OPTICAL SWITCHING

Atoms and photons share quarters

The demonstration of all-optical switching by confining light and cold rubidium atoms in a hollow-core photonic band-gap fibre may help bring the goal of single-photon switching closer to reality.

Barak Dayan and Yaron Silberberg

Photons are ideal for transmitting information: they travel at the speed of light over long distances and they do not interact with each other (and only weakly with most other media). It is unsurprising, therefore, that communication in our information-hungry society is performed mostly by photons. However, to process this information we typically have to convert it into electrons. Electronics is then used to switch, sort and otherwise manipulate it. This need to convert information back and forth between photons and electrons has long been a limiting stage in communication systems. It has fuelled the long quest to develop an 'all-optical switch' — the optical equivalent of the transistor — that will enable processing of light by light. The latest step in this direction has been reported recently by Michal Bajcsy and co-workers in *Physical Review Letters*[1].

Bajcsy *et al.* have constructed an optical switch that operates with light pulses containing only a few hundred photons[1]. To achieve this, they exploited the nonlinear interaction between photons and cold rubidium atoms, both confined in the central few micrometres of a hollow-core photonic band-gap (PBG) fibre[2]. As photons do not normally interact with each other, an all-optical switch must contain an optically active nonlinear medium to mediate between them — in this case, the rubidium atoms. The principle is that in a nonlinear interaction, one light beam affects the system in a way that changes the transmission of a second light beam. However, nonlinear interactions are usually very weak, and therefore very powerful light beams are required to affect the material sufficiently — this is impractical for most applications. One of the goals in all-optical switching has been, therefore, to strengthen the light–matter coupling to lower the optical power required for optical switching. Generally, this enhancement can be achieved by two different methods: focusing the light into a smaller area (thereby increasing the electric field associated with each photon in the beam) or by increasing the light–matter interaction time. So far, nonlinear interactions with single photons have been achieved solely in the context of cavity quantum electrodynamics by confining the photons in tiny high-quality resonators, thereby achieving both small beam area and long interaction times[3–5].

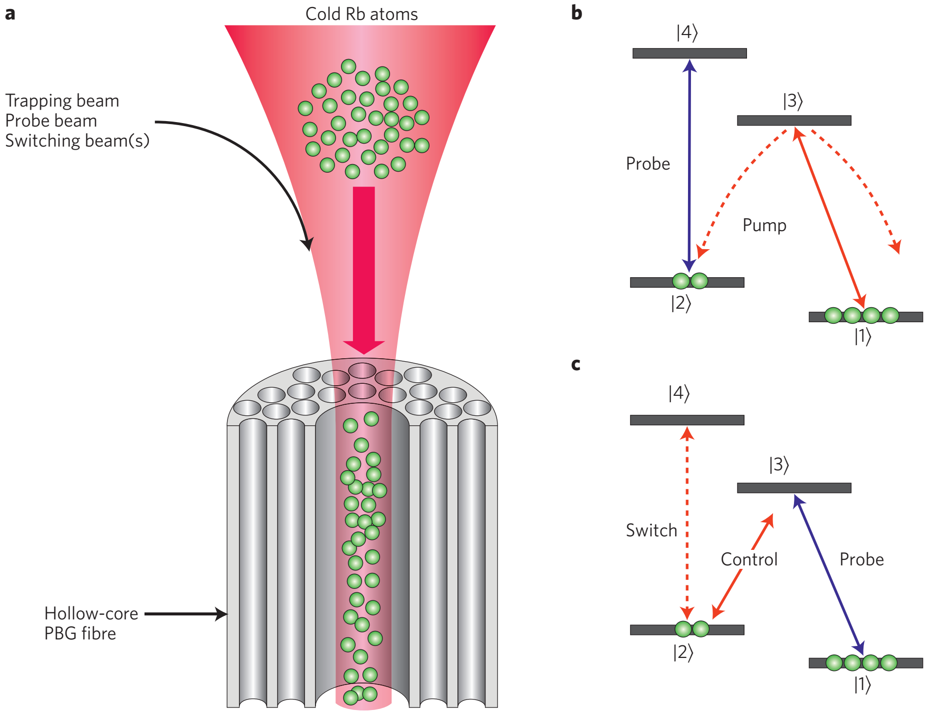

Figure 1 | Experimental set-up and switching schemes. **a**, In the experiment, cold rubidium atoms are loaded into the hollow core of the photonic band-gap fibre, where they are held near the axis by a trapping beam. **b**,**c**, Switching schemes with two or three additional laser beams coupled to the same waveguide to serve as the pump and probe beams in the incoherent switching scheme (**b**) or control, switch and probe beams in the coherent schemes (**c**).

Bajcsy *et al.* operated their switch with a tiny pulse containing only a few hundred photons while avoiding the need for technologically challenging high-quality resonators. In the absence of a resonator, the requirement for long interaction time is partially provided by the fact that the tight confinement (the small beam area) is kept throughout the entire length of the fibre, giving the photons a chance to interact with any of the many atoms that were loaded into its hollow core.

In such a system (where each photon has a chance to interact with many atoms), two processes can take place — incoherent and coherent. In an incoherent process, the probability that a photon interacts with one atom is added to the probability of interacting with the next. In a coherent process, however, it is the probability amplitudes for interaction events that are summed, leading to collective excitation of the entire ensemble of atoms. Of these two types, the coherent processes hold the promise of bringing all-optical switching to the single-photon level. Achieving nonlinear interactions between single photons is not merely a technological goal, but a significant scientific one too: this can enable quantum information processing, with single photons

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functioning as the 'Qbits', the carriers of quantum information[6].

In their experiments, the authors harnessed both incoherent and coherent processes. Their set-up consisted of an ultrahigh vacuum chamber, in which the atoms were collected and cooled using conventional laser-cooling methods and then magnetically guided towards the open end of the hollow-core PBG fibre. The atoms were kept near the axis of the hollow core by a red-detuned laser coupled into the fibre — the 'trapping beam' (Fig. 1a).

After the nonlinear medium (approximately 3,000 rubidium atoms) was placed in the fibre core, several different switching schemes were implemented by coupling the probe beam (that is, the beam that is to be switched on and off) into the fibre, together with the appropriate switching beams.

The simplest scheme was incoherent and included only one switching beam, referred to as the 'pump'. In this configuration, for the 'on' state the atoms were initiated in a 'wrong' ground state, |1⟩ (Fig. 1b), which was uncoupled to the probe field (hence keeping the medium transparent to the probe beam). To switch the probe beam off, the pump beam was turned on, transferring atoms to the 'correct' ground state, |2⟩, which was coupled to the probe field through the cycling transition |2⟩⇔|4⟩. A 'cycling' transition means that once at the excited state, |4⟩, the atom can decay only back to the initial ground state, |2⟩. In this manner, each atom can repeatedly scatter photons from the probe, making the medium opaque, as required in the 'off' state.

This simple scheme reveals the power of confining both light and atoms in a waveguide as small as the PBG fibre, enabling just a few hundred atoms to block the beam completely. Because many atoms were loaded into the fibre, every photon from the pump was guaranteed to be absorbed, thereby exciting the atoms from |1⟩⇔|3⟩. Unlike the |2⟩⇔|4⟩ transition, the |1⟩⇔|3⟩ transition induced by the pump is not a cycling one, and so the atoms could decay to either ground state. Therefore, to transfer ~150 atoms to the |2⟩ state, approximately twice that number of photons were required in the pump pulse to block the probe beam. Although not discussed, switching the device back to the 'on' state would seem to require a significantly larger number of pump photons (now resonant with the |2⟩⇔|3⟩ transition) than switching the device to the 'off' state. This is because all the atoms need to be transferred back to state |1⟩ to render the medium completely transparent again — a task that becomes harder as fewer atoms are left in state |2⟩ to absorb the pump photons.

The other two switching schemes reported by the authors implement the coherent effect of electromagnetically induced transparency (EIT)[7]. In this effect, a control field between levels |2⟩ and |3⟩ enables the coherent transfer of some of the atoms from one ground state to the other, creating a destructive quantum interference that prevents the absorption of photons from the probe beam. Thus, the authors demonstrate all-optical switching by turning the EIT effect on and off. This is achieved by either switching the control beam on and off, or by keeping it on and toggling another switching beam (resonant with the |2⟩⇔|4⟩ transition) that can disable the EIT effect. In both schemes, the switching effect was demonstrated with a few thousand photons (~5000 photons in the first scheme and ~1000 in the second), with 500-ns-long pulses.

Although nonlinear behaviour, and even all-optical switching, have been demonstrated in free space at even lower power levels (as low as 20 photons per pulse[8]), the potential that lies in combining hollow-core fibres and cold atoms for nonlinear light–matter interactions at ultralow power levels makes this demonstration very interesting. In fact, merely the task of loading cold atoms into the fibre's hollow core and preventing them from colliding with its walls is a significant technological achievement that was accomplished successfully only recently[9].

However, the switch developed by Bajcsy *et al.* is currently far from the technological needs of practical optical communication systems — its operation is narrowband and outside the preferred wavelength window of telecommunications, and its modulation is far too weak and slow. It seems that real-world systems will continue to use photons for communications and electrons for logic for the foreseeable future. However, if the concepts presented could indeed be pushed towards the single-photon limit, they could help fulfil some of the needs in the growing field of quantum information, needs that simply cannot be answered by conventional electronic devices. ❐

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QUANTUM OPTICS

Single photons shape up

The successful control of the phase of light within a single photon wavepacket paves the way to a range of applications in quantum information science.

Sean Barrett

A classical propagating electromagnetic wave can be defined by just two parameters: the amplitude and phase of its oscillating electromagnetic field. Engineers have long been able to manipulate the phase of such waves with high precision, enabling a variety of applications, including FM radio, wireless local area networks and radar pulse shaping.

On page 469 of this issue, Specht *et al.* extend this ability into the quantum realm, demonstrating the ability to manipulate the phase of light within a 'wavepacket' (a pulse of light) containing just a single photon[1]. Previously, phase modulation of single-photon wavepackets involved delaying the entire light pulse[2]. Instead, Specht *et al.*

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