TUTORIAL

# Amplifying Few-Cycle Pulses with OPCPA

One way to ramp up ultrashort-pulse energy—by eight orders of magnitude.

The award of half of the 2018 Nobel Prize in Physics to OSA Fellows Donna Strickland and Gérard Mourou for chirped-pulse amplification (CPA) speaks to that technology's centrality in enabling high-power laser science. Emerging, petawatt-scale facilities such as the European Extreme Light Infrastructure (ELI) and China's Shen Guang-II 5-PW facility are also taking advantage of a particular flavor of CPA: optical parametric CPA (OPCPA). OPCPA combines CPA with optical parametric amplification (OPA), which excels at boosting the energy of broadband, few-cycle pulses. Here's a look at how it can take a nanojoule seed pulse to terawatt-scale power.

OPCPA excels at boosting the energy and peak power of broadband, few-cycle pulses.

## 1. Seed and pump pulses

The process begins with the creation of two short pulses. One is a weak (nJ), broadband, few-femtosecond "seed" pulse, commonly generated from a Ti:sapphire or other oscillator. The other is a much stronger (tens to hundreds of mJ), 10-ps to few-ns pump pulse, generally from a green laser source such as a frequency-doubled Nd:YAG laser, a Yb fiber laser, or another platform.

## 2. Synchronizing the pulses

Because OPA requires the seed and pump pulses to arrive at the amplifier crystal simultaneously, the two pulses must be synchronized with sub-picosecond accuracy. One approach (shown here) is active synchronization of the mode-locked pump and seed pulse oscillators via high-frequency electronic feedback loops. In an alternative, all-optical synchronization approach, both the pump and seed pulse come from the same oscillator, using a nonlinear process to give the seed pulse its required wavelength and bandwidth.

## 3. Stretching the seed

Next, the seed pulse is stretched in time, or chirped, to give it a comparable duration to the pump pulse. Commonly in CPA systems, this is done using pairs of diffraction gratings as the dispersive elements. For stretching broadband seed pulses on the order of 10 to 100 fs or less, however, the greater number of frequencies packed into the pulse means that higher-order dispersion terms (beyond the group-velocity term) become important. This has led researchers to experiment with other approaches to pulse stretching (and later re-compression) to avoid distortions: Öffner stretchers combining mirrors and gratings; prism pairs; "grisms," or prisms with gratings etched into the side; arrays of chirped mirrors with specialized dielectric coatings; and these and other elements in combination.

## 4. Parametric amplification

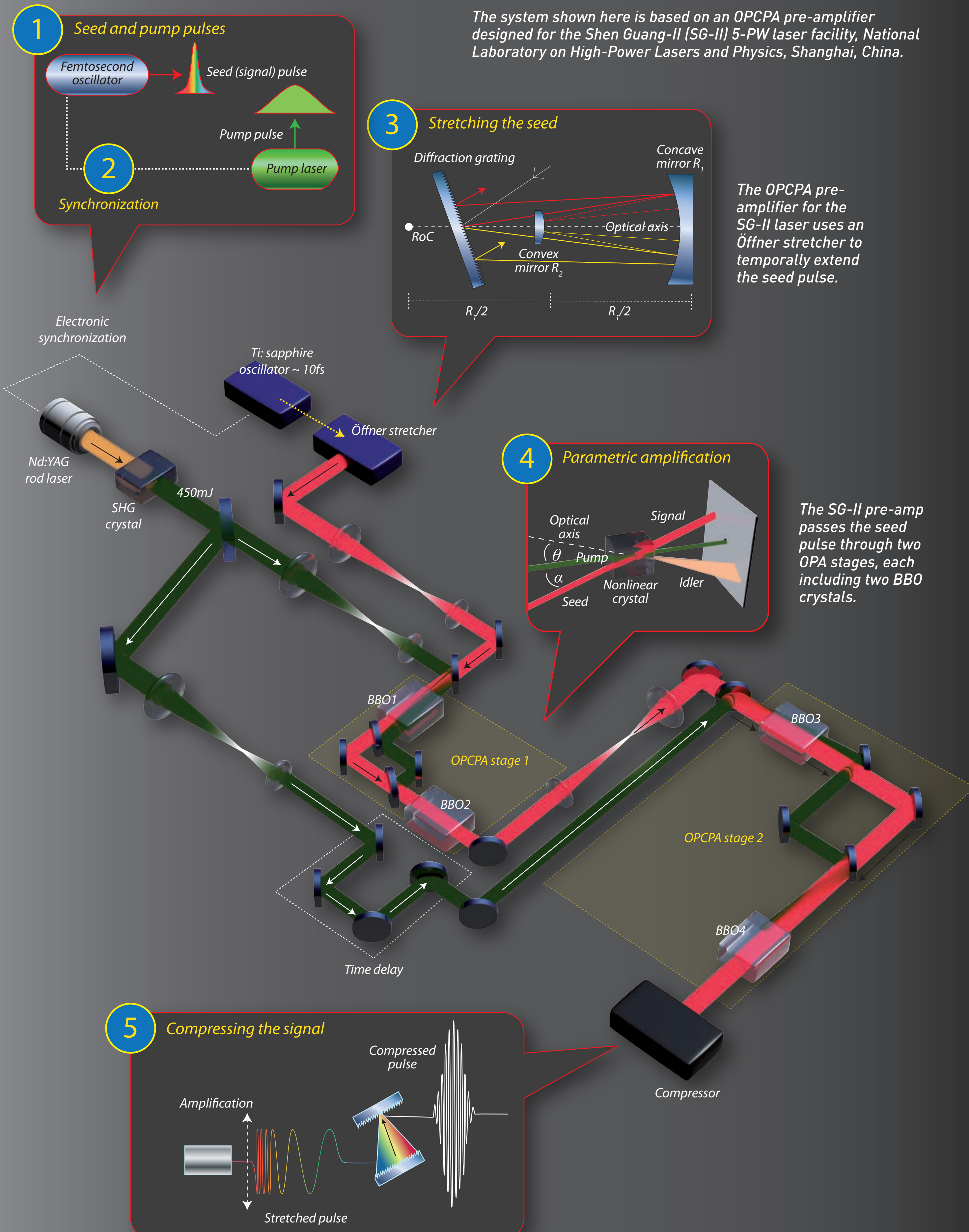
The synchronized pump and stretched seed pulses are then routed to one or several crystals—typically of a material such as beta-barium borate (BBO), which is transparent at visible to near-infrared wavelengths—that exhibit parametric or $\chi^{(2)}$ nonlinearity. This nearly instantaneous nonlinear process transfers part of the energy from the pump pulse to the seed pulse, creating three outputs: a much stronger seed pulse, or signal pulse; a weakened pump pulse; and a smeared-out idler pulse at the difference frequency between the pump and the seed. Typically, the seed and pump pulses are set up to converge in the BBO crystal at a small, carefully controlled angle, for exact phase- and group-velocity matching at different wavelengths across the crystal's small length, (a few mm to a few cm).

## 5. Compressing the signal

Finally, the strong signal pulse is re-compressed to its original, fs-scale width, using similar dispersive elements to the ones that did the initial stretching. The result can be a few-cycle, 10-fs pulse, but one whose original nanojoule energy has been amplified by eight orders of magnitude, for a peak power in the terawatts. In the design of the ELI Nuclear Physics (ELI-NP) facility in Romania, low-energy OPCPA is merely the front end to additional stages of high-energy CPA in a chain of laser amplifiers—ultimately generating tightly focused, 10-PW pulses with intensities of $10^{23}$ W/cm$^2$ or more. OPN

For more on OPCPA, including references and a Q&A, go online: www.osa-opn.org/tutorials/opcpa.

*The system shown here is based on an OPCPA pre-amplifier designed for the Shen Guang-II (SG-II) 5-PW laser facility, National Laboratory on High-Power Lasers and Physics, Shanghai, China.*




*The OPCPA pre-amplifier for the SG-II laser uses an Öffner stretcher to temporally extend the seed pulse.*

*The SG-II pre-amp passes the seed pulse through two OPA stages, each including two BBO crystals.*

OPN thanks Stefan Witte, Vrije Universiteit Amsterdam, Netherlands, for assistance with this tutorial. Source: Main diagram adapted from X. Liang et al., High Power Laser Sci. Eng. 6, E58 (2018) / Art by Phil Saunders