

# Direct measurement of an electric field in femtosecond Bessel–Gaussian beams

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Received May 6, 2009; revised June 23, 2009; accepted June 30, 2009;  
posted July 21, 2009 (Doc. ID 111017); published August 4, 2009

We demonstrated the mapping of the spatial oscillation of electric fields in the transverse plane of a femtosecond Bessel–Gaussian laser beam from the first principle of classical electrodynamics. An attosecond burst of electrons for probing the electric force was placed in the Bessel beam through photoemission with single isolated 276 as extreme ultraviolet pulses. The direction reversal of the electric field in adjacent Bessel rings was directly confirmed by observing the momentum shift of the probe electrons. © 2009 Optical Society of America

OCIS codes: 020.2649, 320.7100.

The observation of periodic electric field oscillations of light pulses from the first principle of the Maxwell theory of light was demonstrated with the advent of attosecond extreme ultraviolet (XUV) pulses [1]. Here the phrase “first principle” refers to the direct measurement of the electric force of the light field acting on a point charge. The measurements that have occurred thus far, however, have looked only at the temporal, rather than spatial, profiles of ultrashort laser beams. In this Letter, we present the measurement of the electric field variations in *space* and report what is believed to be the first *direct* observation of the periodic field direction reversal in the transverse plane of a Bessel–Gaussian (BG) beam.

In cylindrical coordinates, the electric field of a pulsed, linearly polarized Bessel beam with center frequency  $\omega_0$  that propagates in the  $z$  direction is expressed approximately as

$$\epsilon(r, z, t) = E_0 f(t) J_0(k_r r) \cos(k_z z - \omega_0 t), \quad (1)$$

where  $E_0$  is the peak amplitude at the center of the beam,  $f(t)$  is the envelope function that specifies the shape of the pulse,  $J_0$  is the zeroth-order Bessel function of the first kind, and  $k_r$  and  $k_z$  are the propagation constant components in the radial ( $r$ ) and  $z$  directions, respectively. A Bessel beam has a unique property referred to as “nondiffracting” in free space [2]. In other words, the transverse intensity distribution does not change as the beam propagates. This invariance allows for many applications, such as optical tweezers [3] and harmonic generation [4].

The electric field vector changes direction periodically along the transverse direction, which is expressed by the sign change of the Bessel function between adjacent intensity rings. In principle, the change of field direction can be measured by interferometric methods, since the direction reversal can be treated as a  $\pi$  phase shift of the light wave. However, such a phase shift also exists in scalar field Bessel beams (such as sound waves [5]); thus the measurement is indirect. The change of field direction with  $r$  has never been observed for light beams using the first principle of classical electrodynamics,

which defines the electric field as the force exerted on a point charge of unit value. Although measurements have been conducted in the microwave region [6], there are no such measurements with optical frequencies.

According to Newton’s law, the time derivative of the momentum,  $p$ , of a probe electron is proportional to the force and thus the electric field of the BG beam. The measured momentum value of a probing electron placed at point  $r$  is

$$\begin{aligned} p(r)|_{t=\infty} &= p_0 - e \int_{t_0}^{\infty} \epsilon(r, t') dt' \\ &\approx p_0 + \frac{e}{\omega_0} E_0 J_0(k_r r) f(t_0) \sin(\omega_0 t_0). \end{aligned} \quad (2)$$

Here  $e$  is the charge of the electron,  $p_0$  is its field-free momentum, and  $t_0$  is the time that the probe electron is placed in the field. Equation (2) indicates that the electric field variation in the transverse plane,  $E_0 J_0(k_r r)$ , can be determined by the measurement of the momentum of an electron placed at various  $r$  positions while keeping  $t_0$  constant. This can be accomplished by scanning an XUV beam across the BG light beam. The  $z$  dependence is dropped in Eq. (2) when the laser and XUV beam copropagate [1].

In our experiments, the attosecond burst of electrons was placed in the BG beam through photoemission from argon atoms with 276 as XUV pulses. The single isolated attosecond pulses were produced using a double optical gating (DOG) with  $\sim 8$  fs laser pulses [7]. The laser system is a carrier-envelope phase-stabilized chirped pulse amplifier followed by a hollow-core fiber compressor [8], producing 1 mJ pulses centered at 780 nm at 1.5 kHz repetition rate. The DOG field was created by using two birefringent quartz plates and a thin BBO crystal [9]. The DOG is able to generate isolated XUV pulses even when the driving laser pulse contains many optical cycles.

To temporally characterize the attosecond XUV pulses, we used the complete reconstruction of attosecond burst (CRAB) method based an attosecond

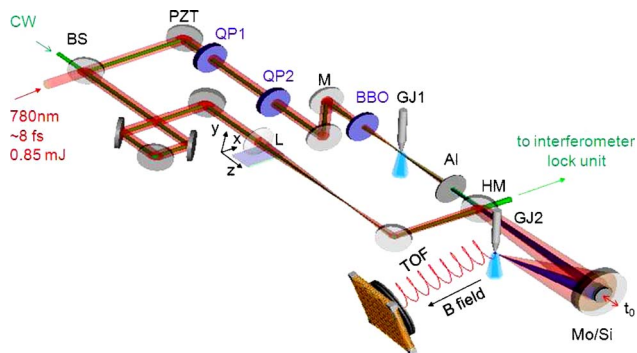


Fig. 1. (Color online) Schematic of the attosecond streak camera. BS, beam splitter; PZT, piezoelectric transducer; QP1 and QP2, quartz plates; M, spherical mirror; GJ1 and GJ2, gas targets; Al, aluminum filter; HM, hole-drilled mirror; L, lens.

streaking [10]. The setup with a Mach-Zehnder configuration is illustrated in Fig. 1. First, the input near-infrared (NIR) laser was split into two beams. The reflected one passed through the DOG optics and was focused to an argon-filled gas cell for the attosecond pulse generation. Meanwhile, the reflected portion of the beam remained linearly polarized and was used for streaking. The two pulses then recombined at a hole-drilled mirror. To stabilize the interferometer, active control of a mirror with a piezoelectric transducer (PZT) was accomplished by copropagating a 532 nm CW laser through the interferometer and using its interference pattern as a feedback signal.

The XUV beam was then incident onto a spherical Mo/Si mirror that was concentric with a spherical silver mirror used to focus the streaking beam. A 50  $\mu\text{m}$  diameter argon-filled gas jet was placed at the focus of the XUV beam, to generate photoelectrons, and the NIR beam to give the photoelectrons a mo-

mentum kick. The inner Mo/Si mirror was movable with a PZT allowing delay between the XUV and the streaking field. By recording the kinetic energy spectrum of the emitted photoelectrons as a function of delay with a position-sensitive time of flight detector, a streaked spectrogram was created. Using a blind iterative algorithm, the principle-components generalized-projections algorithm, the attosecond pulse could be reconstructed from the spectrogram [11].

Figures 2(a) and 2(b) show the measured and reconstructed CRAB traces, respectively. The temporal profile shown in Fig. 2(c) indicates the pulse duration to be 276 as, which is one tenth of the fundamental optical cycle ( $\sim 2.6$  fs). The validity of the measurement was confirmed by the excellent frequency marginal comparison shown in Fig. 2(d), which is a comparison of the unstreaked spectrum (dashed curve) and the reconstructed spectrum (solid curve). Satellite pulses are less than 0.1% of the main pulse, indicating a clean temporal profile, as shown in the insert of Fig. 2(c) [11].

Owing to the annular aperture effect from the Ag-coated annular focusing mirror, the spatial profile of the streaking NIR beam near the focus was similar to a BG beam. Images of the focused NIR beams were captured with a CCD camera, as shown in Fig. 3. A lineout across the center of the image indicating the intensity variation is also shown.

A thin lens mounted on a 3-D translation stage was added to the streaking arm as shown in Fig. 1. By moving the lens position in the transverse direction, we scanned the XUV beam across the BG beam. The time delay between the NIR field and the attosecond pulse was fixed, assuring  $t_0$  in Eq. (2) was constant. The position of the gas jet that produced the probing

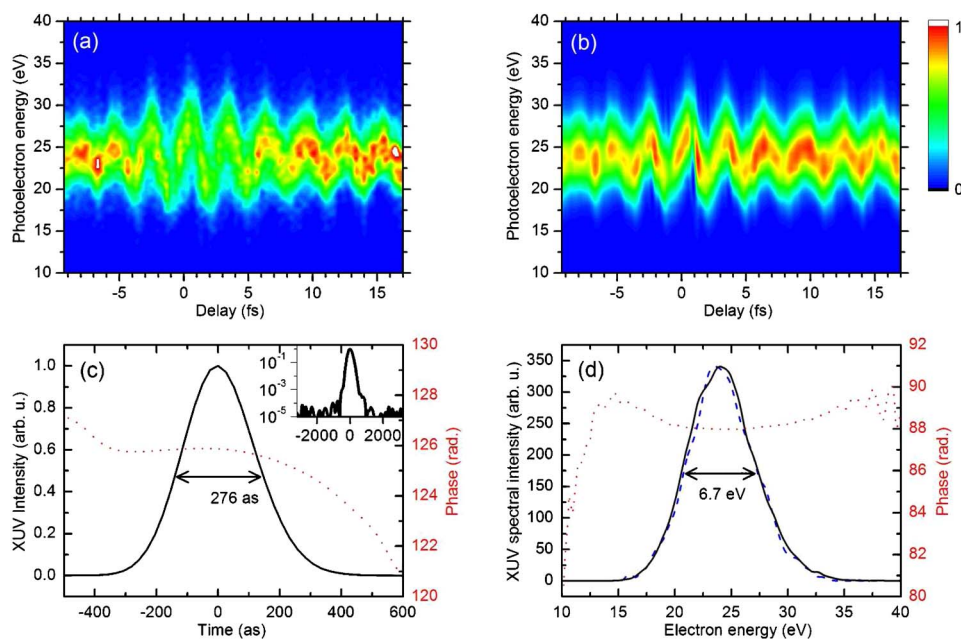


Fig. 2. (Color online) Measurement of isolated attosecond pulse generated by double optical gating with CRAB. (a) Measured CRAB trace. (b) Reconstructed CRAB trace. (c) Reconstructed XUV pulse shape (solid curve) and phase (dotted curve). (d) Reconstructed XUV spectrum (solid curve) and phase (dotted curve). Also shown is the measured XUV spectrum (dashed curve) without the streaking laser for marginal comparison.

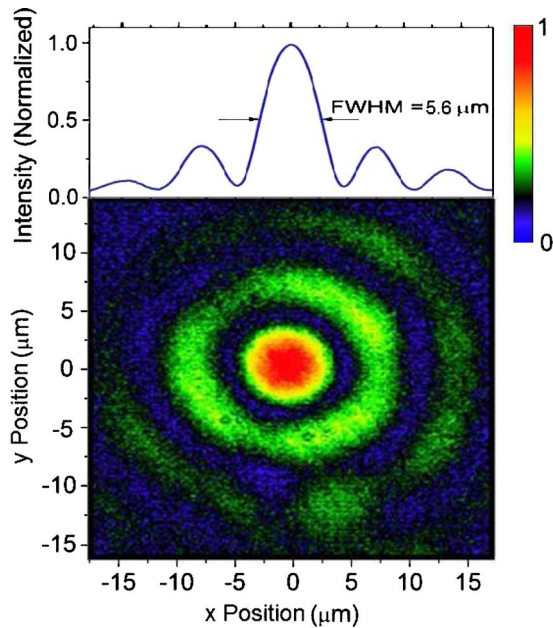


Fig. 3. (Color online) (Top panel) the lineout through the center of the image. (Bottom panel) CCD image of the focal spot of the streaking laser beam after reflection by the annular mirror.

electrons was fixed relative to the XUV beam. Figure 4(a) shows the streaked electron spectrum plotted as a function of the transverse displacement between the focused streaking beam and the XUV beam. As the streaking beam shifts across the XUV, the momentum of the electrons shifted either above or below the field-free value,  $p_0$ .

By choosing  $t_0$  near the peak of the streaking pulse,  $f(t_0)=1$ , and at the maximum streaking point,  $\sin(t_0)=1$ , the electric field value at point  $r$  was determined from  $(p(r)|_{t=\infty}-p_0)\omega_0/e$ . The momentum value was obtained by finding the centroid of the electron kinetic energy distribution at each spatial point in Fig. 4(a), as shown by the white line. The resultant electric field and corresponding intensity are shown in Fig. 4(b). The field value directly gives the direction and magnitude of the electric field. Thus the spatial distribution of the electric field in the BG beam was determined from the first principle of electrodynamics. The difference in streaking amplitude between the central spot and the first minimum was  $\sim 60\%$ , in agreement with the measured CCD image and indicating an accurate mapping of the transverse field distribution. Also, since the XUV spot size is an important experimental parameter for attosecond pump-probe experiments, a transverse scan can be used to nonintrusively determine the spatial size of the XUV beam by deconvolving the spectrogram.

In conclusion, the transverse electric field of a Bessel-Gaussian laser beam was directly measured by using an attosecond electron probe. The electric field direction reversal from one Bessel ring to the next was clearly observed. Together with the direct measurement of the electric field oscillation with time [1], attosecond streak cameras allow the noninvasive full characterization of the light field in both

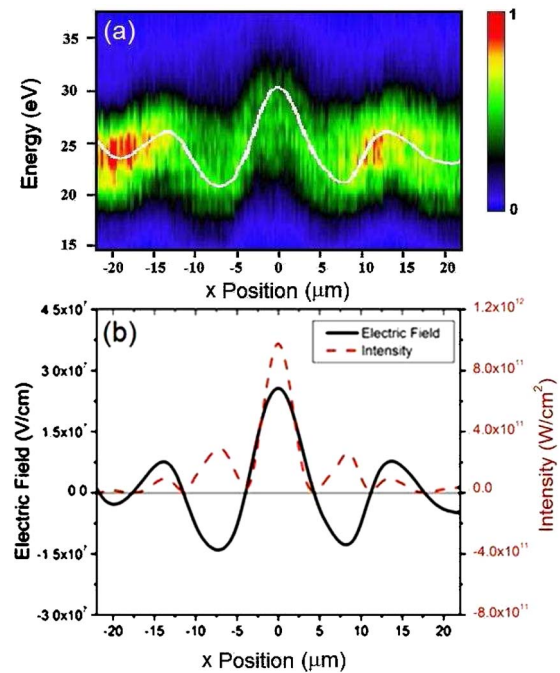


Fig. 4. (Color online) (a) Streaked photoelectron spectrum plotted as a function of the radial position of the streaking beam. (b) Electric field and intensity derived from (a).

time and space and could be used to map temporal variations of light fields through a laser focus.

This material is supported by the U.S. Army Research Office (USARO) under grant W911NF-07-1-0475 and by the U.S. Department of Energy (DOE).

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