Overcoming Gas Ionization Limitations with Divided-Pulse Nonlinear Compression

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Nonlinear compression in gas-filled hollow-core fiber (HCF) has been very successful for the spectral broadening and subsequent temporal compression of high-average-power Yb systems to ~10-fs pulses. Pulse energy in an HCF is limited, however, by self-focusing and ionization.[1] In this summary, we examine the limits on HCF energy scaling and simulate a method to overcome those limits: divided-pulse nonlinear compression.

In HCF nonlinear compression, a glass cladding guides light within a gas-filled hollow core. The gas provides the nonlinearity to broaden the pulse's spectrum through self-phase modulation, and after the fiber, the pulse can be compressed to a shorter duration with devices such as chirped mirrors and prisms.[2] Self-focusing can be controlled by reducing the nonlinear index of the gas as the peak power of the pulse is increased.[3,4] The gas pressure is a convenient variable to tune the nonlinear index and can be set to keep >90% of the power in the fundamental mode. Ionization is controlled with fiber diameter. At small diameters, the peak intensity is high enough to ionize gas and give rise to plasma effects. A small-diameter fiber is optimal for maximum spectral broadening, as long as plasma effects remain small.

To overcome ionization limits, we have simulated divided-pulse nonlinear compression (DPNLC), as depicted in Fig. 1(a). The intensity of the divided pulses will be lower than the intensity of the single pulse so smaller fibers can be used without ionizing the gas. We simulated a 10-mJ, 1-ps (FWHM) pulse centered at a 1030-nm wavelength, propagating through a 1.8-m, xenon-filled HCF with a model adapted from Horak and Poletti.[5] We set the gas pressure to half the value given by Tempea and Brabec[3] and varied the fiber radius to vary the strength of plasma effects.

Simulations with one pulse show significant energy loss from plasma effects, as shown in Fig. 1(b). Due to intrinsic fiber losses, some energy loss is unavoidable, and the ideal pulse would only lose energy to the intrinsic loss of the fundamental mode. The ideal energy is plotted as a black dotted line for reference. The output energy tracks the ideal energy line well for large fiber diameters, but with the onset of ionization around 550 μm, there is a sharp loss of energy. Using two pulses shifts the onset of ionization to a diameter of around 400 μm, and using four pulses shifts the onset to around 300 μm. Figure 1(c) plots all loss channels for the two-pulse simulation and shows that energy losses are dominated by linear fiber losses and recombination losses. The linear fiber losses increase after the onset of ionization because the generated plasma defocuses the pulse.[6] The HCF lacks total internal reflection, so it fails to confine the defocused pulse. Recombination losses increase because the trailing pulses pass through a gas–plasma mixture ionized by the first pulse and acquire phase artifacts from the index difference. Those phase artifacts appear as interference between the pulses when they are recombined and are removed by the polarizer. By shifting the onset of ionization to smaller fiber diameters, these losses can be avoided and the spectral broadening can be increased.

The ultimate figure of merit that demonstrates improvements from DPNLC is the peak power of the compressed pulse. We assumed we could compensate Kerr and plasma effects with up to second-order spectral phase during compression and plotted the peak power in Fig. 2. Because smaller-diameter fibers provide more spectral broadening, the general trend is that the smaller fibers give a higher peak power as long as plasma effects are avoided. Plasma effects decrease the energy more than a small diameter and increase the bandwidth, so the peak power falls after the onset of ionization. DPNLC improves the optimum peak power achievable from 60 GW with one pulse to about 90 GW with four pulses.

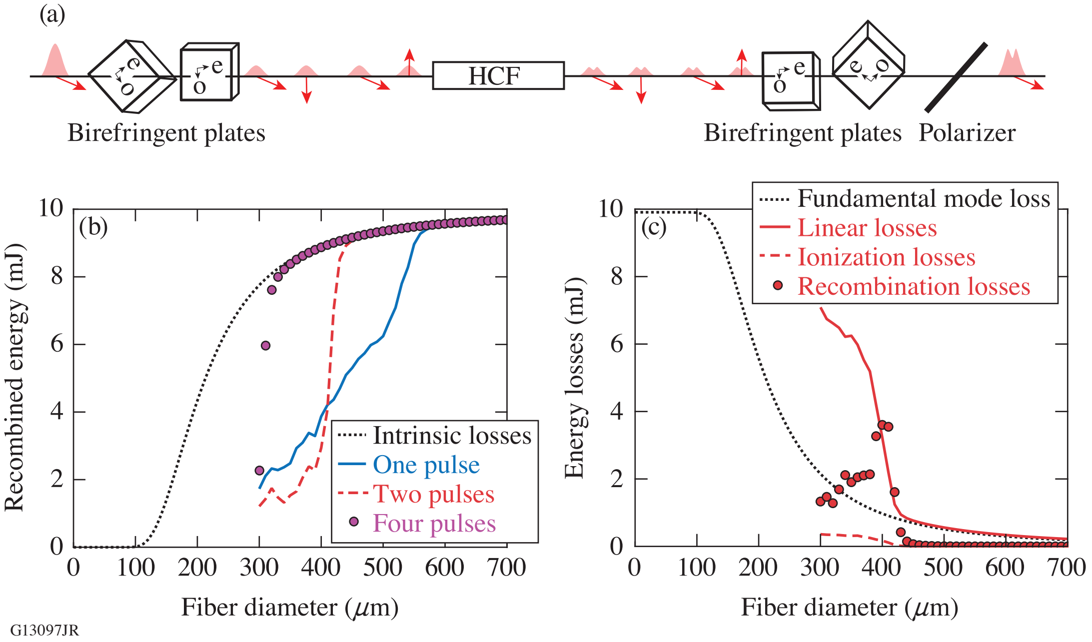

Figure 1
(a) Schematic of DPNLC with four pulses. Birefringent plates with extraordinary axis "e" and ordinary axis "o" can be used to separate the pulses temporally, and identical birefringent plates and a polarizer recombine the pulses. Red arrows indicate the pulse's polarization. (b) Simulated output energy after HCF and recombination for a range of fiber diameters. Onset of ionization is clearly visible and results in large energy losses. (c) Simulated energy losses for two divided pulses. The majority of energy loss is due to plasma-defocusing-induced linear and recombination losses.

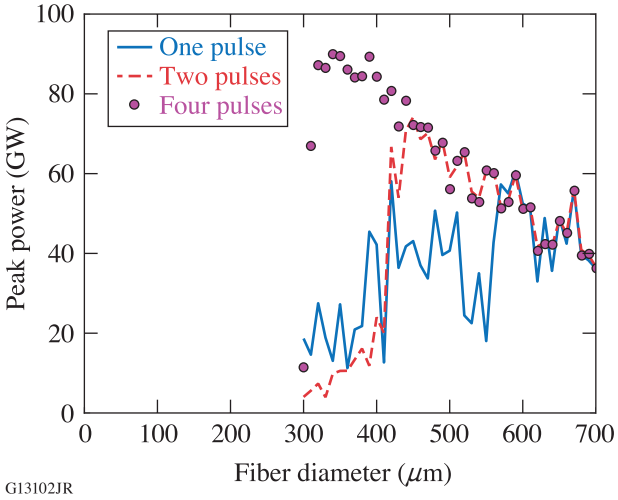

Figure 2
Peak power after recombination and compression with up to second-order spectral phase. Energy improvements from DPNLC give a significant improvement in peak power, with 60 GW achievable with one pulse improved to 90 GW with four pulses.

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