Measuring the spatiotemporal field of ultrashort Bessel-X pulses

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We present direct measurements of the spatiotemporal electric field of an ultrashort Bessel-X pulse generated using a conical lens (axicon). These measurements were made using the linear-optical interferometric technique SEA TADPOLE, which has micrometer spatial resolution and femtosecond temporal resolution. From our measurements, both the superluminal velocity of the Bessel pulse and the propagation invariance of the central spot are apparent. We verified our measurements with simulations. © 2009 Optical Society of America

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Bessel-X pulses are of great interest because they propagate in vacuum or linear media over large distances like an optical bullet—without exhibiting any diffraction or temporal spread. Bessel pulses have many applications, such as plasma generation [1], light filamentation (see reviews [2,3]), imaging [4], particle micromanipulation [5], and cell transfection [6]. Bessel-X pulses are one type of axially symmetrical localized wave (see [7–10] and references therein) that corresponds to a broadband wave packet of coaxial zeroth-order Bessel beams. Their longitudinal and transverse wavenumbers (which determine the spacing of the Bessel rings) are proportional to the temporal frequency of the individual Bessel beam constituents, and it is this characteristic that distinguishes them from other possible superpositions of Bessel beams [7]. Their three-dimensional intensity profile $I(x,y,z)$ or $I(x,y,t)$ consists of a bright central spot surrounded by weaker interference rings all inside of two cones that start at the origin, and one extends forwards and the other backwards in time (or z). Therefore, an x–t or x–z slice of the field resembles the letter X. In principle Bessel-X pulses can propagate over an infinite distance without any spread. But in practice, owing to finite aperture sizes and aberrations in the Bessel beam generators, the propagation invariant zone is restricted, though this is still usually several orders of magnitude larger than the Rayleigh range of a Gaussian beam with the same focal spot size. Interestingly, the field of a Bessel-X pulse propagates along the z axis with equal phase and group velocities that are greater than c in vacuum. It is important to measure these pulses, not only to observe their interesting and useful properties but also to aid in their generation and application. But Bessel-X pulses have a complex spatiotemporal shape, so a *spatiotemporal* measurement technique with simultaneous femtosecond temporal resolution and micrometer spatial resolution is needed.

Several previous publications have reported experimental studies of Bessel-X pulses. The propagation invariance of the small central spot of a Bessel-X pulse in a dispersive medium was first shown in [9], where a holographic element generated the field. Evidence of X-like spatial profiles and the superluminal propagation of Bessel-X waves were demonstrated using an annular slit and a pinhole to generate cross correlations of the fields with a white-light source [10]. Later, direct autocorrelation measurements were made of the X profile of the pulses generated from sub-10 fs laser pulses [11]. The superluminal speed of Bessel-X pulses has also been measured by observing the ionization front in argon gas owing to the central spot of an intense Bessel-X pulse generated using an axicon and 70 fs pulses [1]. Recently a Hartman–Shack sensor and frequency-resolved optical gating were used to separately characterize both the spatial and the temporal fields of a Bessel-X pulse [12]. But, to our knowledge, a direct measurement of the field [i.e., $E(x,z,t)$] of a Bessel-X pulse in the course of its propagation has never been made.

In this Letter we do so, reporting "snapshots in flight," or measurements of the spatiotemporal X-like profile of a femtosecond Bessel-X pulse, including the phase versus time. Our results show propagation invariance over 8 cm, as well as the superluminal velocity of the Bessel-X pulse. To generate the Bessel-X pulse, we propagated ~37 nm bandwidth, ~30 fs pulses from a KM Labs Ti:Sa oscillator through a fused-silica axicon with an apex angle of 176°. The spot size of the beam at the axicon's front surface was 4 mm. For the measurements we used the linear-optical spectral interferometric technique, SEA TADPOLE [13,14], and we compared our measurements with numerical simulations.

A detailed description of SEA TADPOLE can be found in [13,14]. Briefly, this device involves sampling a small spatial region of the Bessel pulse with a single-mode optical fiber (having a mode diameter of 5.4 μm) and then interfering this with a reference pulse in a spectrometer to reconstruct the pulse intensity and phase $E(\lambda)$ [and hence also $E(t)$] at a point in space. We scan the fiber transversely (versus

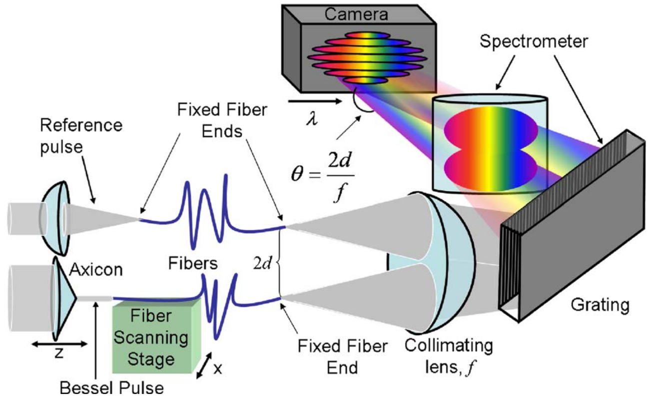

Fig. 1. (Color online) Experimental setup. A single-mode optical fiber samples a small region of a Bessel pulse, generated using an axicon. The reference pulse is coupled into an identical fiber. At the other end of the fibers, one lens is used to collimate both beams, and this also causes them to cross. A CCD camera is placed at their crossing point to record the resulting interference. Wavelength is mapped to the camera's horizontal dimension, so that a two-dimensional spectral interferogram is recorded, and $E(\lambda)$ is retrieved from this image [14]. To measure the spatiotemporal field, we scan the Bessel pulse's sampling fiber in x and the axicon in z, so that an interferogram at each fiber position is measured, and from this, the field $E(\lambda,x,z)$ is measured.

x) and the axicon longitudinally (versus z) to yield the spatiotemporal field, $E(x,z,t)$. Our Bessel-X pulses had cylindrical symmetry about the z axis, so we did not scan versus y, but we could if necessary. Our temporal resolution was 17 fs, enough to measure a pulse with 37 nm of bandwidth, and zero filling decreased the point spacing to 4.6 fs. Our spatial resolution is at most equal to the fiber's mode size, $\sim 5\ \mu$m, but, because we resolve the complex field, rather than the intensity, we often measure features several micrometers smaller than this [14]. SEA TADPOLE measures the spectral phase difference between the unknown and the reference pulse. So, for these measurements we placed a flat glass window with a thickness equal to the center thickness of the axicon in the reference arm to cancel the group-delay dispersion (GDD) introduced at the center of the axicon. In principle there will still be a little radially varying GDD left in the beam, but because the axicon angle is so large, considering our bandwidth, this will be negligible. Therefore, our measurements reflect the spatiotemporal intensity and phase introduced by the axicon geometry, and not the group-velocity dispersion (GVD) of its material, or the input pulse. Our experimental setup is shown in Fig. 1.

Three of our measurements are shown in Fig. 2. While our device measures the spatiotemporal intensity and phase, most of the interesting features are in the intensity, and the measured pulse is chirp-free owing to dispersion compensation, so here we only show the measured pulse amplitude (the square root of the intensity).

We also performed numerical simulations, shown on the right in Fig. 2 that are in good agreement with the measurements, except that the wings in the $z=5.5$ cm image are shorter in the measurement, and at $z=13.5$ cm the fringe patterns are slightly different. Both of these features are influenced by aberrations in the axicon that occur because they are difficult to machine perfectly and, for example, the tip of the cone is usually slightly round [15]. Although we have accounted for the shape of the tip in our simulations, these aberrations are difficult to model precisely, and so some discrepancies are present.

There are several interesting features in our measurements. The central maximum of the measured beam has a FWHM spot size of $17.2\ \mu$m at $z=5.5$ cm, $17.3\ \mu$m at $z=9.5$ cm, and $18.6\ \mu$m at $z=13.5$ cm, and the beam shape remains essentially unchanged over a propagation distance of 8 cm. At $z=13.5$ cm, the interference pattern is just beginning to change owing to the aberrations in the axicon. Note that, for a Gaussian beam of this size, the waist would have expanded by 26 times after propagating 8 cm. Also, the fringe periodicity is $27.8\ \mu$m in the first two images and $27\ \mu$m in the last image, which is in good agreement with the theoretical prediction of $27.8\ \mu$m. Again, in our measurements this quantity changes with z by a small amount owing to the aberrations.

We also see the Bessel-X pulse's superluminal group velocity along the propagation axis, which does not violate Einstein's causality if distinguished from

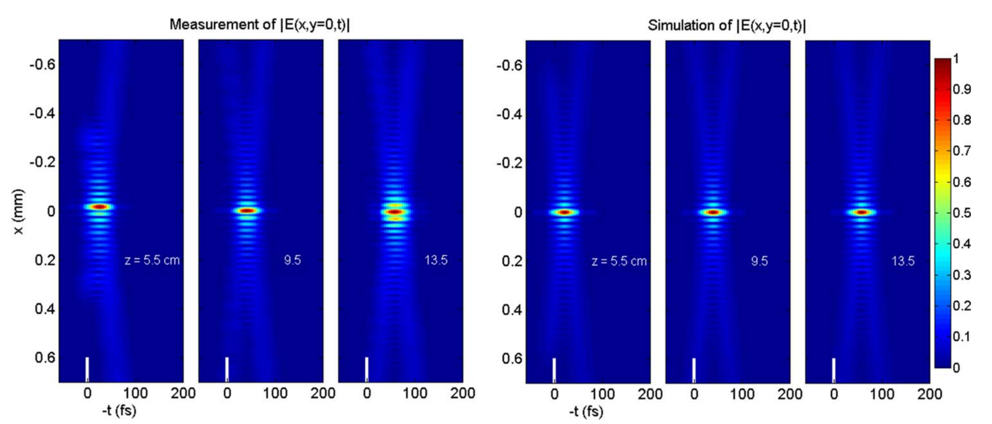

Fig. 2. (Color online) Left, the measured field amplitude at three different distances (z) after the axicon; right, the corresponding simulations. Intensity is indicated by the scale. We normalized each field to have a maximum of 1. The white bar is to emphasize the location of $t=0$.

the signal velocity [16]. SEA TADPOLE measures the Bessel-X pulse's arrival time with respect to the reference pulse, the latter of which is approximately Gaussian in both space and time and travels 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 spatiotemporal intensity would be centered at the same time (here $t=0$ and emphasized with the white bar), but it is easy to see that this is not the case. Our simulations predict that for our axicon's angle the Bessel-X pulse's speed along the z axis should be $1.00013c$. Therefore, over a distance of 8 cm the Bessel-X pulse would lead our moving reference frame (the reference pulse) by 35 fs. In our results the center of the pulse is shifted in time by 32 fs between $z=5.5$ cm and $z=13.5$ cm, which is in good agreement with our theoretical prediction. To verify this result, we repeated the experiment five times and consistently measured time shifts close to our predictions for this axicon. We also realigned the experiment in between these trials to assure that this delay was not due to (or significantly affected by) misalignment of the axicon's scanning stage.

While both the phase and group velocity along the propagation axis of the Bessel-X pulse are superluminal, these velocities should not be confused with the propagation speed of the information or the signal velocity [10]. Because these pulses are solutions to the wave equation, they do not transmit information superluminally and do not violate Einstein's causality. Any attempt to make a signal "mark" in a Bessel-X pulse would result in reshaping of the spatial profile, and the mark would spread out luminally and not propagate superluminally. On the other hand, a different type of Bessel wavepacket, where the lateral wavenumbers of the constituent Bessel beams are all the same and are independent of their temporal frequencies, would not possess the X-like profile and can carry a signal without undergoing the reshaping. But such pulses propagate subluminally and spread out in time owing to their inherent free-space GVD.

In conclusion, using SEA TADPOLE, we made direct spatiotemporal recordings of the electric field of Bessel-X pulses, and we verified these results with simulations. We demonstrated both the propagation invariance of the Bessel-X pulse and its superluminal group velocity along the z axis, which we found to be $1.00012c$—within 0.001% error of the expected value.

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