHG of the OPCPA signal, which is significant in the second crystal, is suppressed. The first crystal could be oriented in an antiparallel direction and matched with SHG angle, but parasitic SHG is negligible there due to low intensity of the OPCPA signal in the first crystal. Furthermore, both preamplifier crystals are tipped out of the phase-matching plane to avoid round-trip amplification of spontaneous parametric fluorescence that is reflected off the crystal faces. Referred to as optical parametric generation, this incoherent pulse is seeded by vacuum noise and is different from the OPCPA signal because it is not chirped or compressible, and has a much larger divergence and spectrum. While all crystals have antireflection coatings, even a residual reflection of crystal faces could be amplified due to extremely high gain of OPCPA. If the output surface of the second crystal "sees" the input surface of the first crystal, a reflected beam will re-enter in the first crystal of the preamplifier while the pump pulse is still there and will take a significant portion of pump energy into optical parametric generation (OPG), but not in seeded amplification. As result, the output OPCPA pulse (and spectrum) has a step shape.

The PreAmp stage operates at a nominal pump intensity of 1 GW/cm^2. The 3 × 3-mm (FWHM) square pump beam is surrounded by the Gaussian round seed beam (~4.5-mm-diam FWHM) from the stretcher. The high-gain parametric process reshapes the seed beam, making the output signal beam spatial profile very close to the pump beam.

If the ultrafast optical parametric amplifier (UOPA) is bypassed, the seed pulse is amplified from 600 pJ to 30 mJ, corresponding to a net gain of 5×10^7 with a conversion efficiency exceeding 24% (Fig. 2). Separately, the pump depletion is measured by blocking and releasing the seed beam. This shows a value of 71%, which is in good agreement from the value calculated from the measured signal-to-pump conversion efficiency. Driving the OPCPA preamplifier slightly into the reconversion regime optimizes the two-stage system's efficiency, as well as the energy stability. With gain from the UOPA, the seed energy into the PreAmp is ~8 μJ. It requires much less pump beam intensity to obtain an even better conversion efficiency of 27% (Fig. 2). Pumping the PreAmp at a lower intensity significantly reduces OPG and improves compressed pulse contrast.

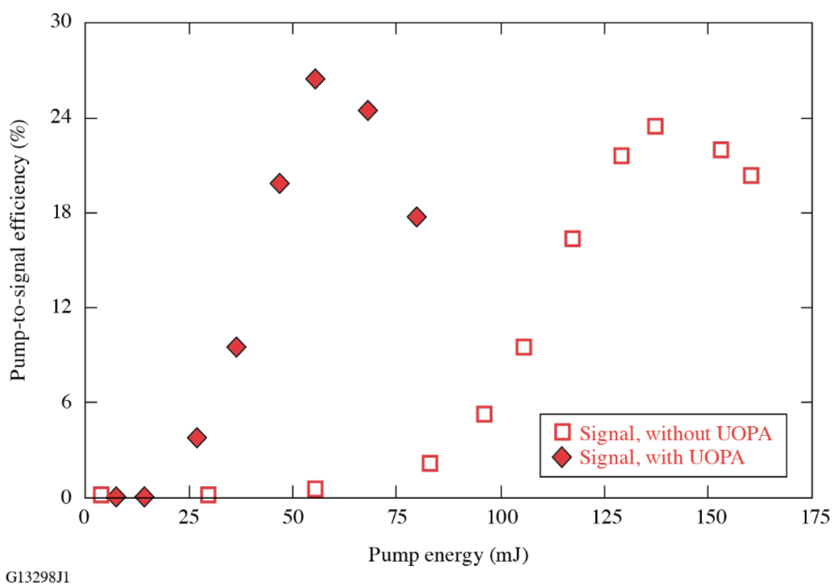

Fig. 2. PreAmp pump-to-signal conversion efficiency with (diamonds) and without (squares) the UOPA stage in the seed beam.

The PreAmp output signal beam is image relayed with a magnification of about 2× to the OPCPA PowAmp stage. Pump-pulse energies up to 640 mJ are delivered to a 10- × 10- × 11-mm LBO power-amplifier crystal. The pump intensity in the power amplifier exceeds that of the preamplifier by 20% to 40%. This is possible without increasing the risk of damage because the PowAmp beam is 2× larger and therefore has less modulation from diffraction effects at optics that are not at a pump-beam image plane. At the maximum pump energy, 265-mJ pulses have been measured at the output of the PowAmp, corresponding to 37% pump-to-signal conversion efficiency reached with no saturation effect observed. The total system efficiency, including preamplifier and power amplifier, is 34% with an energy stability of 1% (rms) over 100 shots.

The spatial reshaping of the seed is mostly due to the high-gain PreAmp, but the output signal spatial profile is strongly modulated because of the nonlinear dependence of the gain with respect to the pump intensity. In the PowAmp, the gain dependence on the pump energy is more favorable: low-intensity areas in the seed beam will see a higher gain, while initially high-intensity areas will reach saturation faster and therefore see a lower gain. This smooths the signal spatial profile, and the range of intensities across the beam is reduced with a peak-to-mean value of less than 20%. The amplified signal beam's near-field profile shown in Fig. 3(a) was measured with an 8-bit charge-coupled–device camera. The corresponding spectrum is shown in Fig. 3(b).

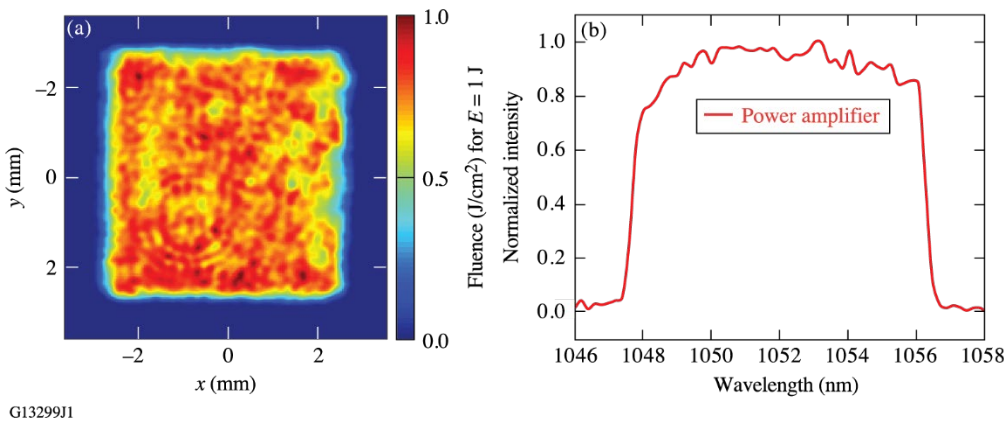

Fig. 3. (a) OPCPA output beam and (b) spectrum.