Spatiotemporal Control of Laser Intensity Through Cross-Phase Modulation

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Spatiotemporal pulse shaping provides control over the trajectory and range of an intensity peak. While this control can enhance laser-based applications, the optical configurations required for shaping the pulse can constrain the transverse or temporal profile, duration, or orbital angular momentum (OAM). Here we present a novel technique for spatiotemporal control that mitigates these constraints by using a “stencil” pulse to spatiotemporally structure a second primary pulse through cross-phase modulation (XPM) in a Kerr lens. The temporally shaped stencil pulse induces a time-dependent focusing phase within the primary pulse. This technique, the “flying-focus X,” allows the primary pulse to have any profile or OAM, expanding the flexibility of spatiotemporal pulse shaping for laser-based applications. As an example, simulations show that the flying-focus X can deliver an arbitrary-velocity, variable-duration intensity peak with OAM over distances much longer than the Rayleigh range.

Spatiotemporal pulse shaping offers a new paradigm for controlling laser intensity. By exploiting space–time correlations in the amplitude or phase of a laser pulse, a number of recent techniques have created arbitrary-velocity intensity peaks that remain nearly propagation invariant over distances much longer than the Rayleigh range. These features promise to revolutionize a wide range of laser-based applications, including high-power amplifiers and compact accelerators. Nevertheless, each of the existing techniques requires an optical configuration that constrains properties of the intensity peak, such as its transverse or temporal profile, duration, or OAM. As an example, the original “chromatic” flying focus uses a chirp and a chromatic lens to control the time and location at which each temporal slice of a laser pulse comes to focus, respectively. While this technique offers some flexibility to shape the transverse profile of the far field, the chromatic aberration and chirp can place a lower bound on the duration of the intensity peak that is much larger than the transform-limited duration.[1,2] An alternative technique, the “achromatic” flying focus, employs the spherical aberration of an axiparabola to focus different annuli in the near field to different axial locations in the far field and an echelon to adjust their relative timing.[3,4] Here, the intensity peak can have a near-transform-limited duration, but the flattop transverse profile required in the near field and the spherical aberration of the axiparabola fully determine the far-field profile.

We describe a novel technique for spatiotemporal control: the “flying-focus X,” which combines temporal pulse shaping with XPM to produce an ultrashort, arbitrary-velocity intensity peak, with or without OAM, over distances far greater than the Rayleigh range. Specifically, a temporally shaped, high-intensity “stencil” pulse induces the time-dependent focusing of a second “primary” pulse through XPM in a medium with an intensity-dependent refractive index (Kerr lens) (Fig. 1). The minimum and maximum intensity of the stencil pulse set the focal range of the primary pulse, while its duration sets the velocity of the resulting intensity peak. Use of a stencil pulse mitigates the constraints on the primary pulse, allowing for spatiotemporal control independent of properties such as the far-field duration, transverse profile, or OAM. In effect, these constraints are offloaded onto the stencil pulse. As a result, flying-focus X provides unprecedented flexibility for structuring the far-field properties of the intensity peak, promising to further enable or enhance a wide range of laser-based applications.

Figure 1 illustrates how temporal pulse shaping and XPM can be used to control the trajectory and range of an intensity peak. A stencil pulse and a primary pulse, overlapped in space and time, co-propagate along the z axis and enter a convex, parabolic

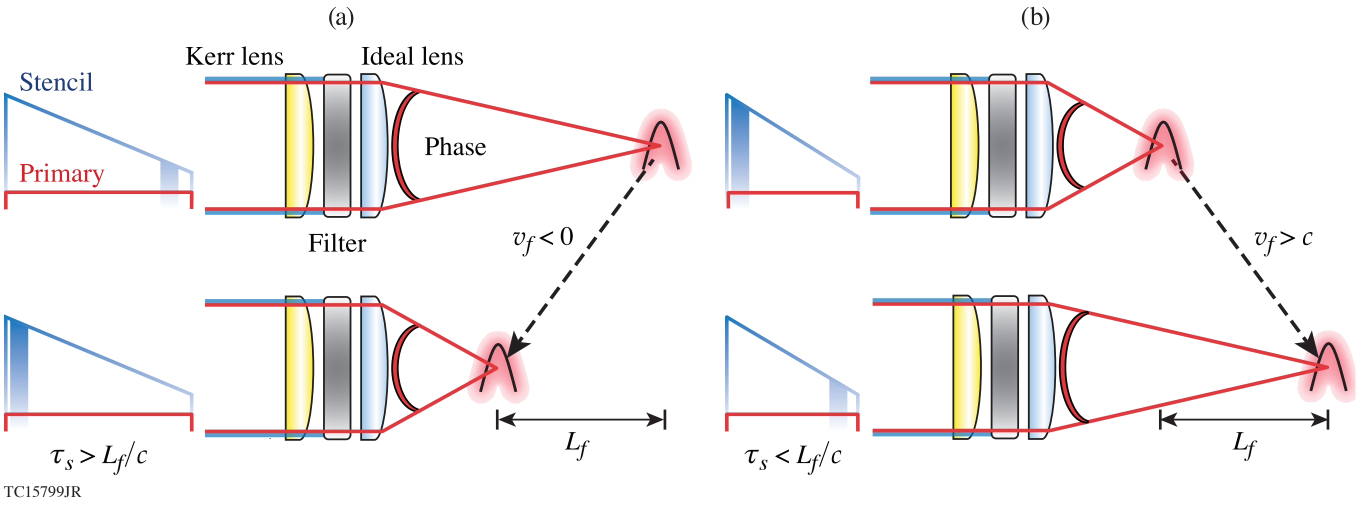

Figure 1
A schematic of the flying-focus X. A high-intensity stencil pulse with a flattop transverse and shaped temporal profile co-propagates with a low-intensity primary pulse. The stencil induces a time-dependent focusing phase on the primary in a parabolic Kerr lens. A filter removes the stencil, while an ideal lens provides additional focusing for the primary. The resulting focus travels over a distance L_f at a velocity v_f, both of which can be tuned by shaping the temporal profile of the stencil. A stencil pulse with an intensity that ramps up in time can produce either (a) negative or (b) positive superluminal focal velocities depending on its duration τ_s.

Kerr lens. The two pulses have distinct wavelengths or polarization vectors, and the stencil intensity is much greater than the primary intensity. The stencil pulse has a flattop transverse profile, which, in combination with the parabolic shape of the Kerr lens, ensures that the primary pulse acquires an aberration-free wavefront curvature. The instantaneous intensity of the stencil dictates the time dependence of that curvature, with high stencil intensities inducing greater curvature. The time-dependent wavefront curvature is equivalent to that applied by an ideal lens with a time-dependent focal length. As a result, the primary pulse can have any transverse profile or orbital angular momentum, in addition to the extended focal range and velocity control afforded by previous spatiotemporal pulse-shaping techniques.

Simulations show that the flying-focus X can create an ultrashort-duration intensity peak traveling near the vacuum speed of light over many Rayleigh ranges (Fig. 2)—a configuration ideal for advanced accelerators.[5,6] To produce the desired focal velocity, the stencil intensity ramps up linearly in time over ~330 fs. In the far field, the ≈10-fs intensity peak maintains its diffraction-limited Gaussian spot over the entire focal range (L_f = 1 cm), while traveling at a focal velocity v_f = 1.01 c.

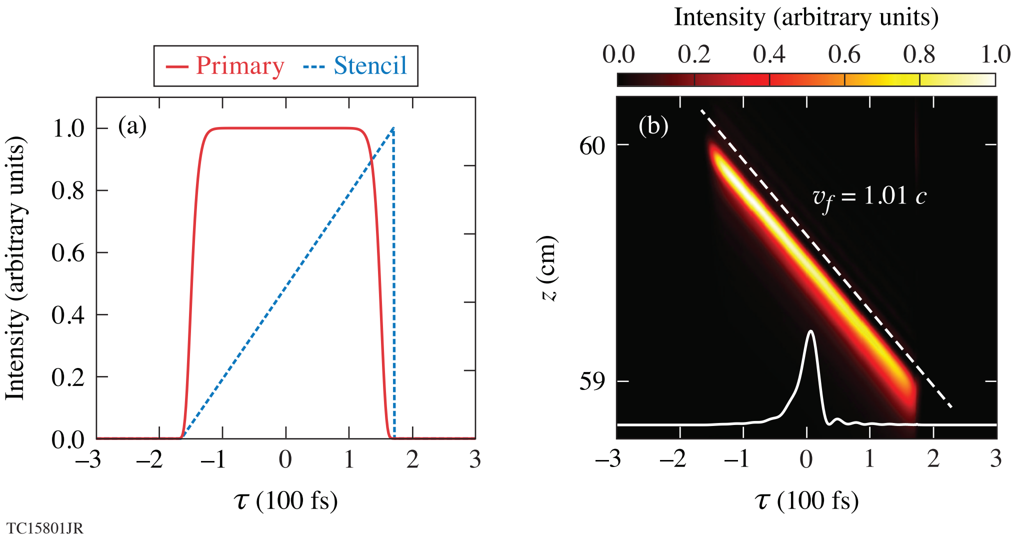

Figure 2
Simulation results for a flying-focus X pulse with v_f = 1.01 c, demonstrating velocity control, an ultrashort duration, and near propagation invariance through the focal range. (a) The temporal profile of the stencil and primary pulses at the entrance of the Kerr lens. (b) The maximum intensity of the primary pulse in the far field and a lineout of its temporal profile. All values are normalized to their respective maxima and $\tau = t - z/c$.

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