Direct Measurement of Light Waves


The electromagnetic field of visible light performs $\sim 10^{15}$ oscillations per second. Although many instruments are sensitive to the amplitude and frequency (or wavelength) of these oscillations, they cannot access the light field itself. We directly observed how the field built up and disappeared in a short, few-cycle pulse of visible laser light by probing the variation of the field strength with a 250-attosecond electron burst. Our apparatus allows complete characterization of few-cycle waves of visible, ultraviolet, and/or infrared light, thereby providing the possibility for controlled and reproducible synthesis of ultrabroadband light waveforms.

Although the wave nature of light has long been known, it has not been possible to measure directly the oscillating field of light. Radiation in the visible and higher frequency spectral ranges can so far only be characterized in terms of physical quantities averaged over the wave period. Nonlinear optical techniques now allow measurement of $E_\perp(t)$, the amplitude envelope, and $\omega_\perp(t)$, the carrier frequency, as a function of time $t$, for light pulses with durations that approach the wave cycle ($\lambda/2$). The carrier-envelope phase, which determines the timing between $E_\perp(t)$ and $\omega_\perp(t)$, can also be measured ($\delta t$). These measurements rely on carrier-envelope decomposition, which is physically meaningful only as long as the frequency spectrum of the wave is confined to less than one octave ($\lambda/4$). If the radiation is composed of frequencies spanning a broader range ($\lambda/5 - \lambda/17$), direct access to the field is required. Attosecond pulses of extreme ultraviolet (XUV) light were predicted to suit this purpose ($\lambda/18 - \lambda/19$). We report the direct measurement of the buildup and disappearance of the electric field of a light pulse through the use of an attosecond probe.

The electric field is defined as the force exerted on a point charge of unit value. Its conceptually most direct measurement must therefore rely on measurement of this force. In a light wave, the electric field $E_\perp$, and hence the force $F = qE_\perp$ it exerts on a particle with charge $q$, are subject to rapid variations. Access to this force is possible only if the probe charge is instantly placed in the field, i.e., within a time interval $\tau_{\text{probe}}$ over which the temporal variation of the force is “frozen”, i.e., $\tau_{\text{probe}} / \tau_0 = (2\pi)\omega_0$, where $\tau_0$ is the wave period. The probe charge can be launched into the field by knocking electrons free from atoms or ions instantly. In a linearly polarized wave, the change of the electrons’ momentum $\Delta p(r, t)$ at location $r$ and time $t$ along the direction of the electric field is given by

$$\Delta p(r, t) = e \int E_\perp(r', t') \, dt' = e A_\perp(r, t)$$

where $e$ is the electron charge and $A_\perp(r, t)$ is the vector potential of the electric field $E_\perp(r, t) = E_0 k_r(r, t) \cos(\omega_0 t + \varphi)$, where $E_0$ is the maximum field amplitude, and $k$ is the wave vector. In our analysis, we assumed the wave to propagate along the $z$ direction, and $t = t_{\text{real}} - z/v_\perp$ was defined in a retarded frame to yield $t = 0$ as locked to the peak of the pulse travelling at the group velocity $v_\perp$.

The relation $E_\perp(r, t) = -A_\perp(r, t)/\varepsilon_0$ implies that measuring the momentum boost $\Delta p(r, t)$ imparted to the freed electrons by the field at the location $r$ at two instants differing in time by $\Delta t \ll \tau_0/4$ will yield the electric field strength and direction directly as $E_\perp(r, t) = (\Delta p(r, t - \Delta t/2) - \Delta p(r, t + \Delta t/2))/e\Delta t$. This measurement procedure relies on the momentary release of the electrons within $\tau_{\text{probe}} \ll \tau_0/4$. For near infrared, visible, and ultraviolet light, this condition dictates that $\tau_{\text{probe}} < 1$ fs. Varying the timing of such a subfemtosecond electron probe across the laser pulse provides complete information on the electric field of the light wave.

These considerations suggest that the electron probe needs to be localized not only in time to a tiny fraction of the wave period $\tau_0$, but also in space to a tiny fraction of the wavelength $\lambda_\perp$ of the light wave to be measured. The latter requirement can be substantially relaxed if we trigger the electron release with an energetic photon pulse that copropagates with the laser wave in a collinear beam (Fig. 1). Because the timing of the probe electrons relative to the light field is invariant to space in this case, in a gently focused laser beam they can be released and are subsequently allowed to move over distances substantially larger than $\lambda_\perp$, in a volume within which the spatial variation of the field amplitude $E_\perp(r, t)$ negligibly small for a fixed value of $t$.

Putting the above concept into practice requires the electron probe to be scanned through the entire laser pulse. For each newly set timing $t$, measurement of the momentum shift $\Delta p(r)$ of the probing electrons requires the laser pulse to pass through the measurement apparatus again. Full characterization of the light waveform is therefore only feasible if it can be reproducibly generated for repeated measurements. Another equally important prerequisite for implementation of the above concept is the availability of an energetic instantaneous excitation (for launching the probing electrons) that is not only confined temporally to a fraction of 1 fs but is also synchronized to the light wave with similar

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accuracy. With the generation of waveform-controlled, intense, few-cycle light pulses (20) and their successful application to produce a single 250-as XUV pulses synchronized to the driver light wave (21), these preconditions are now fulfilled. The waveform-controlled pulses—after having produced the attosecond photon probe—allow through nonlinear optical frequency conversion the synthesis of reproducible, synchronized, ultrabroadband, few-cycle waveforms (5–17). These can be repeatedly sent into the measurement apparatus with exactly the same waveform, and the subfemtosecond XUV pulse is able to produce the electrons by photoionization for probing the oscillating light field with sufficient temporal resolution.

The electrons knocked free from the atoms by the XUV pulse can be most conveniently detected if the direction of their movement is left unchanged by the light field. This applies if electrons are detected within a narrow cone aligned with the electric field vector of the linearly polarized laser wave along the x direction and are ejected with a large-enough initial momentum p to fulfill |p| > |Δp max|, where Δp max is the maximum momentum shift induced by the field. A large initial momentum also benefits the measurement by enhancing the change of the electrons’ kinetic energy ΔW, according to ΔW ≈ (p/m)Δp, and m is the electron’s mass. This expression, together with Eq. 1, implies that the energy shift scales linearly with both the electric field and the wavelength of the light field to be probed (22). The importance of a large ΔW lies in the facts that the probing electrons are emitted with an inherent uncertainty ΔW ΔΔW probe ≈ h/2π (where h is Planck’s constant h divided by 2π) and that the dynamic range over which the light field strength can be reliably measured scales with ΔW max/ΔW probe (ΔW max is the maximum shift in the pulse).

Measurement of E(t) over a substantial dynamic range requires a ΔW max of several tens of electron volts. For an initial kinetic energy of W i ≈ 100 eV, this condition is satisfied for E0 < 108 V/cm for near-infrared light and requires E0 ≈ 3 × 108 V/cm for ultraviolet light (22). Noble gases with a low atomic number (such as helium and neon) safely resist ionization by a few-cycle field at these field strengths (23). The accuracy of definition of the location r is dictated by the size of the volume within which the electrons are detected. A large initial momentum also benefits the probing electrons (Fig. 2, inset), we calculated the measured spectrum of the few-cycle laser pulse (Fig. 1). Linearly polarized, waveform-controlled, <5-fs, 0.4-mJ, 750-nm (T0 = 2.5 fs) laser pulses (20), with carefully optimized values of φ and Ep, produce single 250-as XUV pulses at (hωUV/mc2) ≈ 9 eV in a gas of neon atoms (21). The XUV pulse copropagates with the laser pulse in a colinear, laserlike beam to a second neon target placed in the focus of a spherical, two-component, Mo/Si multilayer mirror (21). The mirror, of 120-nm focal length, reflects XUV radiation over a band of ~9 eV, centered at ~93 eV. Consequently, the XUV pulse sets electrons free by photoionization with an initial kinetic energy of p2/2m = hωUV − W i (where W i is the electron’s binding energy) spread over an ~9-eV bandwidth, implying that ΔW probe ≈ 9 eV. The electrons’ energy shift ΔW(t) ≈ e(p/m)ΔW probe(t) probes the vector potential. The volume of light-field probing is defined laterally by the ~10-μm diameter of the XUV beam at its waist and longitudinally by the ~50-μm size of the neon jet, which is well confined within the focal volume of the laser beam (diameter, <60 μm; confocal parameter, >5 mm). For p2/2m = 100 eV, the electrons traveled less than 1 μm within 100 fs and hence remained safely confined to the region of constant laser field amplitude.

The field-induced variation of the final energy spectrum of the probe electrons versus delay between the XUV burst and the laser pulse (Fig. 2) reveal, without the need of any detailed analysis, that probing is implemented by a single burst of subfemtosecond duration that is synchronized with subfemtosecond accuracy to the measured laser field. E0(t) can now be directly (i.e., without any iterative steps) obtained through the procedure outlined above (Fig. 3). From the measured spectrum of the few-cycle laser pulse (Fig. 3, inset), we computed E0(t) by a simple Fourier transformation on the assumption of absence of spectral phase variations. The result, with E0 and φ chosen to yield the best match to the measured values, is shown in gray. The excellent fit to the measured field evolution indicates a near-transform-limited pulse. Its duration was evaluated as 4.3 fs, in good agreement with the result of an autocorrelation measurement.

It has been predicted by theory that the few-cycle pulse pumping the XUV source has a “cosine” waveform (φ ≈ 0) if a single subfemtosecond pulse emerges from the ionizing atoms (24). Our results (Fig. 3) yield the exper-
Direct probing of light-field oscillations represents what we believe to be a substantial extension of the basic repertoire of modern experimental science. The door to practical applications is opened by the creation of the key element of the demonstrated light-field detector, the synchronized attosecond electron probe, in a noninvasive manner. In fact, our intense \( \sim 5 \text{ fs} \) laser pulse appears to be capable of producing the necessary XUV trigger burst without suffering any noticeable back-action to its own temporal shape (Fig. 3). After having produced the attosecond photon probe, this powerful few-femtosecond pulse is ideally suited for the synthesis of ultrabroadband, few-cycle, optical waveforms (5–17). Being composed of radiation extending from the infrared through the visible to the ultraviolet region, the resultant few-cycle, monochromatic, and conceivably even subcycle waveforms will offer a marked degree of control over the temporal variation of electric and magnetic forces on molecular and atomic time scales.

These light forces, in turn, afford the promise of controlling quantum transitions of electrons in atoms and molecules and—at relativistic intensities—the center-of-mass motion. Reproducible ultrabroadband light wave synthesis, a prerequisite for these prospects to materialize, is inconceivable without subfemtosecond measurement of the synthesized waveforms. Beyond providing the subfemtosecond electron probe for these measurements, the substantial experimental efforts associated with the construction and reliable operation of a subfemtosecond photon source will pay off in yet another way. The envisioned control of electronic motion with light forces can only be regarded as accomplished once it has been measured. Owing to their perfect synchronism with the synthesized light waveforms, the subfemtosecond photon probe will allow us to test the degree of control achieved by tracking the triggered (and hopefully steered) motion in a time-resolved fashion.

References and Notes