**X-RAY LASERS**

Coherent and compact

Bright X-ray free-electron lasers are beginning to unveil the properties of matter on atomic and femtosecond scales. A truly useful laser must be not only bright but also exhibit simultaneous spatial and temporal coherence, and researchers have now demonstrated a technique that may help to achieve this goal.

Philippe Zeitoun, Marta Fajardo and Guillaume Lambert

For decades, the realization of a high-performance X-ray laser has been a key goal of laser science, owing to its potential to create time-resolved three-dimensional images of atoms, molecules, viruses and solids. In 2009, researchers at the Linac Coherent Light Source (LCLS) free-electron laser in Stanford, USA, achieved the first demonstration of lasing in the X-ray range with the emission of femtosecond pulses at a wavelength of 1.5 Å. This outstanding accomplishment has attracted the attention of scientists all over the world who wish to take part in the pioneering experiments at the LCLS, which will undoubtedly serve as the flagship of next-generation X-ray sources for performing new science. However, the LCLS, along with all future X-ray free-electron lasers (X-FELs), must still address the long-standing issue of their poor temporal coherence. Now, writing in Physical Review Letters, Dao Xiang and co-workers have experimentally confirmed a new concept for realizing X-ray lasers that are both spatially and temporally coherent.

In an FEL, light is produced by the oscillation of relativistic electrons under the effect of a periodic magnetic structure called an undulator. Two regimes of short-wavelength FELs have been demonstrated so far. Self-amplified spontaneous emission, which relies on amplifying stochastic noise, results in emission that is extremely intense but has weak temporal coherence and relatively large shot-to-shot fluctuations in both the power and spectral characteristics. The LCLS is based on this process (Fig. 1a). Seeding the FEL with an external laser achieves coherent amplification and so leads to stable emission that is fully coherent in both space and time. This amplification scheme requires an intense laser-like X-ray source as a seed to dominate the incoherent spontaneous emission. At short wavelengths, the only source available today involves high-harmonic generation (HHG) through the highly nonlinear interaction of a laser with a rare gas. HHG seeding (Fig. 1b) has been successfully performed at 160 nm (ref. 4) and 60 nm, leading to fully coherent beams. However, due to the strong intensity drop of HHG at shorter wavelengths, it is unrealistic to imagine the HHG seeding of an X-FEL in the near future.

Another seeding scheme relies on using a pair of undulators (Fig. 1c), the second of which has its fundamental wavelength tuned to the nonlinear harmonic of the first (called a modulator). A chicane is used to couple the two undulators. However, due to the strong exponential decrease in intensity with harmonic order, it is difficult to achieve strong lasing above the 6th harmonic. Note that the LCLS's wavelength of 1.5 Å corresponds to the 1,333th harmonic of a 200 nm laser. Several theoretical works have studied the possibility of using many successive stages of the modulator–undulator set (known as HHG-cascading). Drawbacks of this technique include the strong amplification of noise and the need for the laser to interact with a fresh part of the electron bunch in every modulator.

To our knowledge, this scheme has never been demonstrated in the vacuum UV (∼1–60 nm) or the X-ray region. Xiang and collaborators have exploited a fourth scheme known as ‘echo-enabled harmonic generation’ (EEHG; Fig. 1d) to achieve coherent operation at wavelengths down to 400 nm. Behind this exciting work is Stupakov’s theory, which proposes that EEHG can...
overcome most of the bottlenecks in the road to achieving fully coherent X-ray lasers. The extremely short timescale between the publication of the theory and its first experimental validation is impressive, particularly given the technical challenges involved. Several critical issues with EEHG have now been successfully resolved, suggesting that this new scheme could be extrapolated to the X-ray regime to realize the first truly coherent and compact X-FEL.

EEHG is realized by inserting an extra set of components (a chicane, modulator and seed laser) before the undulator. The electron bunch resonates with the harmonics of the two successive modulators, which are seeded with lasers having wave numbers $k_{1}$ and $k_{2}$. The final harmonic order, $k_{n}$, is given by $k_{n} = mk_{1} + nk_{2}$, where $m$ and $n$ are integers. The trick, predicted by Stupakov, is that the harmonic efficiency scales very slowly (as $k^{6}$), thus allowing excitation of the 70–90th harmonics to be achieved in a single stage.

Xiang’s proof-of-principle experiment was performed at the Next Linear Collider Test Accelerator at the SLAC National Accelerator Laboratory. The 120 MeV SLAC electron beam was injected successively into three ten-period undulators, each separated by a chicane. The first and second undulators were seeded by 795 nm and 1,590 nm lasers, respectively. The 1,590 nm laser was initially sufficiently intense to excite the 3rd and 4th harmonics. As the 795 nm was turned on, a strong signal at 530 nm was generated. This is the first direct proof of EEHG as it appears only in the presence of both lasers. To discriminate the echo signal ($n = -1, m = 5$) from the superimposed 3rd harmonic of the 1,590 nm laser, Xiang and co-workers chirped the electron energy, allowing three clear echo signals named $E1$ (373 nm, $n = -5, m = 4$), $E2$ (405 nm, $n = -1, m = 6$) and $E3$ (458 nm, $n = 1, m = 2$) to be recorded. The electron beam chirp was then varied, resulting not only in the shift of the second harmonic of the 795 nm laser (as predicted by classical harmonic theory), but also in the shift of $E2$ and $E3$, which is in good agreement with EEHG theory. The displayed spectra showed signals for both the echo and the harmonic, which seem, in the absence of exact values, to be of similar intensities, with the echo signals coming from higher orders ($n = -5$ or $m = 6$) than harmonics (2nd or 3rd). Although subjective, this suggests that the signal decay scales slowly with $k_{n}$, as predicted.

The theory and experimental realization of EEHG are both groundbreaking, with profound implications for FEL science. Several issues remain to be investigated, such as the confirmation of the harmonic intensity scaling law over a wide spectral range and the demonstration of EEHG at vacuum UV wavelengths. Nevertheless, if these scaling laws are verified, we may see most vacuum-UV FELs upgraded to exploit EEHG sooner or later. It is not straightforward to introduce EEHG to an X-FEL seeded by UV laser due to the large jump in harmonic number (~1,333th). Instead, seeding the first modulator at 13 nm with intense HHG (Fig. 1e) is an attractive option. For example, the LCLS’s fundamental wavelength of 1.5 Å could be tuned in this way by ‘only’ the 87th harmonic. It also seems that EEHG is less affected by the electron bunch quality (emittance and energy spread) than other FEL schemes. Thus, EEHG may also rekindle the promise of compact FELs driven by laser-produced plasmas — a means of accelerating electrons that is convenient but suffers from inferior electron bunch quality.

Philippe Zeitoun and Guillaume Lambert are at the Laboratoire d’Optique Appliquée, Chemin de la Hunière, 91671 Palaiseau Cédex, France; Marta Fajardo is with the Group for Lasers and Plasmas at the Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal. e-mail: philippe.zeitoun@ensta-paristech.fr

References

VIEW FROM... JSAP AUTUMN MEETING

Talking optics in Nagasaki

Research on solar cells, optical frequency combs, high-power laser diodes and brain monitoring were all topics of discussion at the autumn meeting of the Japan Society of Applied Physics in Nagasaki this September.

Noriaki Horiuchi

Early in the 17th century, the feudal government of Japan broke off all relations with foreign countries, prohibited foreign travel and enforced national isolation until the mid-19th century. It was only at the port of Nagasaki, around 1,300 km southwest of Tokyo on the island of Kyushu, where information about the outside world on subjects such as politics, science and culture could be obtained. As a result, Nagasaki became an important centre for education in Japan — a reputation maintained by the recent 2008 Nobel Prize in Chemistry, which was awarded to Osamu Shimomura from the University of Nagasaki. It therefore seems fitting that Nagasaki University was home to this year’s autumn meeting of the Japan Society of Applied Physics (JSAP), which was held on 14–17 September 2010. The event featured around 3,400 presentations, of which approximately 30% were relevant to photonics. This year, the sessions on solar cells were particularly popular, most likely due to the abundance of research centres and factories fabricating solar-cell-related products in Kyushu.

Here’s a brief summary of some of the presentations that caught our eye in other areas of photonics. The first was concerned with the development of atomic clocks that exploit ultranarrow optical transitions (also known as optical clocks), which are expected to become an important highly precise frequency measurement standard and a successor to the caesium microwave clocks used today. To realize such optical clocks, an ultrastable laser source with a narrow linewidth and high frequency stability is required. Kazumoto Hosaka of the National Institute of Advanced