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.

Michal Bajcsy and Arka Majumdar

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 number of photons in the original pulse. The photon subtraction is implemented in a system that the authors recently also used to demonstrate an all-optical switch controlled by a single photon[5]. The system is based on an on-chip whispering-gallery microresonator coupled to a single three-level quantum emitter with ground states |α⟩ and |β⟩ and an excited state |e⟩ (Fig. 1). The resonator is formed by a silica microsphere (15 μm radius) and is probed by a nearby tapered optical fibre that couples light into and out of it. The coupling between the resonator and the optical fibre can be tuned by controlling their respective distance. The quantum emitter is a laser-cooled rubidium atom that interacts with the evanescent field from the resonator.

The demonstrated method for deterministic extraction of a single photon relies on two mechanisms. First, the evanescent field of the whispering-gallery modes of the microsphere has the property that clockwise- and anticlockwise-propagating photons are both predominantly circularly polarized. However, while the anticlockwise photons have right circular polarization (σ^+), the clockwise photons have left circular polarization (σ^-) — a phenomenon that has only recently been described by Petersen, Volz and Rauschenbeutel[6]. The second phenomena used in the photon extraction scheme is that the selected three-level emitter (in this case a cooled rubidium atom) can only absorb a σ^+ photon when in state |α⟩ and only a σ^- photon when in state |β⟩. Conversely, when the emitter starts in state |e⟩ it will decay into state |α⟩ by emitting a σ^+ photon or into state |β⟩ by emitting a σ^- photon.

During the experiment, a cloud of rubidium atoms is first cooled in a region above the chip with a combination of laser beams and magnetic field to a temperature of less than 10 μK, at which point their thermal motion is slowed down to just a few centimetres per second. The atomic cloud is then released and allowed to freely expand as it falls towards the optical resonator. By the time the atomic cloud reaches the microsphere, the atoms are sufficiently dilute thanks to thermal expansion so that at most one atom will interact with the evanescent field of the whispering-gallery mode of the resonator. Rosenblum and colleagues then verify the presence of this single atom near the surface of the silica microsphere with a sequence of weak light pulses coupled into the resonator from the optical fibre.

In addition to detecting the presence of the atom, these pulses also prepare the atom into state |α⟩. Following these preparations, a pulse of σ^+ circularly

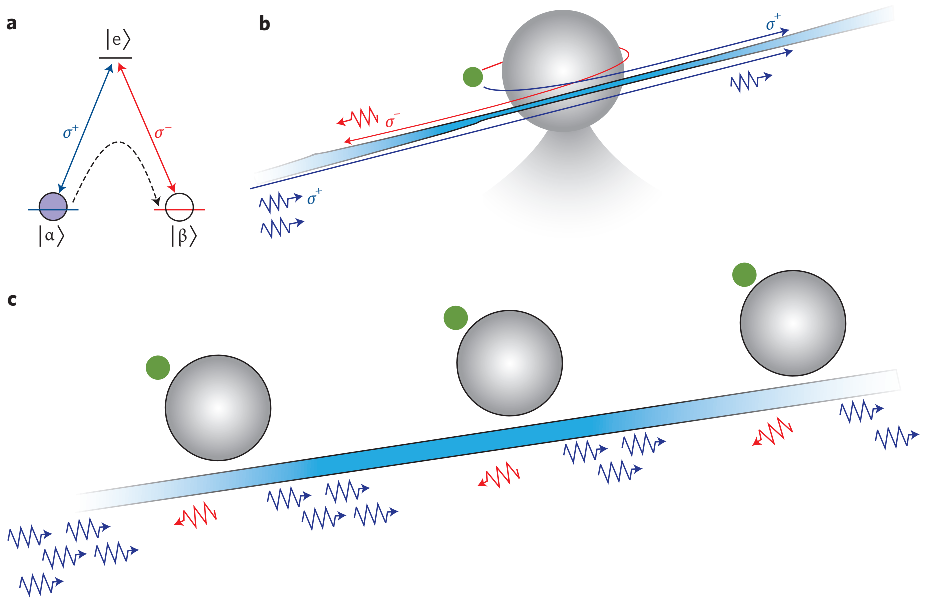

Figure 1 | Principles of photon subtraction. **a**, Energy diagram of a three-level quantum emitter (a cooled rubidium atom) with two ground states |α⟩ and |β⟩ and an excited state |e⟩. **b**, When the atom (green dot) is located near a spherical whispering-gallery-mode optical resonator it interacts with it. Incoming light is coupled into the resonator via a nearby optical nanofibre. When a pulse of right circularly polarized light (σ^+) is coupled into the resonator, the atom absorbs one σ^+ photon from the pulse and in turn emits one σ^- photon (left circularly polarized) into the resonator. The original pulse (minus one photon) couples back into the fibre and continues propagating forward in the original direction. The subtracted single photon also couples back into the fibre but travels in the opposite direction. **c**, Concatenating several of such systems could be used to create a photon-number-resolving detector, in which the photons in the incoming pulse (dark blue) are counted by detecting the individual extracted photons (red).

polarized light containing a selected average number of photons is sent into the optical nanofibre from which it couples into the anticlockwise-propagating whispering-gallery mode of the silica microsphere resonator. Because of the tight confinement of the light in the mode and close proximity of the atom to the surface of the sphere, photons in the anticlockwise and clockwise whispering-gallery modes interact with the atom with a probability nearly equal to unity and the atom's emission into free space is strongly suppressed.

In a cartoon description, this interaction can take two paths. For path one, one of the anticlockwise-propagating σ^+ photons excites the atom into state |e⟩, which is followed by an emission of a σ^- photon as the atom decays into state |β⟩.

However, the emitted photon circulates clockwise in the resonator because of its polarization and couples back into the optical nanofibre but in a direction opposite to that of the incoming pulse. Meanwhile, the remaining photons in that pulse will not interact with the atom anymore — as their polarization now does not match the polarization required by the |β⟩ to |e⟩ transition — and the pulse will simply couple back into the optical nanofibre and continue travelling in its initial direction but with exactly one photon missing. For path two, after one of the anticlockwise-propagating σ^+ photons excites the atom into state |e⟩, the atom will decay back into state |α⟩, while emitting a σ^+ photon. This photon will have an opposite phase compared with the photons in the original pulse and, assuming the photon flux in the incoming pulse is not too high, will interfere with those photons destructively, effectively blocking their transmission.

Overall, the system will not transmit any photons until path one is taken, which results in reflection of exactly one photon and the system becoming fully transparent for the rest of the pulse. For comparison, when the authors did not place an atom next to the resonator or started with an atom in state |β⟩, the light pulse would be fully transmitted through the system with no photons reflecting backwards. Although the purity of the reflected and transmitted states gradually decreases with increasing number of photons within the input pulse it can be retrieved at the price of reduced efficiency in this scheme. At the same time, numerous applications of deterministic single-photon extraction do not require pure states, such as photon-number-resolving detectors, as well as many protocols of quantum cryptography and quantum information processing.

Altogether, this experiment is clearly a significant step forward for quantum optics, but to become practical and suit widespread use the system ideally needs to be further integrated and miniaturized. One possible strategy for achieving this could be coupling the emitter to smaller planar resonators[7] or integrating the atom-cooling set-up onto the chip[8]. Another direction could be to use solid-state quantum emitters of photons, such as quantum dots[9] or defect centres[10]. ❐

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MICROWAVE PHOTONICS

The programmable processor

Reconfigurable optical chips made from 2D meshes of connected waveguides could pave the way for programmable, general purpose microwave photonics processors.

José Capmany, Ivana Gasulla and Daniel Pérez

The emergence of new communication applications, such as 5G wireless systems, smart cities and the Internet of Things, will call for a new paradigm in the design of access networks[1]. In particular, future wireless networks will need to satisfy two fundamental requirements. First, the need to accommodate unprecedented data bit rates per end user (for instance, 5G targets up to 10 Gb s^{-1} per user). Second, they will need to cope with an ever-increasing number of simultaneous wireless connections, for instance man–man, man–machine and machine–machine communications[2]. Addressing these challenges necessitates the use of radiofrequency carriers with higher frequencies and smaller coverage cells (that is, pico- and femtocells) serviced by base stations with smaller antennas. It will also require the extension of the photonic segment of the network (that is, optical fibre plant) into wireless base stations. A key to success will be the realization of a smooth interface between the radio and the photonic parts of the access network[1,2]. Microwave photonics[3] (MWP) is the natural option for this interface. It enables the generation, processing and distribution of microwave and millimetre-wave signals by optical means, benefiting from the unique advantages inherent to photonics, such as low loss, high bandwidth and immunity to electromagnetic interference.

Until recently, applications for MWP systems have been limited by the high cost, bulky size and power hungry nature of such systems. The emergence of integrated microwave photonics[4] (IMWP) circuitry is changing this situation by integrating MWP components and/or subsystems in miniature monolithic or hybrid photonic circuits. IMWP has the potential to change the power scaling laws of high-bandwidth systems through architectures that combine photonics with electronics to optimize performance, power, footprint and cost. IMWP has focused so far on the so-called

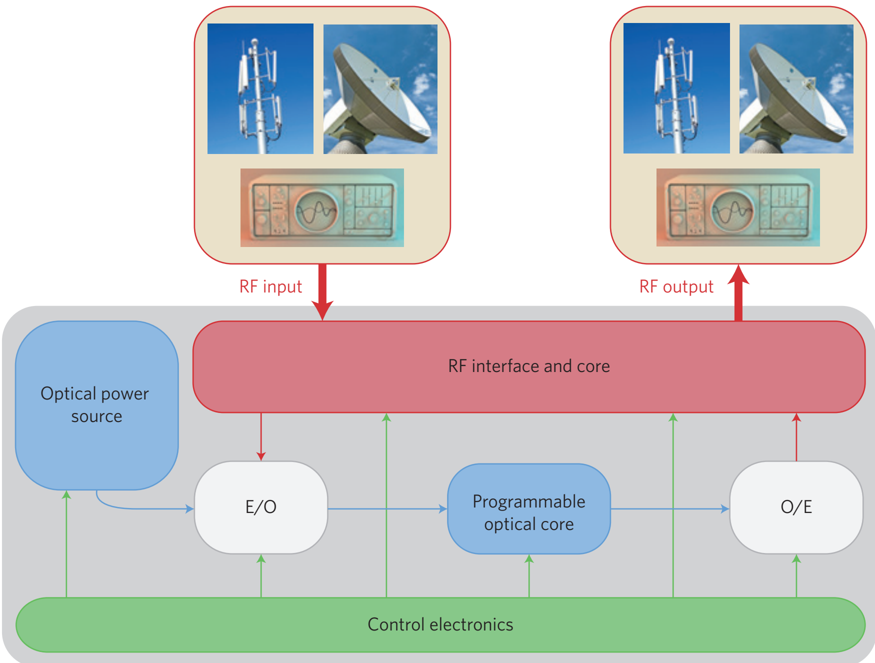

Figure 1 | Generic concept of the universal integrated microwave photonics processor. RF, radiofrequency. E/O is electrical-to-optical conversion and O/E is optical-to-electrical conversion. All images from Thinkstock: antenna, swisshippo/iStock; satellite dish, Zoonar RF/Zoonar; oscilloscope, kanishiotu/iStock.