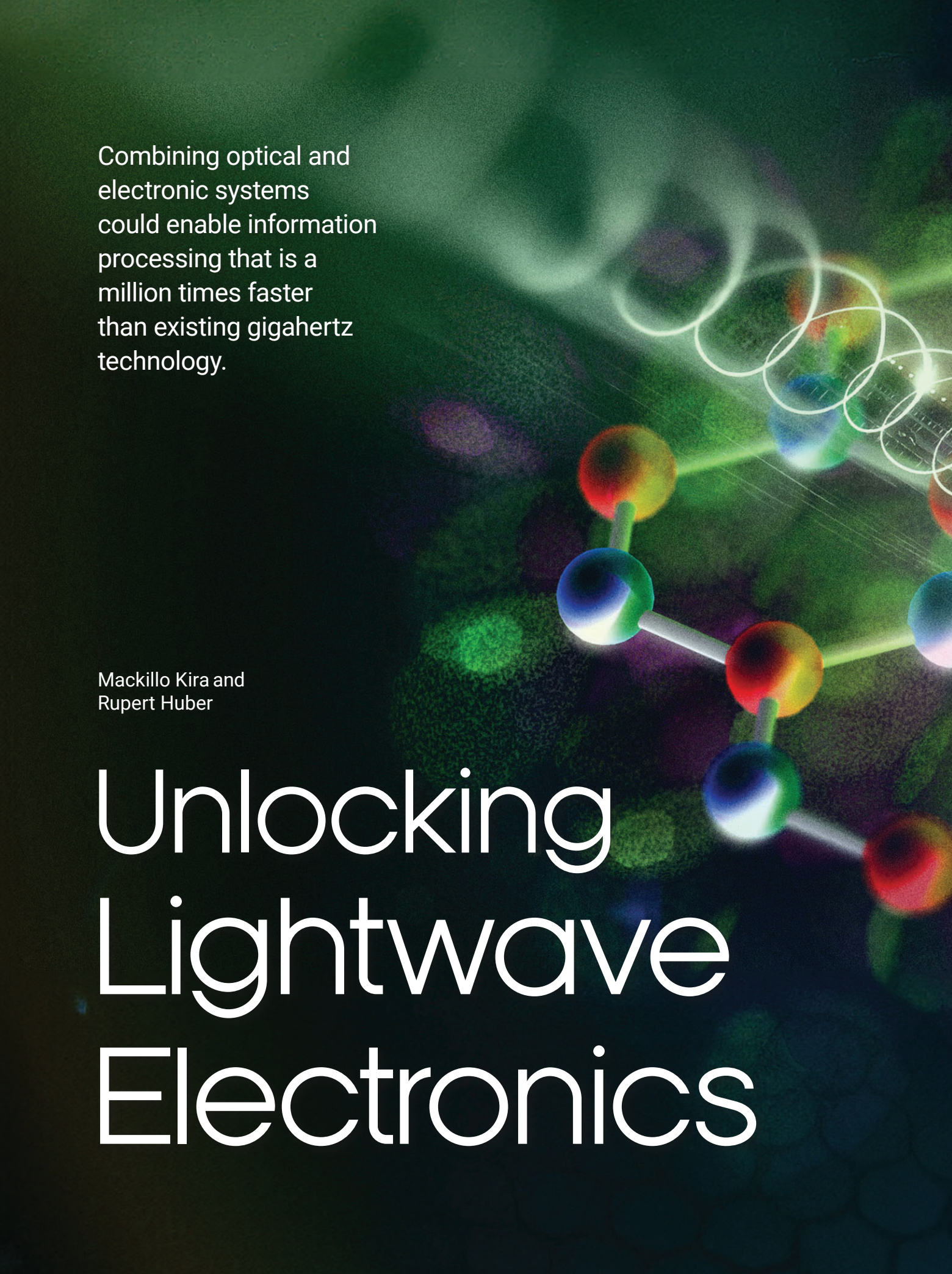
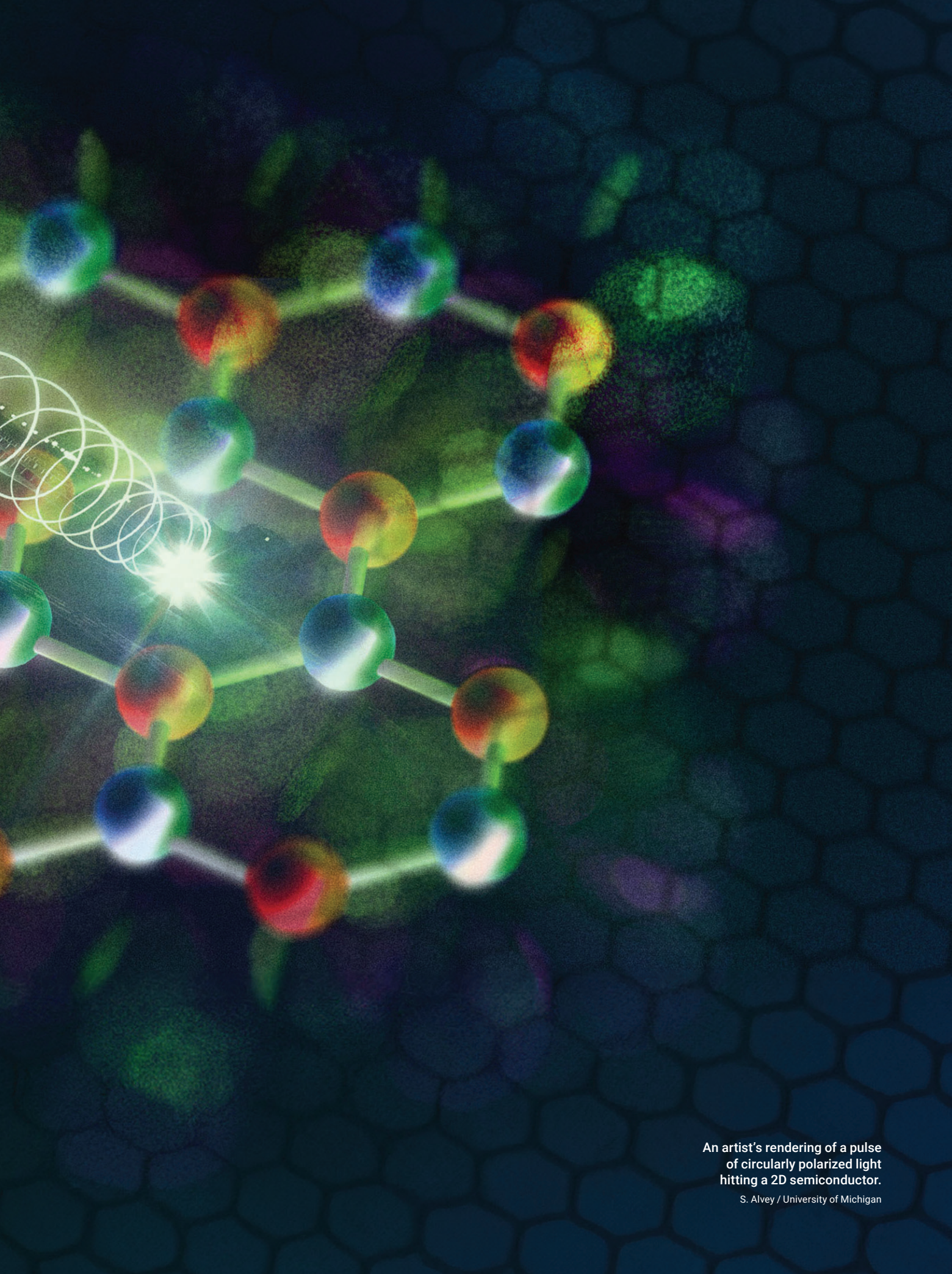


Combining optical and electronic systems could enable information processing that is a million times faster than existing gigahertz technology.

Mackillo Kira and
Rupert Huber

Unlocking Lightwave Electronics



An artist's rendering of a pulse of circularly polarized light hitting a 2D semiconductor.

S. Alvey / University of Michigan

Mackillo Kira (left) reviews light emission properties for semiconductors with former student Markus Borsch, who received his Ph.D. in electrical and computer engineering from the University of Michigan in 2023.
B. Ahearn / University of Michigan

Imagine leveraging nature's fastest processes to power the electronics in semiconductor chips, quantum sensors and quantum computers. Such transformative speed would not only greatly improve the performance of technology, but unveil new vistas for fundamental science as well. Researchers could literally see how quantum information is processed, or how phenomena like superconductivity and topological phases emerge at the quantum level.

This vision is becoming a reality through lightwave electronics (LWE), which uses intense optical-carrier waves as ultrafast biasing fields to drive the quantum flow of electronic coherences. Lightwaves of sufficient strength can alter this flow at speeds much faster than a single oscillation cycle of the wave—the fundamental unit of high-precision atomic clocks. In essence, LWE can flip an electronic state in a quadrillionth of a second (1 femtosecond [fs] or 10^{-15} s), enabling operations that are unimaginably faster and more precise than traditional light-induced transitions.

Such LWE events can be clocked at attosecond (10^{-18} s) timescales, where light barely travels the width of an atom. This is the realm of attoscience, the subject of the 2023 Nobel Prize in Physics. As we unlock the potential of LWE, we open doors to a future where innovation itself will seem to move at the speed of light.

Most of all, LWE gives us the ability to perform operations at petahertz (PHz) clock rates—a millionfold faster than today's gigahertz technology, wherein electrons scatter thousands of times per cycle, effectively destroying quantum information. LWE transcends this limitation, operating rapidly enough to maintain quantum integrity, while also benefitting the classical world. Envision smartphones, laptops and even household appliances that could predict and react to environmental conditions by processing vast streams of data from our surroundings in real time with minimal energy consumption. This is the promise of LWE.

LWE also holds potential for artificial intelligence, where energy-efficient and rapid data processing can significantly accelerate learning algorithms and decision-making capabilities. In sensing technologies, LWE may tap into delicate quantum processes to create more accurate sensors for everything from medical diagnostics to environmental monitoring. For businesses, this means faster computations, better quality control, more sophisticated data analysis and instantaneous communication, which would radically transform industries from finance to health care.

Going ultrafast

LWE traces its origins to high-harmonic (HH) generation in atomic systems using intense light pulses. This process involves ionizing electrons from an atom, accelerating them, and then having them collide back with the atom's core after they gain energy from the lightwave. These collisions release high-energy photons around discrete photon energies, known as HHs. This groundbreaking mechanism forms the foundation of attosecond science, or attoscience, a field that has revolutionized our ability to control electronic wave functions on incredibly short timescales. As the crowning achievement of attoscience, lightwaves can now follow electronic motion at the natural timescales of reactions.

Unlike atomic systems with their pristine, less complicated and highly energetic electronic states, crystalline solids like semiconductors present an intricate and fascinating landscape of states for LWE excitations (see "Solid-state-specific LWE," p. 32). Within these crystals, electrons inhabit widespread, delocalized states that span the entire lattice, making it impossible to confine lightwave excitations to a single excitation trajectory. Far from being simple particles, electrons in crystals also display wave-like behaviors. As these electron waves are accelerated through the crystal, they meet regularly spaced atomic ions, reflecting to generate periodic motion known as Bloch oscillations.

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The dynamic interplay among electrons, vacancies, photons and phonons within and among these clusters presents opportunities to generate novel phenomena.

The periodicity of electrons combined with their wave nature also confines them to specific energy bands, separated by distinct gaps that no electron can inhabit. Such unique characteristics open a world of possibilities: LWE can trigger transitions across these energy gaps, functioning similarly to flip-flop operations between binary quantum states, or qubits—bringing us closer to realizing quantum information processing on a chip.

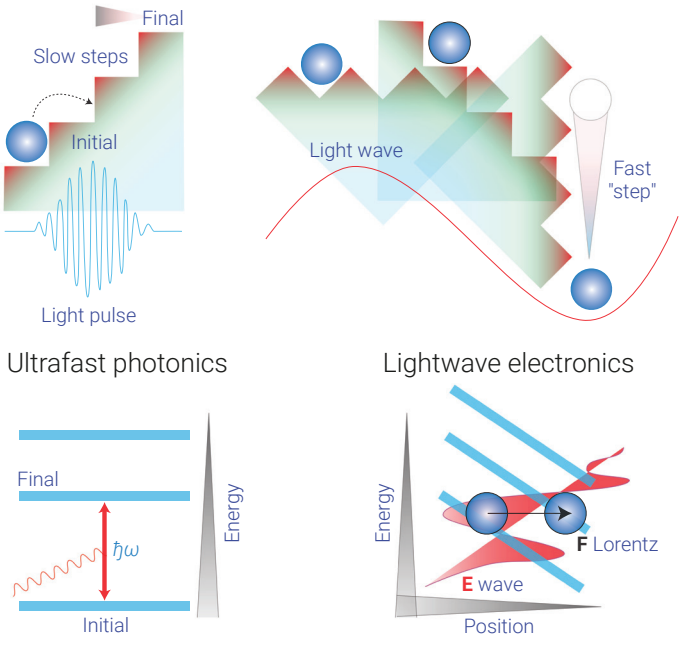
Lightwaves usually excite many electrons that inevitably interact through Coulomb force or lattice vibrations (phonons). These many-body effects offer a treasure trove of possibilities for discovery and innovation. For instance, interactions can bind electrons into small clusters that exhibit distinct resonances associated with relatively long-lived quantum coherences relevant for sustaining entanglement—the currency of quantum information. Picture excitons, which are atom-like states formed between an electron and an electronic vacancy; exciton molecules, which are pairs of bound excitons; and dropletons, where a few electrons and vacancies coalesce into a liquid-like droplet.

The dynamic interplay among electrons, vacancies, photons and phonons within and among these clusters presents opportunities to generate novel phenomena, such as quantum information exchange or the triggering of quantum phase transitions with a lightwave.

With LWE, we can, for the first time, image electron–hole clusters at natural time and length scales. The profound understanding gained from these studies of fundamental interaction processes in solids forms the foundation

Lightwave electronics in action

Suppose a sphere needs to be moved between two states separated by one or more energy steps. One viable approach is to determine the energy required for each step and then provide the energy needed to climb these steps from start to finish. This is essentially what ultrafast photonics does when resonant photons match the energy steps to flip a quantum state between its initial and final states. Heisenberg's uncertainty principle dictates that it takes multiple oscillation cycles for photons to deliver a precise energy packet, denoted by $\hbar\omega$, to the state. The duration of the resulting multi-cycle light pulse may still be fast because the electromagnetic field of light oscillates extremely fast. For example, a red photon with a wavelength of 750 nm has an oscillation period of 2.5 femtoseconds (fs), resulting in 400 oscillations within one picosecond (1 ps = 10^{-12} s). Ultrafast science typically starts with processes faster than 1 ps. Although these processes are about 1,000 times faster than the fastest electronics, ultrafast resonant processes are not necessarily swift on the scale of an oscillation cycle.



An alternative approach uses an extremely strong external stimulus to alter the entire energy landscape, favoring an almost instantaneous transition of the sphere from its initial to final state. A sufficiently strong light wave can achieve this for electronic states because the wave's electric field exerts a Lorentz force, which effectively tilts the energy landscape back and forth during each oscillation. As this occurs, electrons can instantaneously transition between energy states that become equal due to this tilt. The resulting processes are extremely anharmonic and become highly synchronized with the field crests. LWE taps into this property to flip electronic states within a fraction of a lightwave's oscillation cycle. Consequently, even red lightwaves can flip electronic states in less than 1 fs, enabling lightwave-driven processes to approach petahertz clock rates (1 operation per 1 fs).

Illustration by Phil Saunders

for groundbreaking technologies, advancing quantum information applications and pushing the boundaries of materials science and quantum engineering.

Rapid progress of LWE modalities

One of the earliest milestones in LWE was the straightforward generation of HHs in solids. In 2001, scientists successfully generated HHs up to the seventh order in zinc sulfide (ZnS) using strong mid-infrared pulses. In 2011, experiments extended into the extremely nonlinear regime where HH scaling no longer follows a simple power law, leading to the observation of HHs up to order 25, with some reaching beyond the band gap of zinc oxide (ZnO).

A significant advancement occurred in 2014 with the first quantitative theory–experiment analysis of solid-state HH generation using terahertz (THz) driving fields. By maintaining a fixed phase relationship between repeated laser pulses, this study revealed distinct features of dynamic Bloch oscillations in the HH spectra and their phase dependence. However, using HH for precise LWE state control has proven challenging because HH unrestrictedly initiates band-to-band excitations anywhere in the bands and even excites multiple bands—which scrambles electronic details.

These precision challenges can be addressed by an alternative approach known as the harmonic sideband (HSB) modality, which sequences pump–lightwave excitations in the following manner. First, the pump pulse resonantly excites a precise electron–hole cluster, such as excitonic coherence between only two selected bands. Second, the nonresonant lightwave ionizes, accelerates and collides the electron–hole cluster, generating a burst of HSB emission akin to the steps involved in atomic HH generation. High state selectivity is achieved by tuning the pump to match the cluster resonance that is close to the band gap, which can range from the far infrared to the deep ultraviolet, depending on the semiconductor material.

Solid-state-specific LWE

In solids, electronic eigenstates are no longer localized but extend over the entire crystal as Bloch electrons, forming a band structure that is periodic in momentum. In the ground state of a semiconductor, a considerable bandgap separates the fully occupied valence bands from the empty conduction bands above the gap. Electronic motion is often described through quasiparticles—electrons that move in the conduction band and electronic vacancies, known as holes, in the valence bands. The nonlocal and nonparabolic aspects of solids strongly affect LWE operations.

A prime example is Bloch oscillations, observed when a sufficiently strong lightwave acts on electrons and holes via the Lorentz force. Initially, these quasiparticles move like ordinary particles. However, the periodicity in momentum space introduces Bragg reflection at the boundary of the band-structure period, resulting in a back-and-forth motion in real space. These Bloch oscillations significantly affect LWE excitations.

When nonresonant lightwaves are used as a direct excitation tool, they often excite a large number of electrons and holes across multiple bands and momentum ranges. Conversely, ultrafast resonant excitations are typically much more selective. Therefore, high-precision excitation schemes often rely on resonant excitation to generate electron–hole pairs, while lightwaves are applied to translate them.

Regardless of the preparation steps, typical LWE excitations involve billions of electron–hole pairs within the excitation spot. Since they are charged particles, electrons and holes are coupled by Coulomb forces, introducing many-body effects and creating quasiparticles such as bound electron–hole clusters. Coulomb forces can also condition the constituent charges to exhibit coherence and mutual dependencies, leading to entanglement.

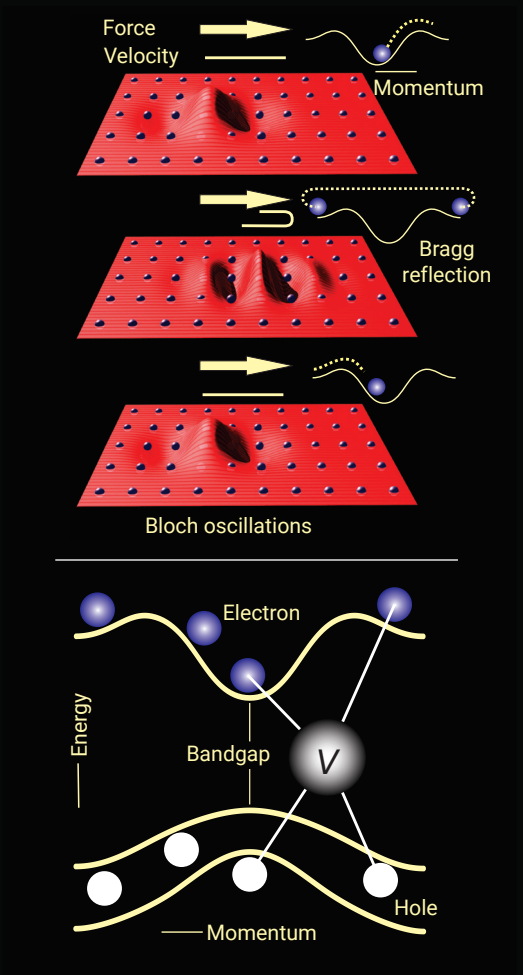
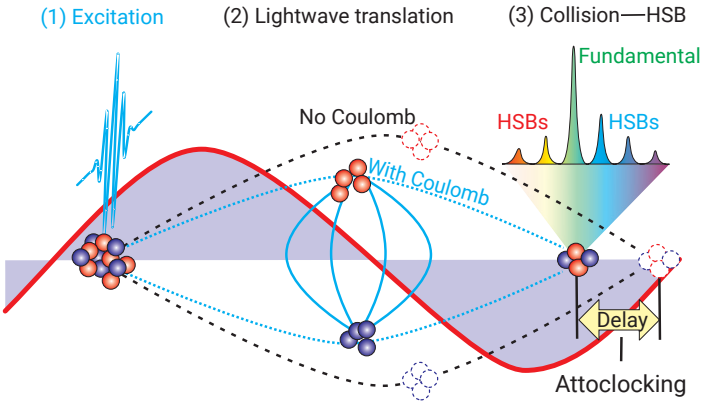


Illustration by M. Kira and R. Huber

Because multi-THz pulses are nonresonant by orders of magnitude compared with the band gap, they serve as ideal lightwaves for driving LWE processes with precision.



A diagram of the mechanism behind a quasiparticle collider.
Illustration by M. Kira and R. Huber

Because multi-THz pulses are nonresonant by orders of magnitude compared with the band gap, they serve as ideal lightwaves for driving LWE processes with precision. In addition, the generated clusters exhibit longer coherence times than pure electrons would and contain internal transitions that multi-THz pulses can control and detect, supporting prospects for quantum information processing.

The HSB modality was first demonstrated in 1997 in gallium arsenide (GaAs) quantum wells using weak THz excitation. However, it took another 15 years to extend HSBs to strong, nonperturbative excitations—a critical milestone for achieving ultrafast LWE control of excitonic states. These early studies used continuous-wave pump and continuous-wave THz lightwaves to generate harmonics around an excitonic state, leaving many ultrafast phenomena beyond reach.

In 2016, researchers precisely controlled the timing of a 100-fs multi-THz lightwave relative to a 100-fs pump pulse, to initially excite coherent excitons in bulk tungsten diselenide (WSe_2). This groundbreaking study unveiled quasiparticle collisions, showing that the timing of these excitations influenced the intensity of the HSBs. This resembles the process of measuring collision debris in a particle collider, introducing the concept of a quasiparticle collider as a novel LWE tool.

A quasiparticle collider is based on a two-color excitation scheme. Following the creation of electron–hole clusters, a nonresonant lightwave displaces the constituent electrons and holes through the Lorentz force. As the field of the lightwave reverses its sign, the particles collide, producing HSBs around the fundamental quasiparticle energy. The resulting debris holds distinctive signatures of both the many-body interactions and the band-structure specifics experienced by the quasiparticles.

A combined theory–experiment effort conducted in 2018 used a right-circularly polarized pump pulse to excite an excitonic coherence exclusively in the so-called K valley (as a qubit-up state) of an atomically thin, two-dimensional WSe_2. This was followed by a specially crafted multi-THz lightwave that moved the excitonic state to the neighboring K′ valley (qubit-down state), where it emitted left-circularly polarized light. Remarkably, this state flip between up and down states took only 5 fs—nearly a million times faster than flipping a classical bit in traditional computers. Simply put, LWE can now switch potential qubits faster than the decoherence time of room-temperature semiconductors, marking a crucial step toward the development of LWE-driven quantum information processing on a chip.

In 2020, the quasiparticle collider was leveraged to precisely map lightwave-induced changes in the quantum states of electrons, creating a detailed picture of the internal workings of quantum materials. This high-precision reconstruction is pivotal for understanding and controlling materials at the quantum level. By 2022, quasiparticle colliders could measure quantum interactions within quasiparticle clusters with attosecond precision. This "attoclocking" technique allows scientists to observe and control extremely fast interaction events between electrons and holes within a cluster. These events are foundational to quantum information processing and quantum phase transitions. Thus, the HSB modality has enabled a deeper understanding and more precise control of quantum information and phenomena, which is essential for the future development of PHz technology and advanced quantum devices.

Shaping lightwaves to a subcycle duration brings new PHz switching opportunities for nonlinear LWE

High-harmonic generation in solids has unlocked new possibilities for creating compact and efficient light sources for ultrafast pulses ranging from UV to soft X-rays.

excitations. As the nonlinear transitions are proportional to some high power of the electric field, the transitions are not only synchronized with the field crests but also happen dominantly during a single field crest of a subcycle wave. This idea was used in 2013 to move electrons of fused silica between electrodes separated by 500 nm in just 2.5 fs, implying 0.4 PHz maximum clock speeds.

The range of transport was extended to multiple micrometers in 2022 to apply a sequence of two lightwaves for controlling currents. Essentially, by firing extremely short bursts of light (a few cycles long), this approach encoded logical operations into the flow of electrons. Think of it like using patterns of light to control switches in a circuit—except these switches turn on and off at unimaginable speeds. Early experiments showed that we can use such light pulses to perform basic quantum-logic operations, paving the way for quantum electronics that could operate at PHz speeds.

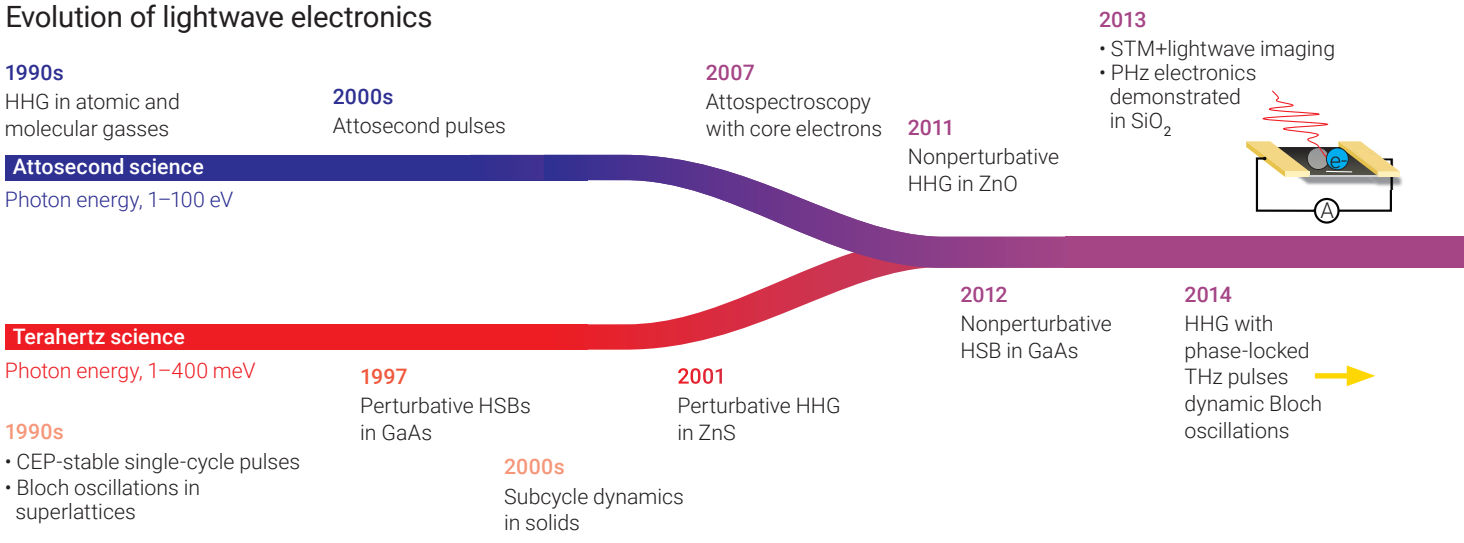
In addition, hybrid LWE approaches could bring transformative possibilities in videography by allowing us to visualize electron movements at incredibly fine temporal and spatial resolutions. In one approach, researchers used a lightwave to move the electrons through the band structure of crystals and a UV pulse to ionize and image them. In 2018, this technique revealed how THz lightwaves accelerate electrons in topological materials like Bi_2Te_3, providing insights into the behavior of topologically protected surface states.

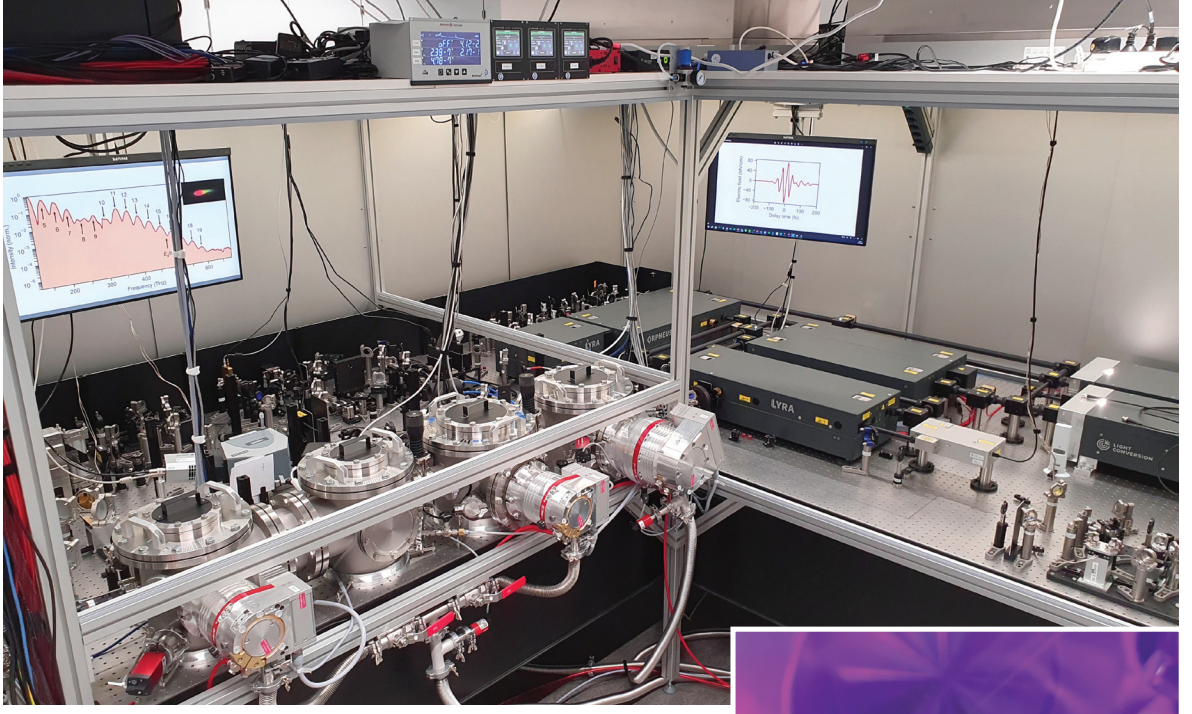
Another technique, scanning tunneling microscopy (STM), was combined with LWE in 2013 to reach sub-nanometer spatial resolution. Three years later, the new concept of single-electron lightwave-driven STM allowed for actual molecular videography by focusing a THz lightwave into the microscopic junction between a single molecule and an atomically sharp STM tip. The approach achieved movies of single molecular orbitals, resolved to ångström scales, showing dynamics on timescales as short as 100 fs. These advancements open new opportunities to explore and control the fundamental building blocks of matter on their intrinsic spatiotemporal scales.

Developments in HH generation

Complementing these new directions, the foundational approach of HH generation has seen tremendous progress as well. For example, it effectively converts low-frequency light into UV and X-rays, tasks that are traditionally challenging without major equipment like particle accelerators. In this frontier, HH generation in solids has unlocked new possibilities for creating compact and efficient light sources for ultrafast pulses ranging from UV to soft X-rays.

Evolution of lightwave electronics





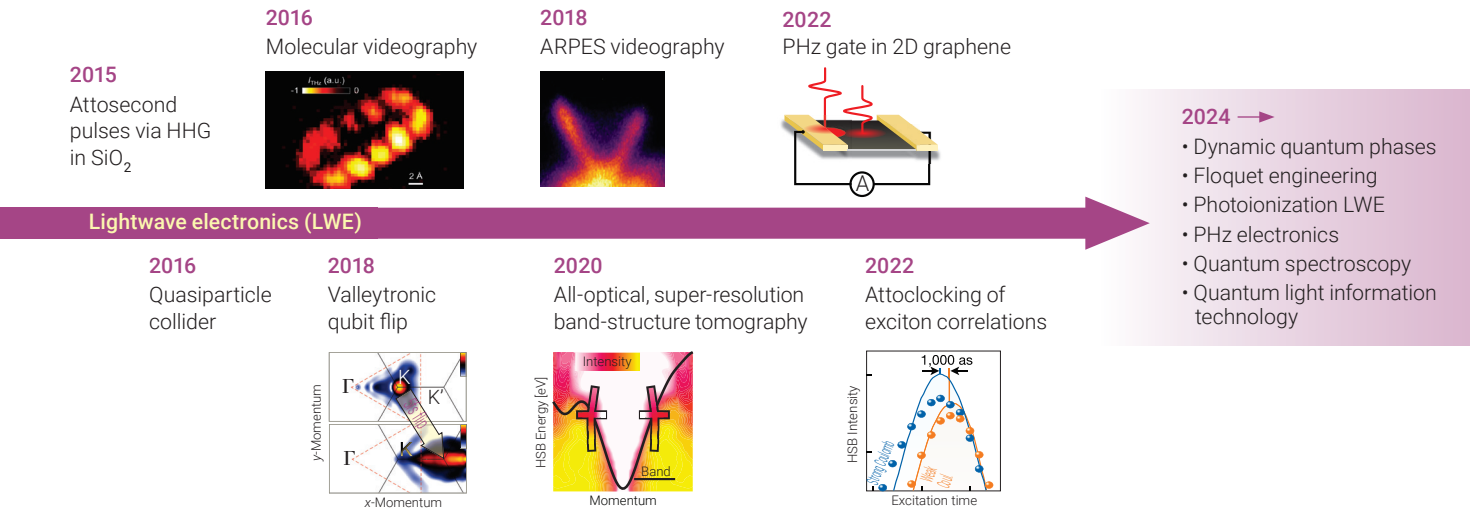
Starting with femtosecond near-IR light pulses from high-power laser amplifiers (right edge of the photo), a cascade of nonlinear optical frequency conversion stages generates phase-stable few-cycle optical waveforms from the far- and mid-IR to the extreme UV spectral range (left side of the photo). Extreme UV pulses are obtained in the vacuum chambers (foreground) by high-harmonic generation in a gas jet (inset).

Courtesy of M. Kira and R. Huber

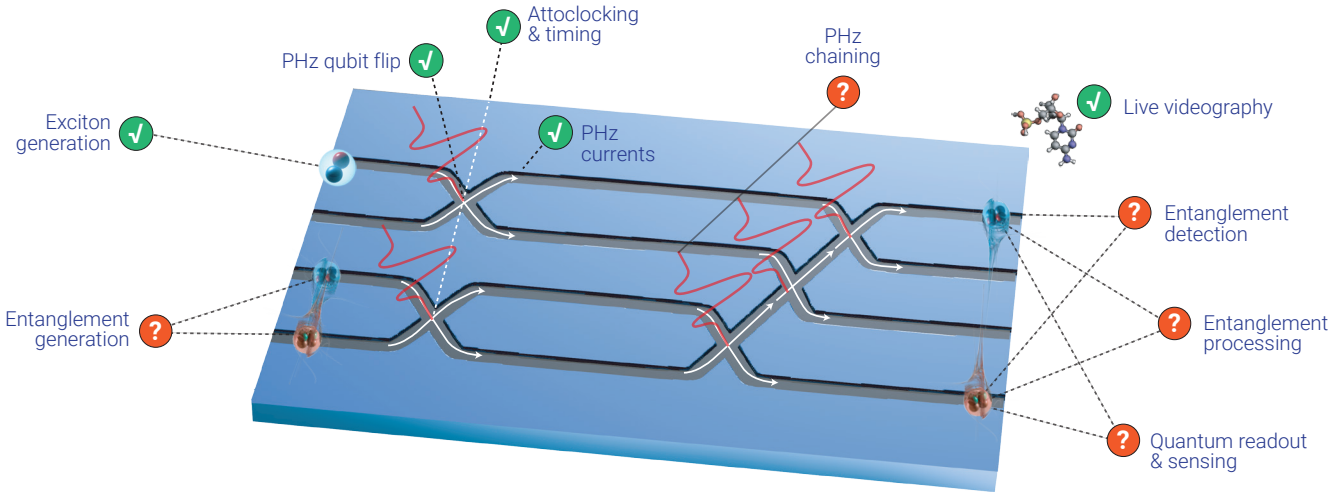
In 2015, HH generation from solids such as fused silica achieved attosecond pulse lengths, reaching the extreme ultraviolet (XUV) range. Moreover, the timing and shape of the emitted HH pulses was finely tuned in 2017 by optimizing the orientation and polarization of the driving field relative to the crystal, demonstrating a robust potential for generating ultrashort, precisely controlled light sources. Unlike traditional gas-based methods, solid-state approaches leverage the dense packing of nonlinear materials, resulting in more effective HH generation with pump-laser intensities reduced by orders of magnitude.

Prior to HSB demonstrations, a two-pulse atto-clocking scheme was implemented using a near-infrared lightwave generated to accelerate electrons, while an XUV pulse excited core electrons as a precise timing reference. Since 2010, this method has revealed various rapid electron transport and scattering phenomena in materials like tungsten, nickel and silicon, pushing the boundaries of detecting electron dynamics to the sub-fs scale.

Moreover, HH generation in solids shows substantial promise for quantum transduction—the conversion of quantum information between different frequency



Timeline image credits: optica-opn.org/link/0125-lightwave



Current progress in quantum light information technology (Q-LIT). Check marks (√) indicate completed LWE steps, while question marks (?) highlight those that remain unresolved.

Illustration by Phil Saunders

ranges. Strong nonlinear optical responses in materials such as 2D graphene produce high third, fifth and seventh harmonics with notable efficiencies. These advancements suggest that solid-state HH sources could play a crucial role in developing efficient quantum transducers and integrating quantum information technologies across a broader spectrum of frequencies.

Pressing challenges

To transition LWE from an experimental marvel into a practical quantum tool, several critical challenges must be addressed. One of the foremost difficulties is figuring out how to perform operations swiftly enough to outpace electron-scattering events, which occur on 100-fs timescales. Achieving this requires a continued search for the best possible materials that maximize scattering times, for example by topological protection.

Additionally, technologies must be developed to ensure high-precision timing and control at the attosecond scales—roughly a thousand times faster than PHz processes. This level of precision is essential for chaining multiple operations in sequence to harness coherent, correlated or entangled electrons. Although significant strides have been made, especially in demonstrating single operations, the complexity grows exponentially when these operations need to be orchestrated in a stable and repeatable manner.

Another major hurdle is creating short, asymmetric lightwaves capable of imparting net directional momentum to electrons. This necessitates the development of flexible and stable methods to generate arbitrary waveforms, similar to direct-current pulses but operating at ultrafast timescales. Furthermore, existing quantum sources and detectors lack the flexibility and reliability needed to efficiently excite and detect sophisticated quantum states.

Advancements in extreme nonlinear quantum materials, photonic structures and nanofabrication technologies are essential to further scaling LWE solutions. The ultimate goal of this research is to integrate both LWE components into the devices themselves, thereby improving efficiency, simplifying instrumentation and adding flexibility.

Accessing and manipulating quantum states with LWE requires a delicate balance between theoretical understanding and practical implementation. The Quantum Dynamic Cluster Expansion (QDCE) represents a cutting-edge method for accurately predicting electron–photon–phonon dynamics over timescales pertinent to LWE interactions. This approach predicts dynamics both exactly and efficiently, using a minimal number of clusters. It taps into the inherent property of many-body and quantum-optical interactions, which induce a strictly sequential, step-by-step formation of clusters, gradually evolving from simpler to more complex ones.

Concurrently, time-dependent density functional theory is advancing rapidly to better accommodate phonon-induced scattering on LWE excitations. Even so, existing computational methods face significant challenges as the computational complexity escalates with increasing cluster sizes. Consequently, developing next-generation predictive tools for LWE is imperative to extending applications toward harnessing the full quantum-information potential of electron–hole clusters.

The next wave of explorations could directly detect multi-electron processes as they unfold in complex reactions, optoelectronics and entanglement generation, at natural length and timescales.

Finally, exploring how lightwaves can induce phase transitions and control emergent phenomena represents an exciting and formidable frontier. Here, the interaction among electronic, magnetic and phononic degrees of freedom must be carefully disentangled and harnessed. Innovations in this area could yield robust quantum–classical interfaces between optical, electronic and mechanical systems, enlarging the scope of quantum investigations and practical classical applications.

Floquet engineering, which involves the periodic modulation of electronic potentials using monochromatic lightwaves, also represents an opportunity for LWE. This can create new energy bands and hybridize Floquet–Bloch sidebands, potentially leading to novel quantum effects such as dynamical localization and photon-dressed topological states. However, the impact of many-body interactions and decoherence is not yet thoroughly understood.

The next wave

The LWE techniques that have been demonstrated by the research community already offer an unprecedented insight into electron dynamics at fs timescales. The next wave of explorations could directly detect multi-electron processes as they unfold in complex reactions, optoelectronics and entanglement generation, all at their natural length and timescales. These investigations could help determine how solids can catalyze chemical reactions, elucidate the mechanisms behind quantum phase transitions, and optimize quantum transduction for the transfer of quantum information between different quantum sensors, qubits or even quantum computers.

Complementary advances in high-harmonic and harmonic sideband generation have already expanded our lightwave toolkit. The lightwaves can now flip quantum states in a few femtoseconds, clock simple multi-electron processes with attosecond precision, perform ultrafast quantum logic operations with coherent currents, improve quantum transduction, film electronic motion within molecules, map electron energy and topology in quantum materials, and generate versatile sources. Yet these are just the initial steps in the quantum-process chains that practical technology must wield.

The essential technological challenge now lies in bridging existing LWE demonstrations with the next generation of innovations. Formidable obstacles persist in generating and imaging multi-electron states down to entanglement, as well as in their high-precision processing, especially when creating multi-step chains optimized for specific quantum functions. Solutions will likely necessitate advanced quantum photonic integration that combines quantum lightwave sources, detectors, memories, qubits and classical components into quantum light information technology (Q-LIT).

As Q-LIT matures, LWE could significantly elevate both classical and quantum technologies by unlocking quantum capabilities in conventional semiconductor materials, scaling these capabilities with existing microelectronics manufacturing, increasing clock rates to the PHz range, sensing microscopic signals through entanglement, and efficiently interconnecting diverse components.

By addressing these challenges, researchers could explore the fundamental properties of complex matter and quantum phases, harnessing the full potential of multielectron dynamics. In parallel, further advances in Q-LIT would facilitate the development of quantum-information technology that is integrable, scalable and compatible with traditional semiconductor chips. Amidst profound progress, LWE is poised to revolutionize both fundamental research and practical applications, inspiring scientific and technological innovation. OPN

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