Utilizing the MTW-OPAL Idler to Seed a Raman Plasma Amplifier

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A Raman plasma amplifier (RPA) promises to overcome the damage limitations of chirped-pulse–amplification (CPA)[1] compression gratings by using a "damage-free" plasma to transfer energy from a multipicosecond high-energy pulse to a longer-wavelength femtosecond seed pulse.[2] This technology promises to achieve focused intensities exceeding 10^{23} W/cm^2 if pumped with the output of an Nd:glass-based CPA system laser[3] but requires a 1100- to 1250-nm seed pulse. Simulations show that to achieve an efficient amplifier, a high-intensity (10^{15} W/cm^2), sub-200-fs duration seed pulse is required.[4,5]

One technique for creating such a laser is by using the idler of an optical parametric chirped-pulse–amplification (OPCPA) system.[6] OPCPA systems produce two broadband pulses: a signal, which is seeded, and an idler, which has a wavelength that is red shifted. The Multi-Terawatt optical parametric amplifier line (MTW-OPAL) Laser System,[7,8] which produces 7-J, 20-fs pulses at 910 nm, consists of an ultrabroadband front end (UFE), a cylindrical Offner stretcher (COS), a power amplifier (N4), and a final DKDP amplifier (N5) as shown in Fig. 1(b). The idler that exits the N4 power amplifier has a bandwidth that ranges from 1100 to 1500 nm and 70 mJ of energy; if compressed and focused it would provide an ideal laser to seed an efficient RPA.

Using this idler requires overcoming two disadvantages that are a result of phase matching and energy conservation. First, phase matching in N4 produces an idler that is angularly dispersed, which hampers pulse focusing and compression.[9] Second, energy conservation inverts the spectral phase of the idler relative to the signal,[10] significantly changing the typical stretch–amplify–compress process of CPA.[1] Here we address both the phase reversal and angular dispersion of the MTW-OPAL idler with the addition of several optical subsystems to achieve 100-GW pulses at 1170 nm with 120-fs durations.

For ease of switching between the conventional MTW-OPAL configuration [Fig. 1(b)] and an idler OPAL configuration [Fig. 1(a)], many of the subsystems were left unchanged between the two modes of operation. No changes were made to the UFE or the N4 pump laser. The differences include switching from the COS to an alternate grism stretcher (GrS), operating at a reduced bandwidth, and bypassing the final amplifier (N5). This GrS accounts for the inversion of the idler spectral phase and allows for a standard grating compressor to be used to compress the idler (IGC). Angular dispersion was compensated with an angular dispersion compensator (ADC) prior to compression.

The design of the GrS is the result of compromise between a full compression of the pulse and optic manufacturing limitations.[11] Each grism is made from a 45°, N-SF57 prism mounted 1 mm away from a 1480-lp/mm gold grating. This design fully compensates for the two lowest orders of spectral phase (group-delay dispersion and third-order dispersion) but has some residual fourth-order dispersion. The stretcher also reduces bandwidth of OPAL to wavelengths that correspond those of interest for an RPA and a roof mirror double passes the pulse to a duration of 1 ns.

The idler exiting N4 is imaged with a 3× achromatic image relay onto two custom prisms to reduce angular dispersion from 123 μrad/nm to <0.5 μrad/nm. The idler is then compressed with a pair of parallel 1285-lp/mm gratings (PGL) and a roof mirror. Slant distance and input angle are selected to maximize peak power as measured with a custom IR-SPIDER (APE).[12] The compressed pulse was measured to have a full-width-half-maximum (FWHM) pulse duration of 120±10 fs (Fig. 2).

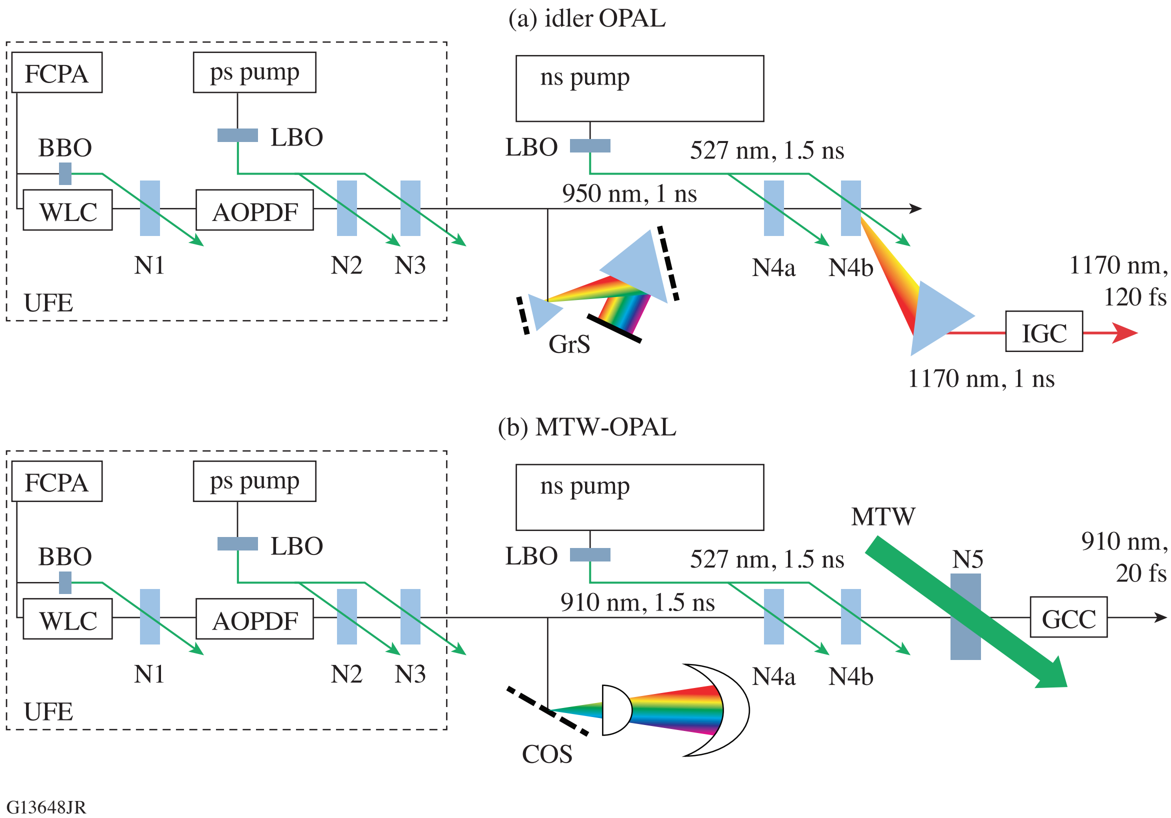

Figure 1
(a) A schematic of the idler OPAL and (b) standard MTW-OPAL configurations shows that they share many components including the UFE, the pre- and power amplifiers (N4a and N4b), and a nanosecond pump laser. (a) Systems added to operate the OPAL idler include an alternate grism stretcher (GrS), ADC, and an IGC. (b) The components of MTW-OPAL that are unused are the final amplifier, which is pumped by the MTW laser (N5), a COS, and grating compressor chamber (GCC). FCPA: fiber chirped pulse amplifier; WLC: white-light continuum; AOPDF: acoustic-optic-programable dispersive filter.

The focused and compressed idler had an average peak intensity of 5×10^{15} W/cm^2, which is about an order of magnitude lower than the transform-limited and diffraction-limited (TL-DL) intensity. The diffraction- and transform-limited intensity is based on the measured near-field beam profile and spectrum (row 1 in Table I). Reduction of this peak intensity is calculated from a subset of spatiotemporal effects: linear angular dispersion (AD), residual spectral phase, and monochromatic wavefront. Residual spectral phase was measured with the IR-SPIDER described above, while monochromatic wavefront was measured with a focal-spot diagnostic. This diagnostic was also used to measure residual angular dispersion by blocking all but two wavelengths in the GrS. How each of these spatiotemporal effects individually impact the achievable peak intensity is calculated in rows 2–4 in Table I. In the fifth row of Table I, all three spatiotemporal effects are applied.

Table I: Contributions to peak intensity.

	FWHM Pulse duration	Spot radii (μm)	AD_x,AD_y (μrad/nm)	Intensity (W/cm^2)
TL-DL	50.2	19.6	0,0	56×10^{15}
Spectral phase	120	–		$14.1\pm0.8 \times 10^{15}$
Monochromatic wavefront	–	21.5 to 70		$18\pm3.7 \times 10^{15}$
Linear angular dispersion	–	–	<0.5, 0.5	35 to 56×10^{15}
Combined	120	21.5 to 70	<0.5, 0.5	$4.7\pm1 \times 10^{15}$

TL-DL: transform-limited; AD: angular dispersion

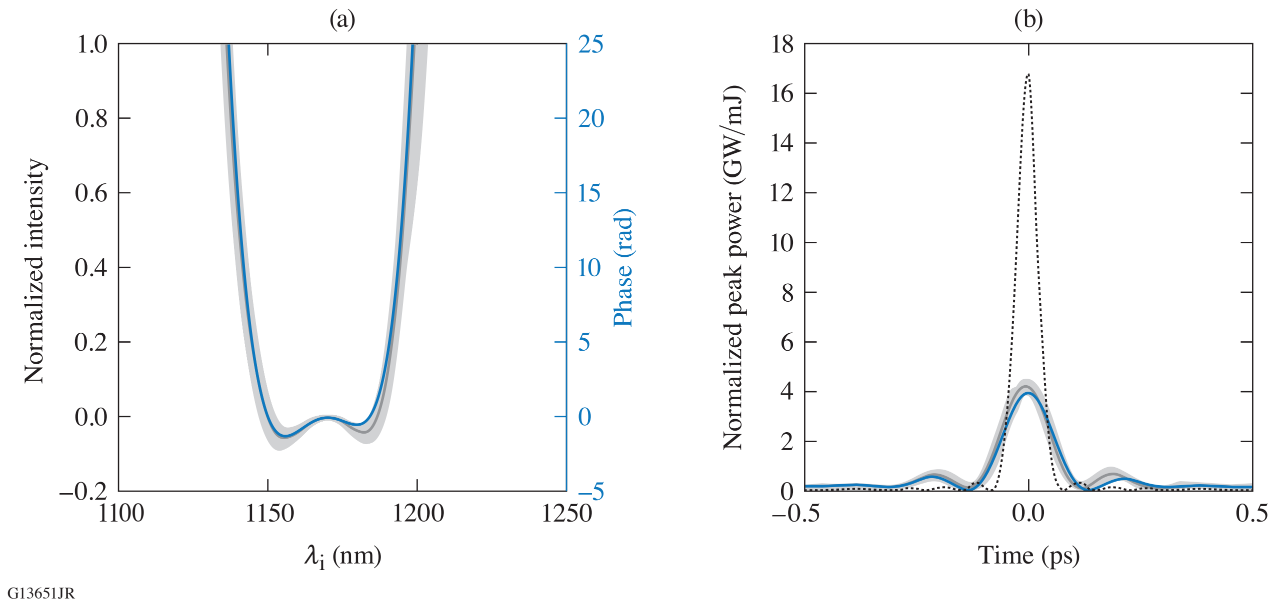

Figure 2
(a) The idler phase is measured over 100 shots by the IR-SPIDER and is denoted by the shaded area. The average phase and spectrum are shown by the solid gray and dotted curves, respectively, and closely matches the expected phase (blue curve). (b) The measured peak power is 4× lower than transform limited (black dotted curve), but matches the temporal pulse predicted by the design of the grism stretcher/grating compressor pair.

In conclusion, the compression of the idler to 100-GW peak powers from an existing OPCPA system has been demonstrated. While operating at a reduced peak intensity from the transform and diffraction limit, the idler from high-peak-power OPCPA systems achieves 100-GW pulses and provides a unique opportunity to further study the limits of laser technology.

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1. D. Strickland and G. Mourou, Opt. Commun. **56**, 219 (1985).
2. V. M. Malkin, G. Shvets, and N. J. Fisch, Phys. Rev. Lett. **82**, 4448 (1999).
3. J. H. Kelly *et al.*, J. Phys. IV France **133**, 75 (2006).
4. J. D. Sadler, "Optimisation and Applications of Raman Plasma Amplifiers," Ph.D. thesis, University of Oxford, 2017.
5. D. Haberberger *et al.*, Phys. Plasmas **28**, 062311 (2021).
6. A. Dubietis, G. Jonusauskas, and A. Piskarskas, Opt. Commun. **88**, 437 (1992).
7. J. Bromage *et al.*, High Power Laser Sci. Eng. **7**, e4 (2019).
8. J. Bromage *et al.*, High Power Laser Sci. Eng. **9**, e63 (2021).
9. T. Wilhelm, J. Piel, and E. Riedle, Opt. Lett. **22**, 1494 (1997).
10. I. N. Ross *et al.*, J. Opt. Soc. Am. B **19**, 2945 (2002).
11. S. Bucht *et al.*, J. Opt. Soc. Am. B **36**, 2325 (2019).
12. "APE Angewandte Physik & Elektronik GmbH," Ultrafast Laser Diagnostics & Tuneable Laser Solutions, Berlin, Germany.