processing[4], and were used, for example, in the experimental demonstration of fundamental quantum protocols such as entanglement, quantum teleportation and quantum key distribution. These protocols all transmit information from one location to another. The storage of information is another crucial tool for quantum information processing. In the context of continuous-variable systems, researchers have demonstrated a quantum memory by mapping the quantum state of an optical field mode to symmetric excitations of an atomic ensemble[5]. The central limit theorem ensures that the atomic system is well-described by a set of continuous variables, and that the write-in, storage and read-out stages are modelled well by a Gaussian channel. In all of these applications, the quantum capacity determines the maximum achievable performance of the channel, and is therefore of prime importance.

Although most applications have so far focused on single-mode channels, the work of Smith *et al.* shows that recent interest in broadband channels[6,7] and multimode quantum memories[8] may lead to a wide range of promising and surprising applications. ❐

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ATOM–LIGHT INTERACTIONS

The nonlinearity of single photons

It has long been known that light can be slowed and stopped in an atomic medium using electromagnetically induced transparency. Researchers have now shown how an optical resonator can help a single photon induce its own transparency, which could have exciting applications in quantum information science.

P. K. Lam and B. C. Buchler

Strongly nonlinear processes with high efficiency have always been of great interest to scientists and engineers. In photonics, such processes are versatile assets that can be exploited to perform a variety of tasks, ranging from all-optical switching to precision metrology. In quantum information science, the ability to operate nonlinear processes at the few-photon-level is interesting because it may enable the generation of exotic quantum states and the realization of deterministic nonlinear gates for quantum computation[1]. Significant progress towards this feat has now been reported in a recent issue of *Science* by Tanji-Suzuki *et al.*[2], who describe a phenomenon they refer to as 'vacuum-induced transparency'.

In general, optical nonlinear processes can be realized through two types of approach. Nonlinear materials whose atomic transition resonances are detuned far from the frequencies of the optical field can be used to achieve effects such as second-harmonic generation, optical parametric oscillation and four-wave mixing. These processes can be enhanced by extending the duration of the interaction with the light field. In fibre-optic or waveguide systems, in which the optical fields remain tightly confined, nonlinearity can be enhanced simply by increasing the length of the nonlinear medium. Alternatively, placing a nonlinear medium in a resonator, such as a Fabry–Pérot cavity, can also enhance nonlinearity by a factor of the resonator finesse. For example, optical parametric oscillators in cavities have been used to produce pure squeezed light for gravitational wave detection[3] and narrowband photon pairs[4,5]. Unfortunately, enhancing nonlinearity using these methods results in a comparable increase in transmission losses.

Another way of enhancing nonlinearity is to create an optical field interaction close to the transition resonances of a system capable of exhibiting a large nonlinearity. Through this approach, optical fields carrying quantum information, which are otherwise mutually non-interacting, can be mapped onto a common system, interact nonlinearly and then be mapped back into optical fields. Two examples of this mapping approach are nano-optomechanical systems[6] and near-resonant interaction with a multilevel atomic ensemble[7].

Electromagnetically induced transparency (EIT) has been suggested as a light–atom mapping process for quantum information applications. In normal EIT, as shown in Fig. 1a, a control field resonant with the $g \leftrightarrow e$ transition is used to induce level splitting in the excited state, which changes the dispersion of the media and thus controls the group velocity. The delay experienced by a pulse of light is determined by the strength of the control field; the smaller the control field power, the slower the group velocity. Hau *et al.* used EIT to slow light down to 17 m s^{-1} in an ultracold atomic gas[8]. Longdell *et al.* showed that EIT can be used to stop and store light for more than 1 s in cryogenically cooled rare-earth crystals when the control field is switched at the right moment[9]. EIT-like behaviour can also be achieved in optomechanical systems. Safavi-Naeini *et al.* recently used optomechanically induced transparency at cryogenic temperatures to slow light[10]. In all of these demonstrations, the dynamics of EIT can be described using a linear polaritonic description[11].

EIT can also be engineered to give a nonlinear response. Shiau *et al.* recently observed nonlinear cross-phase modulation effects from two pulses of light using an asymmetric M-type five-level system formed by two sets of EIT apparatus[12].

Tanji-Suzuki *et al.*[2] have now pushed this paradigm even further. Fig. 1b shows a simplified schematic of their experiment, in which a few-photon field is incident on a cloud of trapped atoms that overlaps with the mode of a high-finesse optical resonator. No external control field is applied, yet a window of transparency is still observed in the atomic absorption

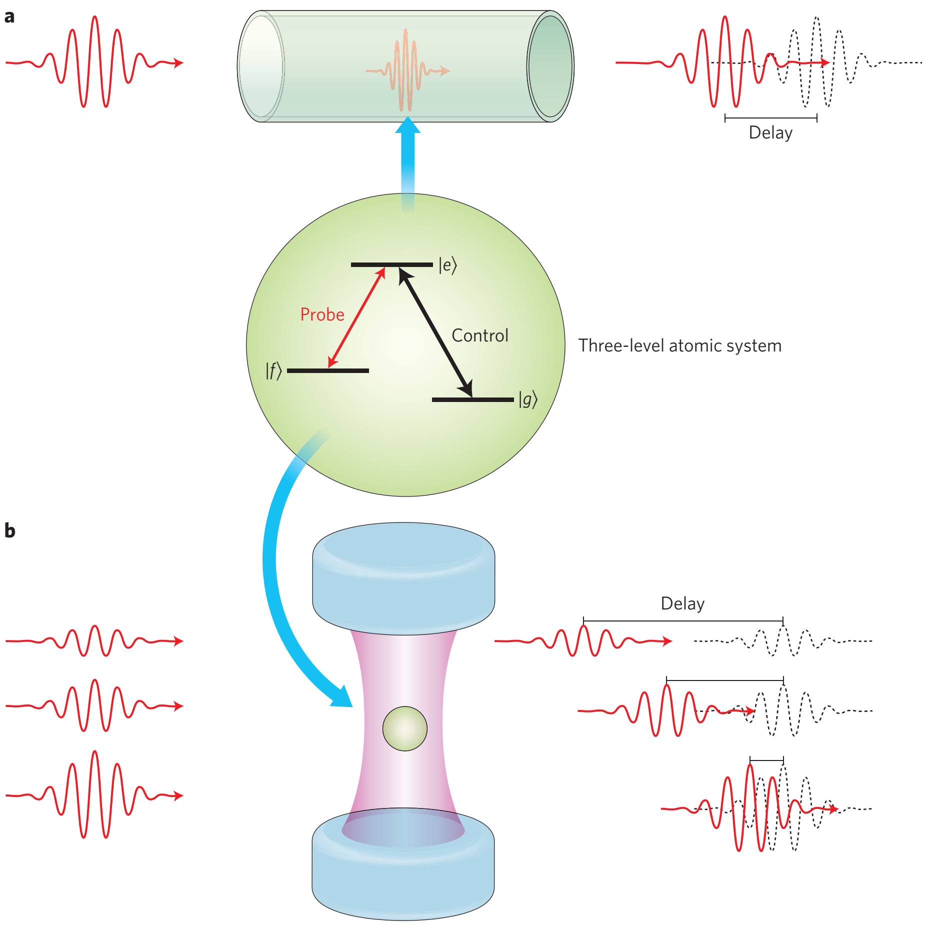

Figure 1 | Exploiting nonlinearity to slow down light in a medium. **a**, In EIT, the control field power determines the delay of the probe. **b**, In VIT, no control field is applied and the delay is determined by the probe photon number.

spectrum. The researchers refer to this effect as vacuum induced transparency (VIT) because no external control field is required. In VIT, the input probe field is set to be resonant with the *f*↔*e* transition, as is the case for EIT. However, the crucial difference with VIT is that the *g*↔*e* transition frequency is resonant with a mode of the high-finesse cavity. Under this condition, there is a coherent coupling between the probe field and the mode of the cavity mediated by the atomic ensemble. The probe field incident on the atoms therefore also plays the role of the control field, which determines the speed of light through the atoms. This delays the transmission of the probe by an amount that is dependent on the strength of the probe field itself; the weaker the probe pulse, the lower the group velocity and the longer the delay. In a theoretical investigation of this idea, Nikoghosyan and Fleischhauer[13] showed how such a system could be used to collapse an input quantum state into the number (Fock) basis. A coherent pulse, for example, is composed of a superposition of Fock states with different photon numbers. During transmission through the VIT system, the number of photons sets the delay experienced by the pulse. VIT therefore constitutes a projective measurement that can transform the coherent statistics of a light pulse into a Fock state. This could, in principle, be used as the basis for a single-photon source.

The experiment of Tanji-Suzuki *et al.* used a cavity with a finesse of 63,000 and a cold cloud of caesium atoms at a temperature of 100 μK. Critical to the success of the experiment was achieving a high optical depth for the atomic ensemble. The researchers trapped around 10^5 atoms in an off-resonant optical lattice to give a single-pass optical depth of 0.4. Probing the system with pulses containing an average of 0.8 photons achieved 40% transmission of the probe light due to VIT at a delay of 25 ns, which corresponds to a group velocity of 1,600 m s^{-1}.

The demonstration of VIT shows that the on-resonant interaction of optical fields with atomic transitions may have the potential to deliver large nonlinearities at low photon numbers. This work will undoubtedly stimulate further interest in the quest for a cleaner and stronger nonlinear mechanism for quantum information applications. ❐

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