Measurement of the Spatiotemporal Electric Field of Ultrashort Superluminal Bessel-X Pulses

Pamela Bowlan, Heli Valtna-Lukner, Madis Lõhmus, Peeter Piksarv,
Peeter Saari and Rick Trebino

Bessel-X pulses are of great interest because they propagate unchanged in vacuum or linear media over large distances.[1] In other words, they act like optical bullets—without exhibiting any diffraction or dispersion—and do not spread in space or time. Bessel pulses have many applications, such as plasma generation, light filamentation, imaging, particle micromanipulation and cell transfection. An *x-z* or *x-t* slice of a Bessel-X pulses's spatiotemporal intensity profile $I(x,y,z)$ or $I(x,y,t)$ resembles the letter "X." Interestingly, theory predicts that the electric field of a Bessel-X pulse propagates with equal phase and group velocities, both greater than *c* in a vacuum. This has been experimentally demonstrated several times since the original pioneering publication;[1] nevertheless, the pulses' superluminal group velocity is still occasionally questioned.

This makes it important to directly measure these pulses. The catch is that Bessel-X pulses have a complex spatiotemporal shape, requiring a measurement technique with simultaneous femtosecond temporal resolution and micrometer spatial resolution.

We recently accomplished this task.[2,3] To measure the electric field of a Bessel-X pulse, we used the new ultrashort-laser-pulse measurement technique, SEA TADPOLE.[4] It involves sampling a small spatial region of the pulse with a single-mode optical fiber and then interfering this with a known reference pulse from another identical fiber in a spectrometer, yielding the pulse intensity and phase $E(\lambda)$—and hence also $E(t)$— at each point in space.

To generate the Bessel-X pulse, we propagated roughly 30 fs pulses from a Ti:sapphire oscillator through a fused-silica axicon with an apex angle of 176°. While SEA TADPOLE measured the spatiotemporal intensity and phase, most
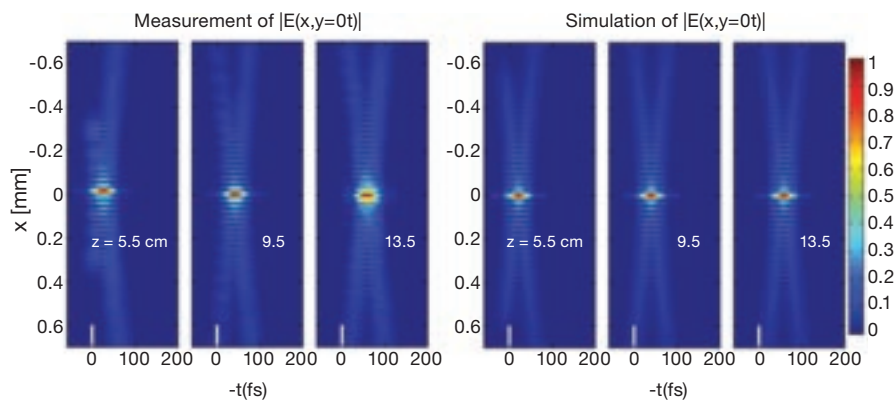
(Left) Measured field amplitude vs. transverse position (*x*) and time (*t*) at three different distances (*z*) after the axicon. (Right) Corresponding simulations. Color indicates the modulus of electric field, normalized to have a maximum of 1. The white bar emphasizes the location of *t* = 0.

of the interesting features were in the intensity, which is shown in the figure. Numerical simulations of the optical wave-packet are in good agreement.

Note that the central part (the apex of the double-conical shape) containing the bright spot remains essentially unchanged over a propagation distance of 8 cm. In contrast, a Gaussian beam of the same waist would have expanded by 26 times over this distance. We also measured the Bessel-X pulse's superluminal speed. SEA TADPOLE conveniently measured the Bessel-X pulse's arrival time relative to the reference pulse, which traveled at the speed of light *c*. So, if the Bessel-X pulse were traveling at the speed of light, then, for each value of *z*, its spatio-temporal intensity would be centered at *t* = 0. However, it is easy to see that this was not the case. We measured our pulse's speed along the *z* axis to be 1.00012*c*— within 0.001 percent of the predicted value. (A superluminal Bessel-X pulse's velocity should not, of course, be confused with the signal velocity.)

In a related study, we added a convex (or concave) lens in front of the axicon,[3] which resulted in an accelerating (or decelerating) modification of the Bessel-X pulse, which had been theoretically studied in a recent paper.[5] The Bessel pulse's group velocity accelerated from 1.0002*c* to 1.0009*c* during 4 cm of propagation, and the decelerating Bessel pulse slowed down from 1.00007*c* to 1.00003*c* over a 12-cm distance. ▲

Pamela Bowlan (pambowlan@gatech.edu) and Rick Trebino are with the Georgia Institute of Technology, School of Physics, Atlanta, Ga., U.S.A. Heli Valtna-Lukner, Madis Lõhmus, Peeter Piksarv and Peeter Saari are with the University of Tartu, Institute of Physics, Tartu, Estonia.

References
1. P. Saari and K. Reivelt. Phys. Rev. Lett. **79**, 4135-8 (1997).
2. P. Bowlan et al. Opt. Lett. **34**, 2276-8 (2009).
3. H. Valtna-Lukner et al. Opt. Express **17**, 14948-55 (2009).
4. P. Bowlan et al. J. Opt. Soc. Am. B **25**, A81-A92 (2008).
5. M. Clerici et al. Opt. Express **16**, 19807-11 (2008).