The electromagnetic field of visible light performs ~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 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.

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accuracy. With the generation of waveform-controlled, intense, few-cycle light pulses (20) and their successful application to producing 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 waves (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 \( p_t \) to fulfill \( |p_t| > |\Delta p_{\text{max}}| \), where \( \Delta p_{\text{max}} \) 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 \( \Delta W \), according to \( \Delta W = (p_t/m) \Delta p \), 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 \( \Delta W \) lies in the facts that the probing electrons are emitted with an inherent uncertainty \( \Delta W_{\text{probe}} = \hbar/\tau_{\text{probe}} \) (where \( \hbar \) is Planck’s constant \( h \) divided by 2\( \pi \)) and that the dynamic range over which the light field strength can be reliably measured scales with \( \Delta W_{\text{max}}/\Delta W_{\text{probe}} \) (\( \Delta W_{\text{max}} \) is the maximum shift in the pulse).

Measurement of \( E_i(t) \) over a substantial dynamic range requires a \( \Delta W_{\text{max}} \) of several tens of electron volts. For an initial kinetic energy of \( W_0 \approx 100 \) eV, this condition is satisfied for \( E_0 < 10^8 \) V/cm for near-infrared light and requires \( E_0 \approx 3 \times 10^8 \) 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 \( E(r,t) \) is approximately independent of \( r \). If the field is probed in the beam focus, this condition requires the probing electrons to be confined—during their interaction with the laser field—laterally (xy) and longitudinally (z) to a small fraction of the diameter and to the confocal parameter of the beam, respectively.

In a proof-of-concept experiment, we directly measured the \( E_i(t) \) of the few-cycle laser pulse used for producing the attosecond photon probe (Fig. 1). Linearly polarized, waveform-controlled, <5-fs, 0.4-mJ, 750-nm (\( T_0 = 2.5 \) fs) laser pulses (20), with carefully optimized values of \( \psi \) and \( E_0 \), produce single 250-as XUV pulses at \( (\hbar \omega_{\text{XUV}})_{\text{mean}} = 93 \) eV in a gas of neon atoms (21). The XUV pulse copropagates with the laser pulse in a collinear, 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-mm focal length, reflects XUV radiation over a band of \( \sim 9 \) eV, centered at \( \sim 93 \) eV. Consequently, the XUV pulse sets electrons free by photoionization with an initial kinetic energy of \( p_i^2/m = \hbar \omega_{\text{XUV}} = W_0 \) (where \( W_0 \) is the electron’s binding energy) spread over an \( \sim 9 \) eV band, implying that \( \Delta W_{\text{probe}} \approx 9 \) eV. The electrons’ energy shift \( \Delta W(t) = E(p)/m \Delta t_i(t) \) probes the laser vector potential. The volume of light-field probing is defined laterally by the <10-\( \mu \)m diameter of the XUV beam at its waist and longitudinally by the <50-\( \mu \)m size of the neon jet, which is well confined within the focal volume of the laser beam (diameter, >60 \( \mu \)m; confocal parameter, >5 mm). For \( p_i^2/m \approx 100 \) eV, the electrons traveled less than 1 mm 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) reveals, without the need of any detailed analysis, that probing is implementeldon by a single burst of subfemtosecond duration that is synchronized with subfemtosecond accuracy to the measured laser field. \( E_i(t) \) 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 calculated \( E_i(t) \) by a simple Fourier transformation on the assumption of absence of spectral phase variations. The result, with \( E_0 \) and \( \psi \) 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 (\( \psi \approx 0 \)) if a single subfemtosecond pulse emerges from the ionizing atoms (24). Our results (Fig. 3) yield the exper-
imetal evidence. From this measurement, we also learn that the electric field points toward the electron detector at the pulse peak and that its strength is \( \approx 7 \times 10^7 \) V/cm. With the temporal evolution, strength, and direction of \( E_t(t) \) measured, we have performed a complete characterization of a light pulse in terms of its classical electric field.

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 \( \approx 5 \) 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, monochrome, 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—their center-of-mass motion. Reproducible ultrabroadband light wave synthesis, a prerequisite for these prospects to materialize, is conceivable 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


In the limit of \( |\Delta m| \ll |p| \), the change in the electrons’ final kinetic energy is given by \( \Delta W_{e,max} = \Delta W_{i,max} \cdot 1/2 \), where \( U_{e,max} = eF_y 1/4m_e \cdot \Delta t^2 \) is the electrons’ quiver energy averaged over an optical cycle at the peak of the light pulse.

Increase of the excitation energy \( h \nu_{exc} \) tends to reconcile the conflicting requirements of avoiding field ionization and ensuring a high dynamic range.


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Nanoribbon Waveguides for Subwavelength Photonics Integration

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Although the electrical integration of chemically synthesized nanowires has been achieved with lithography, optical integration, which promises high speeds and greater device versatility, remains unexplored. We describe the properties and functions of individual crystalline oxide nanoribbons that act as subwavelength optical waveguides and assess their applicability as nanoscale photonic elements. The length, flexibility, and strength of these structures enable their manipulation on surfaces, including the optical linking of nanoribbon waveguides and other nanowire elements to form networks and device components. We demonstrate the assembly of ribbon waveguides with nanowire light sources and detectors as a first step toward building nanowire photonic circuitry.

References and Notes

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Photons, the optical analog of electrons, shares the logic of miniaturization that drives research in semiconductor and information technology. The ability to manipulate pulses of light within sub-micrometer volumes is vital for highly integrated light-based devices, such as optical computers, to be realized. Recent advances in the use of photonic band gap (1, 2) and plasmonic (3, 4) phenomena to control the flow of light are impressive in this regard. One alternative route to integrated photonics is to assemble photonic circuits from a collection of nanowire elements that assume different functions, such as light creation, routing, and detection. Chemically synthesized nanowires have several features that make them good photonic building blocks, including inherent one-dimensionality, a diversity of optical and electrical properties, and, in principle, the ability to operate above and below the diffraction limit. The toolbox of nanowire device elements already includes various types of transistors (5), light-emitting diodes (6), lasers (7, 8), and photodetectors (9). An important step toward nanowire photonics is to develop a nanowire waveguide that can link these various elements and provide the flexibility in interconnection patterns that is needed to carry out complex tasks such as logic operations (10). Our demonstration of nanowire-based photonics complements and expands upon recent work on optical beam steering in mesostructured silica cavities (11) and on subwavelength structures made lithographically (12, 13) and by the drawing of silica microfibers (14).

Nanoscale ribbon-shaped crystals of binary oxides exhibit a range of interesting properties including extreme mechanical flexibility, surface-mediated electrical conductivity (15), and lasing (16). As part of a recent study of the photoluminescence (PL) of SnO2 nanoribbons, we noted that ribbons with high...