Ultrafast electro-optic light with subcycle control

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Light sources that are ultrafast and ultrastable enable applications like timing with subfemtosecond precision and control of quantum and classical systems. Mode-locked lasers have often given access to this regime, by using their high pulse energies. We demonstrate an adaptable method for ultrastable control of low-energy femtosecond pulses based on common electro-optic modulation of a continuous-wave laser light source. We show that we can obtain 100-picojoule pulse trains at rates up to 30 gigahertz and pulses based on common electro-optic modulation of a continuous-wave laser light source.

We show that we can obtain 100-picojoule pulse trains at rates up to 30 gigahertz and demonstrate sub–optical cycle timing precision and useful output spectra spanning the near infrared. Our source enters the few-cycle ultrafast regime without mode locking, and its high speed provides access to nonlinear measurements and rapid transients.

Ultrafast lasers produce trains of femtosecond-duration light pulses and can operate as frequency combs to provide a time and frequency reference bridging the optical and microwave domains of the electromagnetic spectrum (1). Achieving phase control of these pulse trains to better than a single optical cycle has enabled diverse applications ranging from optical atomic clocks (2) to controlling quantum states of matter (3, 4). These capabilities have evolved over decades, and yet they still require the intrinsic stability of a suitable mode-locked resonator.

One alternative method that produces optical pulse trains without mode locking is electro-optic modulation (EOM) of a laser (5, 6). These pulse generators, or “EOM combs,” first gained interest nearly 50 years ago because of their simplicity, tunability, reliability, commercialization, and spectral flatness (7–10). Nevertheless, despite their broad appeal and decades of development, the fundamental goal of electronic switching with the optical cycle precision needed to create ultrafast trains of EOM pulses has remained unmet, limited by thermodynamic noise and oscillator phase noise inherent in electronics.

Here, we report the generation of ultrafast and ultrastable electro-optic pulses without any mode locking. Our experiments demonstrate widely applicable techniques to mitigate electro-optic noise by relying on the quantum-limited optical processes of cavity transmission, nonlinear interferometry, and nonlinear optical pulse compression, as well as low-loss microwave interferometry. This results in phase control of ultrafast electro-optic fields with a temporal precision better than one cycle of the optical carrier. Because electro-

In order for the EOM comb to achieve ultrastable coherence between \( f_p \) and \( f_{rep} \), it is vital to keep the integrated phase noise of each mode below \( \pi \) radians. In the temporal domain, this corresponds to subcycle timing jitter, and for EOM combs this requirement becomes more difficult to achieve as the comb bandwidth is increased because of microwave-noise multiplication (11). For octave-spanning spectra at a 10-GHz repetition rate, this multiplication factor is \( n' \sim 20,000 \) and corresponds to an 86-dB increase in phase noise. Thus, reaching the \( \pi \)-radian threshold with an EOM comb requires careful treatment of the noise at all Fourier frequencies.

As noted earlier (10), broadband thermal noise in the electronic components up to the Nyquist frequency causes the phase-coherence threshold to be exceeded. To compensate, a Fabry–Pérot cavity optically filters the broadband thermal noise fundamental to electro-optic modulation, resulting in a detectable carrier–envelope offset frequency. However, the cavity linewidth (typically a few megahertz) places a lower bound on the range of frequencies where this suppression is possible, and therefore, it is additionally necessary to investigate the use of low-noise microwave oscillators. This is especially important for the Fourier-frequency range between 100 kHz and the filter–cavity linewidth, where high-gain feedback is technically challenging.

In the stabilized EOM comb (a comprehensive system diagram is shown in fig. S1), we use a commercial dielectric-resonator oscillator (DRO) with a nominal operating frequency of 10 GHz and 0.1% tuning range to drive the modulators. Compared to other commercial microwave sources, the DRO offers improved phase-noise performance in the critical Fourier-frequency range between 100 kHz and 10 MHz. The DRO output is then amplified before driving the phase modulators to produce the typical comb spectrum shown in Fig. 2A. After transmission through an optical-filter cavity to suppress thermal noise, the chirped-pulse output of the EOM comb is compressible to durations as short as 600 fs, depending on the initial spectral bandwidth. Unfortunately, pulse durations greater than ~200 fs pose problems for coherent supercontinuum broadening in nonlinear media with anomalous dispersion (12, 13). However, if the nonlinear material instead exhibits normal dispersion, broadening due to pure self-phase modulation is known to produce lower noise spectra owing to the suppression of modulation instability (13). Consequently, we employ a two-stage broadening scheme using a normal-dispersion highly nonlinear fiber (HNLF) to achieve initial spectral broadening (14–16) and pulse compression to 100 fs (17), followed by an anomalous-dispersion SiN waveguide for broadband spectrum generation.

High-repetition rate lasers (\( f_{rep} \sim 10 \) GHz) produce lower pulse energies for the same average power, making it challenging to use nonlinear broadening to produce the octave bandwidths required for self-referencing. However, patterned nanophotonic waveguides have recently emerged...
as a promising platform owing, in part, to their high nonlinearity and engineerable dispersion (18–20). Here, we demonstrate input-coupling efficiency to a SiN waveguide of up to 85% (17) that enables a broadband supercontinuum to be generated with pulses from high-repetition rate ultrafast sources. The spectra generated with our 10-GHz EOM comb spans wavelengths from 750 nm to beyond 2700 nm for two different waveguide geometries (Fig. 2B), producing a total integrated power of ~1.1 W. Individual comb lines across the entire bandwidth exhibit a high degree of extinction (50 dB at 1064 nm; see fig. S2 for data at 775, 1064, and 1319 nm) and do not exhibit any intermode artifacts such as sidebands, a common problem when mode filtering is used to convert low-repetition rate combs to high repetition rates (21).

To investigate the scalability to even higher repetition rates, we made additional supercontinuum measurements using a 30-GHz EOM comb, which produced 600-fs, 70-pJ pulses (Fig. 2D). Despite the three-times reduction in pulse energy compared to the 10-GHz comb, similar broadband spectra are readily obtained. In both cases, if the waveguide input pulse energy is kept below ~100 pJ, the three-times reduction in pulse energy combined with an appropriate color filter, could further improve the power per mode.

For applications requiring very flat spectra over broad bandwidths, such as astronomical spectrograph calibration (22), the supercontinuum light can be easily collected in a single-mode fiber and flattened with a single passive optical attenuator. Under these conditions, fluctuations in spectral intensity can be kept within ±5 dB over wavelengths spanning from 850 to 1450 nm while delivering more than 10 nW per mode in the fiber at 10 GHz. Improved waveguide-to-fiber output coupling, or free-space collimation combined with an appropriate color filter, could further improve the power per mode.

After broadening in the SiN waveguide, the offset frequency is expected with >30 dB signal-to-noise ratio (SNR), suggesting that the scheme of combining normal- and anomalous-dispersion media indeed allows us to overcome the difficulties of producing a coherent supercontinuum using pulses longer than a few hundred femtoseconds; see fig. S3 for SNR versus bandwidth. Stabilization of \( f_0 \) is subsequently accomplished by feeding back to the frequency-tuning port of the DRO. However, owing to optical and electronic phase delay in this configuration, the feedback bandwidth is limited to ~200 kHz (Fig. 3A, blue curve) and thus is insufficient on its own to narrow the comb linewidth set by the multiplied microwave noise of the DRO.

To reach the π-radian threshold for phase coherence between the CW laser and electronic oscillator, the output of one high-power microwave amplifier is stabilized to an air-filled aluminum microwave cavity in the stabilized-local-oscillator (STALO) configuration (23, 24) and yields an immediate reduction in phase noise of up to 20 dB at frequencies less than 500 kHz from the carrier.

In Fig. 3A, we use the \( \beta \)-line (25) to distinguish between regimes where the linewidth of the comb offset \( f_0 \) is adversely affected (phase noise above the \( \beta \)-line) and where there is no linewidth contribution (phase noise below the \( \beta \)-line). Having phase noise below the \( \beta \)-line at all points is approximately equivalent to an integrated phase noise below \( \pi \) radians, and thus provides a convenient visual way to assess the impact of noise at different Fourier frequencies. For our EOM comb, the \( f_0 \) phase noise remains below the \( \beta \)-line at all frequencies only when both the STALO lock and the \( f - 2f \) lock are used in tandem. Under these conditions, noise arising from the microwave oscillator does not contribute appreciably to the comb linewidth and thus, the CW laser stability is faithfully transferred across the entire comb bandwidth. Equivalently, integrating the phase noise of the fully locked \( f_0 \) beat (1.17 rad, 10 Hz to 4 MHz) yields a pulse-to-pulse timing jitter of 0.97 fs (1.9 fs if limited by the \( \beta \) line between 4 MHz and 5 GHz) (17), indicating that the microwave envelope coherently tracks the optical carrier signal with subcycle precision.

The progression of offset-frequency stabilization is also shown by the beat frequencies as each
lock is turned on (Figs. 3, B to D). The coherent carrier seen in the offset frequency when fully stabilized (Fig. 3D) indicates that phase coherence has been achieved between individual comb lines across the entire available spectral bandwidth. The accuracy and precision of the stabilized EOM comb were determined by beating the 10-GHz repetition rate against the 40th harmonic of an independent mode-locked laser operating at 250 MHz (17). After 2000 s of averaging, a fractional stability of $3 \times 10^{-17}$ was obtained with no statistically significant frequency offset observed. This level of accuracy represents an improvement of more than three orders of magnitude over previously demonstrated EOM-comb systems (10) and is likely only limited here by averaging time and out-of-loop path differences between the two combs.

To further show the versatility of the EOM comb as an ultrafast source, we describe how to create pulses that have durations lasting only a few cycles of the optical field. Pulses in this regime can provide direct access to the carrier–envelope phase and high peak intensities but require a well-controlled output spectrum exhibiting a high degree of spectral flatness and coherence. However, achieving such pulses at gigahertz repetition rates with mode-locked lasers is technically challenging. Still, high-repetition rate sources of few-cycle pulses could be valuable for applications like optically controlled electronics (28, 27), where both fast switching speeds and peak intensity are important. Similarly, coherent Raman imaging of biological samples can benefit from transform-limited ultrashort pulses (28), but the acquisition speed for broadband spectra is typically restricted by the megahertz-rate mode-locked laser sources that are used. Extending to higher repetition rates could reduce measurement dead time and also prevent sample damage due to high peak powers (29).

The use of optical modulators to directly carve a train of ~1-ps pulses from a CW laser provides an effective method for generating clean few-cycle pulses thanks to the soliton self-compression effect (30, 31). To achieve this, the pulse power and chirp incident on the SiN waveguide are adjusted such that the launched pulse approaches the threshold peak intensity for soliton fission near the output facet of the chip. A normal-dispersion single-element aspheric lens is then used to out-couple the light without introducing appreciable higher-order dispersion, and a 2-cm-long rod of fused silica glass recompresses the pulse to near its transform limit. Figure 4 shows the reconstructed pulse profile obtained through frequency-resolved optical gating (FROG) (32). Pulse durations of 15 fs (2.8 optical cycles, full width at half maximum) and out-coupled pulse energies in excess of 100 pJ (1 W average power) are readily achievable at a repetition rate of 10 GHz.

The combination of high-repetition rate pulse trains, ultrastable broadband frequency synthesis, few-cycle pulse generation, and extensible construction in our EOM-comb system provides a versatile ultrafast source with other additional practical benefits. For instance, these combs could also support further photonic integration through complementary metal-oxide-semiconductor (CMOS)-compatible modulators (33), alignment-free construction, the use of commercially sourceable components, and straightforward user customization. Moreover, whereas the optical and micro-wave cavities currently limit the broad tuning capability of the repetition rate, the ~300 THz of comb bandwidth places a mode within 5 GHz of any spectral location in this range. By overcoming several experimental challenges related to broadening and stabilizing noisy picosecond-duration pulses, our techniques are widely applicable to existing technologies with demanding requirements, such as chip-based microresonators (34) or semiconductor lasers (35).
Fig. 3. EOM-comb phase noise. (A) Optical phase noise of the comb offset frequency measured at 775 nm (left axis) and scaled to the 10-GHz repetition rate (right axis) under different locking conditions. Prestabilizing the free-running RF oscillator (DRO) using a high-Q microwave cavity in the stabilized-local-oscillator (STALO) configuration lowers the phase noise by up to 20 dB at frequencies below 500 kHz. When servo feedback from the optical \( f_0 \) signal is engaged, a tight phase lock is achieved that suppresses low-frequency noise. The \( \beta \)-line indicates the level above which phase noise causes an increase in the comb linewidth. When both the STALO and \( f_0 \) locks are engaged, the phase noise remains below the \( \beta \)-line at all frequencies, indicating that the coherence of the CW pump laser is faithfully transferred across the entire comb spectrum. (B to D) \( f_0 \) RF beats showing the effects of each feedback loop. A coherent carrier signal is observed (D) only when both the STALO lock and direct \( f_0 \) feedback are engaged.

Fig. 4. Few-cycle pulse generation. (A) Experimental and (B) reconstructed FROG traces. (C) Reconstructed temporal pulse profile with a full width at half maximum duration of 15 fs (2.8 optical cycles). (D) Comparison of reconstructed and experimental spectra. The quasi-CW spectral wings of the initial comb spectrum near 1550 nm do not contribute appreciably to the pulse and thus are not seen in the reconstructed spectrum. At least 75% of the total optical power is concentrated in the compressed pulse. More sophisticated amplitude and phase compensation of the initial comb spectrum could allow an even larger fraction of the power to be compressed (36).
REFERENCES AND NOTES

17. Supplementary materials are available online.

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Competing interests: NIST has a pending patent application related to this work. D.H. is currently employed by KMLabs, Inc. Data and materials availability: All data are present in the paper or supplementary materials.

SUPPLEMENTARY MATERIALS

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Materials and Methods
Supplementary Text
Fig. 51 to S5

References (37–46)

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Making ultrafast cycles of light
The ability to generate coherent optical frequency combs has had a huge impact on precision metrology, imaging, and sensing applications. On closer inspection, the broadband "white light" generated through the interaction of femtosecond mode-locked laser pulses is composed of billions or trillions of precisely spaced wavelengths of light. Carlson et al. demonstrate an alternative to the mode-locked laser approach—the electro-optic modulation of a continuous-wave laser light source can also generate optical frequency combs (see the Perspective by Torres-Company). The electro-optic modulation techniques can operate at much higher repetition rates than mode-locked lasers, which means they could potentially yield even more precise measurements. Science, this issue p. 1358; see also p. 1316

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