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Subject: Graphene plasmonics

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Title: ~~A Bright Future for~~ Extremely Tunable Graphene ~~as a Tunable~~ Light Source~~?~~

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Author: Gordon Robb

~~Or~~

~~Over the Rainbow With Graphene?~~

Free electron-based light sources have long attracted interest due to their continuous tunability which 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 which 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, Liang Jie Wong and colleagues from the USA and Singapore ~~A possible~~have proposed method for realising such a source, and perhaps an initial step towards a chip-scale tunable *laser* source of *coherent* short-wavelength photons~~, has been reported by a team of researchers from the USA and Singapore led by Marin Soljacic in the current issue of Nature Photonics[1]~~. ~~In their paper, t~~The~~y report results of~~ir analysis and numerical simulations~~ which~~ predict that tunable short-wavelength radiation ~~could~~ can be produced via the interaction of an electron beam with plasmons in graphene, ~~potentially~~ offering a potential route to the realisation 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 with, due to resultant electron motion oscillation (i.e. 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 ~~at different points in~~during its trajectory. It is therefore dependent on both the electron beam energy and the period of the magnetic wiggler field.

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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 utilisation of these sources to date has been their large size. Wiggler magnets ~~typically~~ have lengths ranging typically from several metres to around 100 ~~meters~~ metres – orders of magnitude larger than those associated with chip-scale systems. Several schemes have been proposed which retain the continuous tunability of free electron sources ~~but~~ 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 μm scale period of an electromagnetic wiggler relative to cm 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 their analysis ~~and simulations reported by the Soljacic group~~, the crucial ingredient is graphene, a single-layer, honeycomb lattice of carbon atoms which 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, relative to high ~~and their ability to attain high~~ spatial confinement ~~factors~~ , i.e. very short effective plasmon wavelengths which result from plasmon-polariton coupling. It is this short plasmon wavelength i.e. the spatial period of the electric field associated with the spatially modulated charge distribution of the plasmon~~,~~ ~~playing~~ which plays a role similar to that of an ultrashort period wiggler, and which may allow generation of short wavelengths using electron beams with much lower energies than are required using conventional free electron radiation sources utilising 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 ~~reported by the Soljacic group~~ offer a potential route to highly compact, tunable short wavelength radiation. An additional attractive feature of graphene is that, in addition to 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.

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While other compact, tunable free-electron sources e.g. “light wells”[4] have been demonstrated experimentally in the THz/infrared region of the electromagnetic spectrum, the results reported by the Soljacic group offer the prospect of extending the capability of such sources to short-wavelengths in the ultraviolet-and ~~even X-rays~~, soft X-rays with photon energies ~100eV

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using mildly-relativistic electrons with energies ~100keV and even potentially hard X-rays with photon energies ~10keV from mildly 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 ~~the Soljacic group~~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 i.e. 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 which 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 SACLA in Japan (see Ref. 6 for a review of X-ray FELs). The possibility of realising 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. ~~The Soljacic group~~Wong et.al. conclude that realisation of a true lasing regime would require significantly longer interaction lengths and/or electron beam currents than those considered in the current paper but the recent and ongoing rapid progress in graphene fabrication techniques provides encouragement that this an attainable goal. The future of graphene as the basis of tunable, compact light sources could be a bright one.

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