QUANTUM OPTICS

Slowing single photons

The successful integration of a single-photon source with a slow-light medium creates important opportunities for photon synchronization and marks a step towards the development of distributed networks for quantum information processing.

Lene Vestergaard Hau

Studies of slow light have represented a very active area of research over the past decade. Light was first slowed to a speed ten million times lower than that in a vacuum through the quantum manipulation of atomic states in an ultracold, quantum degenerate gas of alkali atoms[1]. Slowing light pulses to this extent also causes significant spatial compression, which allows them to be contained within a small atom cloud. Light pulses can be stopped altogether and even transformed into matter (in the form of quantum states within a Bose–Einstein condensate) for storage and subsequent conversion into light at a later stage[2].

Researchers have devised several methods for slowing light, including the use of hot caesium vapour[3] and atomic quantum state control in on-chip hollow-core waveguides[4]. In all cases, slowing light by a significant amount requires the medium's refractive index to change rapidly with frequency over a frequency band in which the medium is transparent. Operation in this regime makes it possible to slow the light pulse because its group velocity (the speed at which the envelope of the pulse propagates) is inversely proportional to the slope of the refractive index profile.

Writing in *Nature Photonics*, Nika Akopian and colleagues now report the first hybrid semiconductor-atomic slow-light system, in which single-photon pulses are generated in a solid-state material and then passed through a slow-light medium consisting of a gas of alkali atoms[5]. More specifically, single-photon pulses are emitted from individual quantum dots imbedded in a substrate cooled to a few degrees kelvin. The quantum dots are GaAs inclusions in an AlGaAs matrix and are fabricated by molecular beam epitaxy on a GaAs substrate. An optically generated electron–hole pair — an exciton — can be confined in the GaAs inclusions because the material surrounding the dot — AlGaAs — has a larger bandgap than GaAs. The energy levels of the electron–hole pair are determined both by the size of the dot

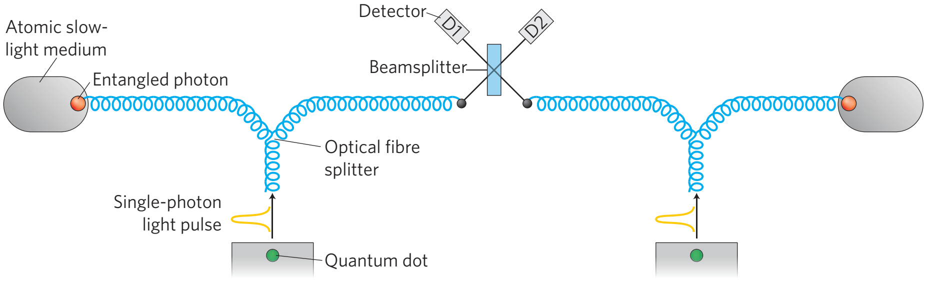

Figure 1 | One segment of a quantum network. A single photon is emitted from each of the two quantum dots (green) and then coupled into an optical fibre splitter. Two of the outputs from the fibre splitters are combined at a beamsplitter. When one of the detectors (D1 or D2) clicks and destroys a photon, we do not know which node (red) the other photon will arrive at. The optical modes at these nodes therefore become entangled. Both modes can be coupled to a slow-light medium that introduces a delay. By controlling the delay, the photon in this segment can be synchronized with those in other, similar segments — a technique that allows entanglement to be extended over many segment lengths.

and the materials comprising the dot and the host, as these factors determine the confinement volume and the depth of the confining box potential.

When a single quantum dot is illuminated with a short (picosecond) laser pulse, an exciton is created and a recombination process, occurring around 500 ps after the creation of the single exciton, leads to single-photon emission. If a double exciton is created, the emitted photon from the first decaying exciton will be frequency-shifted owing to the presence of the second exciton, and can be blocked with a spectrometer[6].

In the work of Akopian *et al.*, the single-photon pulses travel a distance of 1.5 m before being injected into a gas of rubidium atoms, where they are slowed and therefore delayed. The slowing process occurs because the frequency of the photons is centred between two hyperfine-split atomic resonance frequencies of rubidium, thus providing a relatively large refractive index slope while still allowing transmission of the light pulses.

The length of the delay can be controlled by varying the temperature and thereby the density of the gas. The researchers slowed their pulses by 15 pulse widths — corresponding to an optical delay of around 8 ns — for a gas temperature of 140 °C. To precisely control the frequency of the photons emitted from the quantum dots, an external magnetic field of a few tesla was used to fine-tune the emission through the Zeeman effect.

This integration of a slow-light medium with an efficient single-photon source represents an important step towards the implementation of distributed quantum networks, which allow encryption keys to be generated and shared for secure data transfers. Akopian *et al.* have succeeded in combining the two key ingredients required for such a network: robust single-photon sources that can repeatedly and deterministically generate single photons, and slow-light media that can synchronize the outputs from different, single-photon-generating quantum dots in the network.

Quantum networks and quantum cryptography rely on the distribution of entangled states over large distances[7]. Entanglement over relatively short distances (10–100 km) can be achieved by injecting a single-photon pulse from a quantum dot into an optical-fibre splitter (an optical fibre with one input and two outputs). The path of the optical pulse will split in two, but because the photon itself cannot be split, quantum mechanics 'dictates' that the photon must take both paths at once, thereby entangling the optical modes at the two fibre outputs. If we place a photon detector at each of the splitter outputs (each, say, 10 km from the quantum dot source), we don't know *a priori* which of the detectors will 'click' to register the arrival of the photon — but we do know with 100% certainty that if one of the detectors clicks, then the other will not.

Achieving entanglement over larger distances requires a hybrid system of a single-photon source and a slow-light medium. Owing to photon losses in long optical fibres, entanglement between distant locations must be implemented through a series of shorter segments. No photon travels the distance of more than one segment, and entanglement is implemented for each segment individually, in the manner explained above. The segments are then combined pair-wise, eventually achieving entanglement over the full distance of the network (a 'quantum repeater'[8]). Photons in different segments of the network must be synchronized with one another, and this is exactly where the slow-light medium comes into play. Because quantum measurements always involve probabilities — outcomes are rarely certain — it might take several attempts to successfully combine and entangle a pair of segments, whereas another pair might be successfully combined in a single attempt. A photon in the latter segments must be put on hold until a photon in the former segment pair is prepared and ready. The first-ready photon can be 'stored' in a slow-light medium until the second photon is ready, thereby synchronizing the two segment pairs of the network. A joint measurement on the two photons can then be performed to combine the segment pairs, and, if the measurement is successful, the entanglement distance is increased to span the full distance of the two segment pairs. Hence, by copying the set-up of Akopian *et al.* multiple times and replacing the 1.5 m of free space between the quantum dot and the slow-light medium with optical fibres, we will be a good part of the way towards implementing a real quantum network.

It should be mentioned that the observed optical delay times — in the nanosecond regime — are not yet large enough to allow quantum keys to be shared over very large distances (it takes almost 0.1 ms for a light pulse to travel a distance of 10 km in an optical fibre). In the future, it would be very interesting to augment this hybrid system by coupling quantum-dot-generated single-photon pulses into atom clouds in the form of ultracold Bose–Einstein condensates. These atomic gases are ideal for optical manipulation because they allow exquisite control of energy levels and quantum states, which can lead to very dramatic effects[2]. In such atom clouds, optical pulses can be converted to matter copies that in turn can be isolated and 'put on the shelf' for long-term storage. The bandwidth and storage time can also be dynamically and rapidly controlled. This system could also form the basis for powerful quantum information processing. Converting single-photon pulses (quantum bits) to matter would allow rapid processing in two-bit quantum gates because the speed would be determined not by nonlinearities between single-photon (optical) pulses, but rather by the much stronger nonlinearities that govern atom–atom interactions. Finally, using a slow-light medium generated by atoms in a nanotrap may allow the hybrid system introduced by Akopian *et al.* to be fully chip-integrated on the nanoscale. ❐

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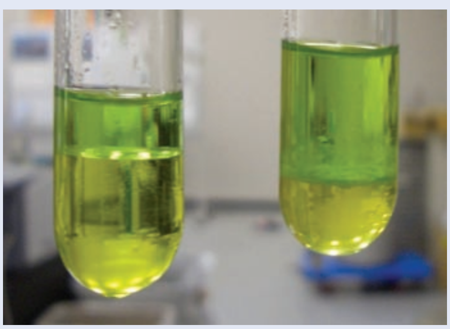
BIOPHOTONICS

Spinach fuels organic LEDs

Although the value of spinach as part of a healthy diet is well-known, its potential role in the optoelectronics industry is only now being understood. Naoki Ohtani and co-workers from Doshisha University in Kyoto, Japan, have successfully fabricated organic light-emitting diodes (OLEDs) that contain chlorophylls extracted from spinach as their active ingredient (*Jpn. J. Appl. Phys.* **50,** 01BC08; 2011). The researchers first spin-coated a 100-nm-thick film containing chlorophylls *a* and *b* onto a glass substrate coated with the transparent electrode material indium tin oxide. They then vacuum-deposited aluminium on top of the organic layer to form the top electrode. No photoluminescence was seen from the sample, which the team attributed to concentration quenching from the chlorophylls. By repeating their experiments using a blend of chlorophyll *a* and the conductive polymer poly(phenylene vinylene), the team successfully created OLEDs that emitted both blue–green and red light when electrically pumped. The blue–green emission peaking at around 500 nm was attributed to the polymer, whereas the longer-wavelength red emission peaking at around 680 nm was attributed to the chlorophyll. The researchers comment that the extraction and fabrication method are important for achieving good results, with chlorophyll prepared in the form of a fat-soluble solution performing much better than that of an acetone or methanol solution. "The OLEDs fabricated using the fat-soluble solution emitted electroluminescent signals for more than one minute, whereas the OLEDs fabricated using the methanol solution worked for less than five seconds," comment the researchers. "The long operation times of OLEDs fabricated using a fat-soluble solution can be attributed to the antioxidant activities of carotenoids."



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