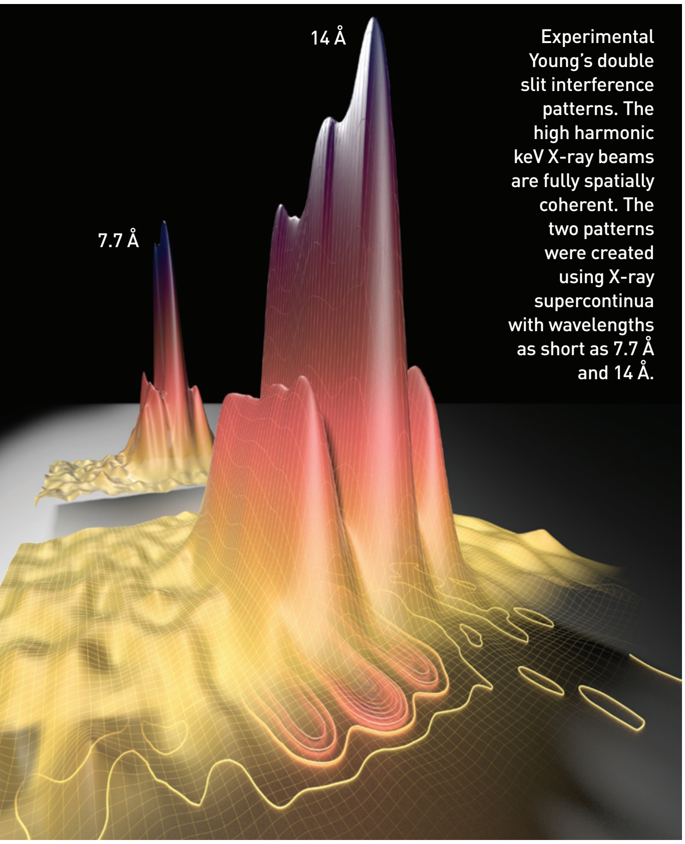
NONLINEAR OPTICS

Ultrafast keV X-rays from Tabletop Femtosecond Lasers



Experimental Young's double slit interference patterns. The high harmonic keV X-ray beams are fully spatially coherent. The two patterns were created using X-ray supercontinua with wavelengths as short as 7.7 Å and 14 Å.

X-rays show elemental and chemical specificity by using characteristic elemental X-ray absorption edges. These advantages spurred development of large-scale X-ray free-electron lasers based on accelerator physics, as well as high harmonic generation (HHG) driven by tabletop femtosecond lasers. When driven nonperturbatively by an intense femtosecond laser field, atoms radiate like microscopic antennae, emitting high-order harmonics of the fundamental laser. Until recently, bright HHG beams were limited to the extreme ultraviolet region of the spectrum, where efficient frequency upconversion is possible using widely available Ti:sapphire lasers. However, many inner-shell absorption edges in advanced magnetic and catalytic materials lie at photon energies nearing 1 keV, providing a strong motivation to extend HHG to higher photon energies and correspondingly shorter wavelengths.

We recently demonstrated that high-harmonic upconversion can be generated up to orders greater than 5,000 and can be implemented in a phase-matched geometry.[1] This takes nonlinear optics to an extreme not previously considered possible. By focusing mid-infrared (3.9 µm) femtosecond laser pulses into a high-pressure, gas-filled waveguide, the HHG process can be fully phase matched, where all the atoms in the gas emit X-rays that constructively interfere.[2]

The resulting high-harmonic beams emerge as a coherent X-ray "white light" supercontinuum spanning the UV to the kiloelectron volt (keV) region of the spectrum, corresponding to wavelengths less than 7.7 Å. This represents a laser-like, coherent, tabletop version of the Roentgen X-ray tube in the soft X-ray region. The keV-bandwidth coherent supercontinuum has a well-behaved chirp that, when compensated, could support a single-X-ray–cycle, 2.5 attosecond pulse duration.

These coherent HHG X-ray beams promise revolutionary capabilities for understanding and controlling the nanoworld, because of the unique ability of ultrafast X-rays to probe how electrons, spins, phonons and photons behave at the space-time limits relevant to function.[3-5] We need this knowledge to design and optimize next-generation electronics, data and energy storage devices and for next-generation medical diagnostics. Moreover, the limits of HHG are not yet known: It may be possible to extend it to hard X-ray wavelengths and broader bandwidths so that zeptosecond time scales are accessible. OPN

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