Overcoming Gas-Ionization Limitations with Divided-Pulse Nonlinear Compression. II. Experimental Demonstration

G. W. Jenkins,[1,2] C. Feng,[1] and J. Bromage[1,2]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Institute of Optics, University of Rochester

Recent work has pushed self-phase modulation (SPM)-based spectral broadening to higher pulse energies and peak powers in both hollow-core fibers (HCF's)[1] and multipass cells (MPC's).[2] While these demonstrations have shown that spectral broadening using gas-based SPM can handle very high pulse energies, they also show that the process is limited by gas ionization. SPM-based pulse compressors must therefore employ large-core fibers or large focal spots in the MPC to avoid gas ionization.

This work demonstrates a more-scalable method to improve the energy limits of SPM-based pulse compression: divided-pulse nonlinear compression (DPNLC) (illustrated in Fig. 1). In DPNLC, a high-energy pulse is divided into multiple low-energy pulses that are spectrally broadened, recombined back into a high-energy pulse, and then compressed to a short duration.[3] The low-energy pulses have peak intensities below the gas-ionization intensity threshold and can pass through the HCF with high efficiency, while the original high-energy pulse would suffer significant ionization losses.

We demonstrated the advantages of DPNLC by spectrally broadening 1030-nm, 1.2-ps laser pulses in a 300-μm inner-diam, xenon-filled HCF. Xenon was chosen for its low ionization threshold to make the ionization effects strong. The advantage of

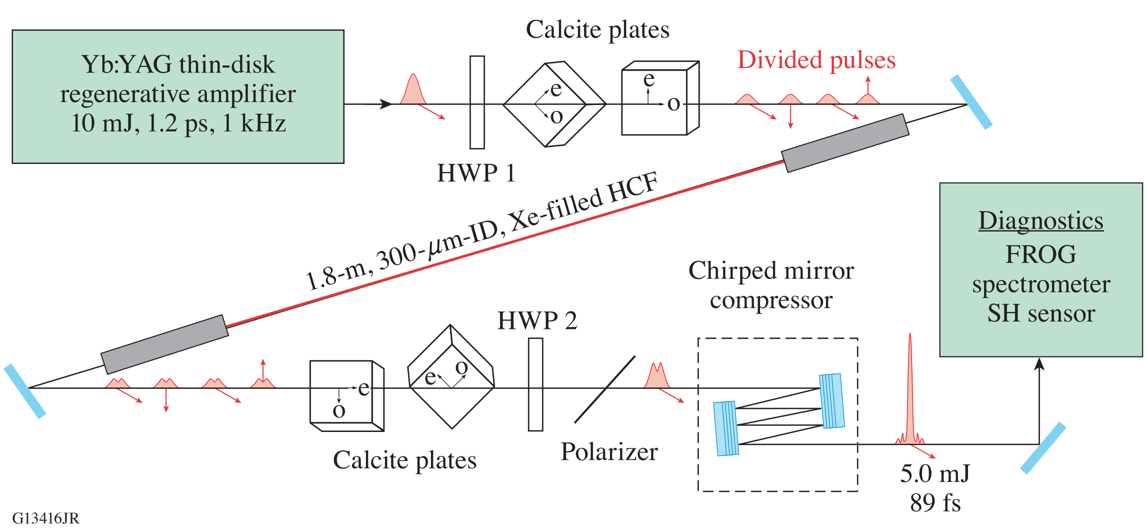

Figure 1
Apparatus for divided-pulse nonlinear compression analyzed in this summary. Birefringent plates with extraordinary axis "e" and ordinary axis "o" are used to divide one pulse into multiple low-energy, orthogonally polarized pulses. Red arrows indicate the pulse's polarization, and the distorted pulse shape after the SPM stage indicates an arbitrary reshaping by nonlinear processes in the SPM stage. FROG: frequency-resolved optical gating; HWP: half-wave plate; SH: Shack–Hartmann wavefront sensor.

DPNLC was immediately obvious based on the output energy from the HCF, as shown in Fig. 2. We measured a near-constant 67% transmission through the evacuated HCF for all input pulse energies, but once the HCF was filled with xenon, the transmission became a strong function of input energy. Above an input energy of 4 mJ, the xenon started ionizing, reducing the fiber throughput dramatically. HCF is a loosely guiding structure so plasma defocusing after the onset of ionization defocused energy out of the HCF and created large energy losses. Larger input energies did not yield larger output energies beyond exceeding the ionization threshold; the ionization clamped the output to approximately 2 mJ, consistent with previous observations of ionization in HCF.[1,4] By dividing the input into two pulses, the cumulative energy threshold for ionization nearly doubled and good HCF throughput was measured up to 8-mJ input energy. Finally, by dividing into four pulses, the full 10-mJ pulse energy of our laser can be broadened in the fiber without ionization losses; we measured 6.6-mJ output (four pulses with 1.65 mJ each).

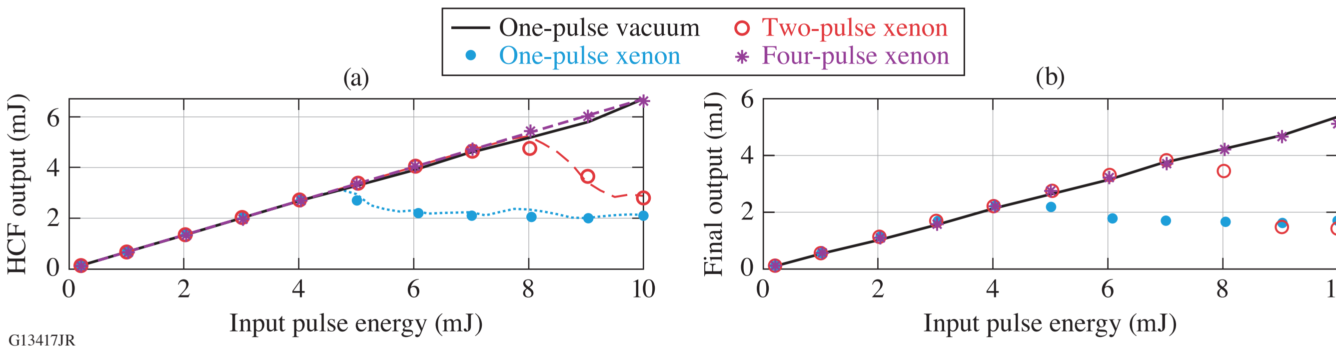

Figure 2
HCF throughput using one, two, and four divided pulses (a) immediately after the HCF and (b) after recombination and compression. Data markers plot the experimentally measured energies and dotted and dashed curves in (a) plot the simulated output energy using the model in our previous work.[5]

After the HCF, the divided and SPM-broadened pulses were recombined using a set of calcite plates identical to the dividing plates. High recombination efficiency was measured. For two pulses, the recombination efficiency was near perfect (>97% limited by the 2.5% polarization reflection on the polarizer) for all energies before the onset of gas ionization. After the onset of ionization, phase artifacts from the gas–plasma mixture prevented good recombination, and we measured losses as great as 50%. For four pulses, recombination efficiency was high for all input energies; we measured only a slow decrease with pulse energy down to 89% efficiency at 10-mJ input. We attribute this decrease to a small misalignment of the first calcite plate.

After recombination, DPNLC produces a high-quality output beam. The measured spectra are significantly broadened and agree with the side-lobed structure produced by SPM-based spectral broadening. The beam profile is high quality, with a measured M^2 of 1.21 and 1.20 along the x and y axes of the beam, respectively. M^2 did not change significantly with pulse energy, or the number of pulse divisions, or ionization plasma effects. We attribute the M^2 invariance to the modal-cleaning properties of the HCF;[6] only the fundamental mode of the fiber has significant energy at the end of the fiber and the fundamental mode sets the beam profile.

Finally, the recombined pulse was compressed with chirped mirrors to a shorter duration. In the best case (10-mJ input with four-pulse division), the pulse was compressible to 89 fs (FWHM), a compression factor of 13.4×. We estimate this pulse has 5.0 mJ of pulse energy at 91% of the transform-limited pulse's peak power. We expect this work will motivate DPNLC for use on higher-energy systems. DPNLC can enable large factors without the need for switching gases or making the system prohibitively large.

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