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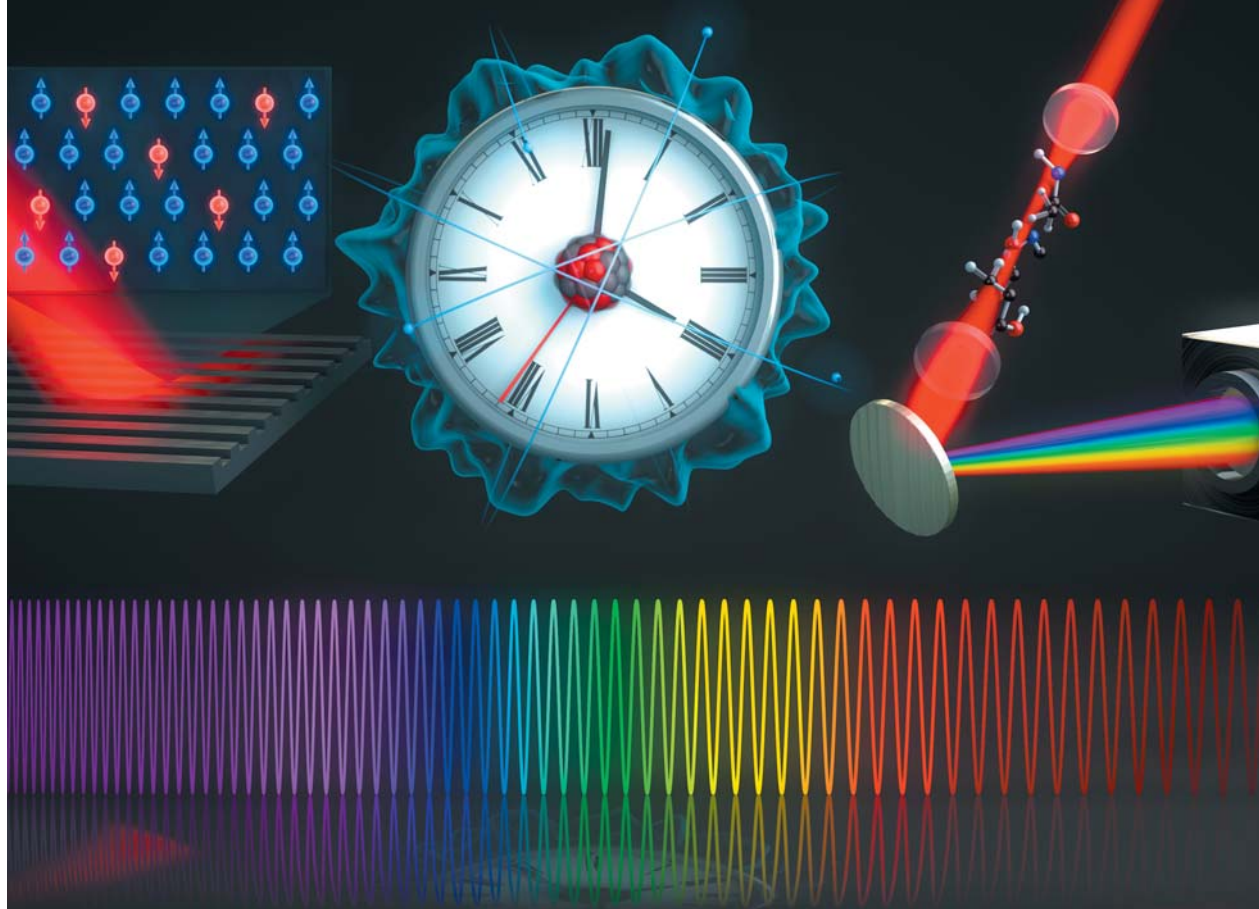
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Coherent light brightens the quantum science frontier

Margaret M. Murnane
and Jun Ye

Controlling coherent light across a vast spectral range enables ultraprecise measurements and the quantum control of atomic, molecular, and condensed-matter systems.

The laser was invented about 60 years ago¹—30 years after the founding of *Reviews of Modern Physics*. That novel light source opened up new windows to the natural world and transformed our understanding of many areas of science. Today, the ability to control every aspect of light—phase, spectrum, waveform, pulse duration, polarization, and individual photons—can be used to coherently probe and manipulate quantum systems.

Research topics include quantum communication via entangled photons, quantum materials manipulation using ultrafast pulses, gravitational-wave detection using long-baseline interferometers, and precision spectroscopies with ultrahigh spectral and temporal resolutions. Indeed, the recent scientific progress on coherent light sources requires the ultimate quantum control over light, atoms, molecules, and solid-state environments, a feat ac-

complished by the strong synergy between fundamental science and innovative technologies.

With laser light's high temporal and spatial coherence, researchers now can produce waveforms that span the visible and IR regions of the spectrum (see the article by Arthur Schawlow, *PHYSICS TODAY*, December 1982, page 46). Moreover, by harnessing the nonlinear optical process of high-harmonic generation (HHG),² they can extend

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laser-like coherence over the entire UV and soft-x-ray regions.^{3,4} Our review showcases how the stunning control of light is revolutionizing ultraprecise measurements and ultrafast science.⁵⁻⁷

The control of optical phases dominates laser science research. In the spectral domain, continuous-wave lasers are providing dramatically enhanced resolving power to expose ever-finer energy structures of matter. Ultrastable lasers that maintain optical phase coherence for tens of seconds make it possible to investigate optical transitions of electrons to an excited state with nearly 1 part in 10^{16} resolution.⁸ New science has emerged, such as testing for fundamental symmetries, developing sensors of increasing sensitivity, probing the quantum nature of many-body physics, and searching for new physics beyond the standard model. The best atomic clocks are now based on stable light interacting with atomic quantum matter controlled by laser fields (see PHYSICS TODAY, March 2014, page 12). With significant increases in the quality of the atomic transition and the improved control and evaluation of systematic effects, optical atomic clocks have progressed⁹ to an accuracy of 10^{-18} .

With the increased temporal resolution enabled by the combination of ultrafast lasers and extreme nonlinear optics, researchers can probe the fastest electron-electron interactions, which occur on femtosecond to attosecond time scales.⁷ As those lasers produce pulses in a periodic train via mode locking, a comb structure emerges in the frequency domain. Then phase stabilization can be applied to the pulse train to control both the repetition frequency and the optical carrier frequency.¹⁰ The broad spectral coverage of a frequency comb provides phase control of optical frequency markers across intervals of many hundreds of terahertz and enables ultraprecise measurements and optical standards that are more than 100 times better than before.⁹

Until recently, coherent light sources at wavelengths shorter than the UV were not widely available. Fortunately, HHG, which produces a series of attosecond pulses or pulse trains, has allowed for exquisite spatial coherence and temporal coherence at wavelengths from the UV to the soft-x-ray region. HHG originates from a nanoscale quantum antenna that is created as an atom undergoes strong ionization in an intense femtosecond laser field.^{11,12} Although the emission from each atom emerges as dipole radiation, when the light fields from millions to billions of atoms are coherently combined with subangstrom spatial and subattosecond temporal precision, a bright, directed HHG beam is produced.³

Because HHG fields are created by manipulating the radiating electron wavefunction of an atom, the resulting quantum coherence of HHG light sources is making it possible to control x-ray light with visible lasers (see the article by Henry Kapteyn, Margaret Murnane, and Ivan Christov, PHYSICS TODAY, March 2005, page 39). By adjusting the driving laser wavelength, re-

searchers can now simultaneously generate a coherent super-continuum spanning the IR, visible, UV, and soft-x-ray regions—over 12 octaves in bandwidth.⁴ Moreover, by adjusting the HHG geometry, they can fully control the direction, spectrum, polarization, divergence, and vortex charge of high-harmonic beams, which is important because extreme-UV (EUV) and x-ray optics are expensive and challenging to manufacture.

The unique properties of HHG are propelling discoveries in other fields. It's now possible to capture the dynamic electronic band structure of a material or the fastest coupled interactions between charges, spins, and the lattice that give rise to remarkable properties of quantum materials.¹³ HHG has also been used to uncover new regimes of nanoscale energy flow and to develop metrologies for next-generation nanotechnologies.¹⁴

Moreover, HHG from a high-repetition laser can, with the help of a femtosecond enhancement cavity, stabilize the generated pulse train to produce a frequency comb in the EUV.^{15,16} That discovery demonstrates a beautiful connection between the two manifestations of coherent light in the spectral and temporal domains. The exceptional coherence properties of the EUV comb open up applications in precision measurement, frequency metrology,^{17,18} and angle-resolved photoemission spectroscopy.

The revolution in producing coherent light continues at all measurement extremes, whether narrow spectral coverage, narrow spectral width, new photon energy scales, or ultrashort pulses. The frontier of light-matter interaction is entering a new phase that is driving scientific discoveries and novel technology development. Researchers are addressing many overarching scientific questions by using lasers, and we foresee more exciting developments on light appearing in the pages of *Reviews of Modern Physics*.

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