GRAPHENE PLASMONICS

Ultra-tunable graphene light source

Compact monochromatic X-ray sources based on graphene plasmons may soon become a reality.

Gordon Robb

Free-electron-based light sources have long attracted interest due to their continuous tunability that has been demonstrated to extend across the electromagnetic spectrum from millimetre waves and microwaves through the infrared and visible to ultraviolet and X-ray regions. However this intrinsic tunability, particularly at short wavelengths, usually involves sources that are large and costly. The prospect of a compact, continuously tunable light source with the capability to generate short-wavelength ultraviolet and even X-ray light is an exciting one for many scientific, medical and engineering applications.

Now writing in *Nature Photonics*, Liang Jie Wong and colleagues from the USA and Singapore have proposed a method for realizing such a source, which is perhaps an initial step towards a chip-scale tunable laser source of coherent short-wavelength photons[1]. Their analysis and numerical simulations predict that tunable short-wavelength radiation can be produced via the interaction of an electron beam with plasmons in graphene (Fig. 1), offering a potential route to the realization of very compact, chip-scale tunable visible and ultraviolet radiation sources and even tunable X-ray sources with sizes far smaller than that possible using conventional methods.

Free electrons can generate light when they are passed through a periodic structure, with which they interact due to resultant electron oscillation (that is, acceleration). In free-electron lasers, which have been used to produce coherent radiation from microwave wavelengths down to X-ray wavelengths, the electrons are passed through a periodic, magnetostatic undulator or 'wiggler' field, which induces oscillations in the electron motion transverse to the direction of beam propagation. The wavelength of light produced is determined by the condition that constructive interference occurs between light waves emitted by an electron after each oscillation during its trajectory. The wavelength is therefore dependent on both the electron beam energy and the period of the magnetic wiggler field. Therefore, generation of continuously tunable light is possible through variation of either the electron beam energy or the spatial period of the wiggler field.

While the tunability of free-electron-based light sources is attractive, a hindrance to the widespread utilization of these sources to date has been their large size. Wiggler magnets have lengths ranging typically from several metres to around 100 metres — orders of magnitude larger than those associated with chip-scale systems. Several schemes have been proposed that retain the continuous tunability of free-electron sources with reduced size. Many of these involve the use of an electromagnetic wiggler generated by an intense laser, which produces short-wavelength radiation from an electron beam via Thomson or Compton scattering[2]. The shorter, typically micrometre-scale period of an electromagnetic wiggler relative to the centimetre-scale period of a magnetostatic wiggler reduces the electron beam energy required to produce a given wavelength of light. Other configurations based on similar principles have also been proposed, including the use of short-period plasma wigglers[3] and crystal wigglers[4] produced by density waves in the plasma and periodically deformed crystals, respectively.

In the researchers' analysis, the crucial ingredient is graphene, a single-layer honeycomb lattice of carbon atoms that has several remarkable properties including extremely high electrical conductivity and the ability to support surface plasmon polaritons. The existence of plasmons is not unique to graphene, but graphene plasmons are notable for their long lifetimes and high spatial confinement, the latter of which is due to very short effective plasmon wavelengths that result from plasmon–polariton coupling. It is this short plasmon wavelength (that is, the spatial period of the electric field associated with the spatially modulated charge distribution of the plasmon) that plays a role similar to that of an ultrashort-period wiggler. This ultrashort-period wiggler may allow generation of short

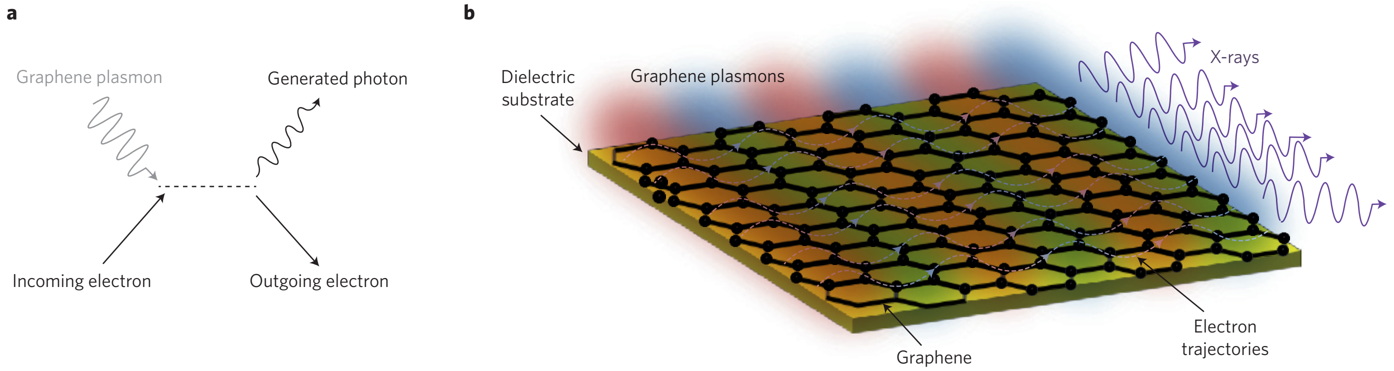

Figure 1 | Generation of tunable radiation in graphene. **a**, A schematic for the proposal of a graphene-plasmon-based free-electron source of short-wavelength radiation. **b**, The dotted white lines represent free electrons that, on interaction with the graphene plasmons (red and blue), offer short-wavelength monochromatic photons (purple). Figure reproduced from ref. 1, Nature Publishing Group.

wavelengths using electron beams with much lower energies than are required using conventional free-electron radiation sources utilizing magnetostatic or electromagnetic wiggler fields in vacuum. As the electron acceleration stage is the main reason for the large size of free-electron sources, the results offer a potential route to highly compact, tunable short-wavelength radiation. Another attractive feature of graphene is that, as well as the possibility of tuning the generated light via electron beam energy and plasmon wavelength, it also offers additional tuning capability via its Fermi energy, which can be varied by doping the graphene layer.

While other compact, tunable free-electron sources, for example ‘light wells’[4], have been demonstrated experimentally in the terahertz or infrared region of the electromagnetic spectrum, the reported results offer the prospect of extending the capability of such sources to short wavelengths in the ultraviolet, soft X-rays with photon energies of ~100 eV using mildly relativistic electrons with energies of ~100 keV and even potentially hard X-rays with photon energies of ~10 keV from relativistic electrons of ~1–10 MeV. Generation of ultraviolet or X-ray radiation from graphene plasmons would itself be of significant value for applications, but the results reported by Wong *et al.* are based on the generation of spontaneous, incoherent radiation from the graphene layer. A significantly more challenging, and potentially rewarding extension of these results is the prospect of a highly compact and tunable source of coherent light, that is, a chip-scale laser with the capability to produce bright, coherent short-wavelength light. The potential of such a source can be estimated by looking at the range of new studies that have been made possible by the recent availability of coherent X-ray radiation produced by free-electron lasers (FELs) such as those at the Linac Coherent Light Source (LCLS) in the USA and the Spring-8 Angstrom Compact Free Electron Laser (SACLA) in Japan (see ref. 5 for a review of X-ray FELs). The possibility of realizing short-wavelength light sources with sizes and consequently costs orders of magnitude smaller than these large facilities is an exciting one. While a compact, graphene-layer-based source would not be capable of generating the extremely high (~GW) powers of conventional, magnetic wiggler FELs, its ability to generate coherent, tunable light in spectral regions where few or no bright, coherent sources exist would be extremely valuable. Wong *et al.* conclude that realization of a true lasing regime would require significantly longer interaction lengths and/or higher electron beam currents than those considered in their work[1], but the recent and ongoing rapid progress in graphene fabrication techniques provides encouragement that this is an attainable goal. The future of graphene as the basis of tunable, compact light sources could be a bright one. ❐

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QUANTUM OPTICS

Arithmetic with photons

Extracting a single photon from a light pulse is deceptively complicated to accomplish. Now, a deterministic experimental implementation of photon subtraction could bring a host of opportunities in quantum information technology.

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The deterministic subtraction of a single photon from a light pulse would intuitively seem like an elementary operation. Yet, it’s actually far more complex and difficult that one might initially assume. The operator description of this removal procedure is in fact not simply equivalent to the photon annihilation operator that students learn about when first studying quantum optics.

Despite its difficulty, the capability to take precisely one photon from the incoming light is important to develop because it potentially opens the door to a tantalizing number of opportunities in quantum photonics. On the fundamental side, this capability could be used to experimentally probe basic rules of quantum optics, for example, quantum commutation rules[1] or coherent state invariance[2]. On the applied side, a number of proposals related to quantum cryptography and quantum computing require the ability to reliably remove an individual photon from a pulse. In particular, today’s most common implementations of quantum cryptography distribute quantum keys by transmitting weak but still classical pulses of light. While this approach is currently considered secure, a deterministic extraction of single photons from such pulses would open vulnerabilities in these quantum-key distribution protocols[3].

Typically, photon subtraction can be implemented in a probabilistic fashion with a low-reflectivity mirror, where a click from a single photon detector collecting the reflected light heralds the removal of a single photon from the original input beam. However, to suppress the likelihood of more than one photon being reflected to a satisfactory degree the subtraction has to be set up to have very low success rates. Furthermore, the success rate of this approach depends on the intensity of the incident light. This inadvertently conveys information on the number of photons in the incoming pulse, hence altering its photon state beyond the minimum resulting from the removal of a single photon. All of these drawbacks severely limit the practical uses of this approach.

Now writing in *Nature Photonics*, Serge Rosenblum and colleagues working in Barak Dayan’s laboratory at Weizmann Institute of Science report a demonstration of a deterministic extraction of a single photon from an incoming pulse[4]. Under realistic conditions, the probability of successful extraction of a single photon by this method can potentially approach unity and, importantly, is independent of the