MICROPHOTONICS

Playing with atoms

Researchers in London have produced a scalable microphotonic chip that can optically detect and address individual atoms. The end result could be atom–photon chips capable of complex, system-level functionality.

Oskar Painter
is at the Thomas J. Watson Sr, Laboratory of Applied Physics, California Institute of Technology, Pasadena, California 91125, USA.
e-mail: opainter@caltech.edu

The scalable manipulation and optical addressing of atomic systems is at the heart of many proposed schemes for quantum communication and quantum information processing[1,2]. In such systems, quantum information is stored in the states of individual atoms and ions, or within macroscopic atomic ensembles and vapours. Photons prepare atomic states, mediate atomic interactions, and act as 'flying quantum bits' for the readout and distribution of quantum information. As such, there is keen interest in developing miniature, chip-scale photonic and electronic devices for the manipulation of atomic systems.

In the field of cavity quantum electrodynamics[3] (cavity QED), atom–photon interactions are tailored through the use of an optical resonator or cavity. The canonical cavity QED system consists of an alkali atom trapped inside a high-finesse Fabry–Pérot cavity that consists of two highly reflecting mirrors (Fig. 1). The cavity finesse represents the number of round trips a photon makes on average before leaving the cavity. Scaling cavity QED systems to allow for multiple-cavity interactions and highly parallel optical readout and control may still be a way off. However, recent work[4] by a team of researchers at Imperial College London provides a hint as to what these integrated systems might come to look like in the not-so-distant future.

The hybrid system developed by the researchers consists of high-finesse Fabry–Pérot cavities formed by mating two very different arrays of mirrors. The first array consists of curved dielectric micromirrors formed on the surface of a silicon wafer; the second is made up of a parallel array of precision-mounted single-mode optical fibres with dielectric coatings on their ends (Fig. 2). The fibre-based mirrors provide an elegant and efficient means of optically interfacing to the microcavity array. Mirror alignment and cavity tuning are accomplished by mounting the silicon wafer on a piezoelectric translator (PZT). Both the fibre array and PZT-mounted silicon wafer are themselves attached to the backside of a regular (macroscopic) mirror. A 1-mm-diameter hole in the mirror enables cooled ^{85}Rb atoms to be transferred from a magneto–optical trap into the microcavity array.

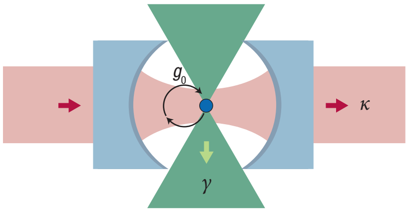

Figure 1 Diagram of a canonical cavity QED system involving an alkali atom trapped inside a high-finesse Fabry–Pérot cavity. The ability to optically detect the presence of an atom by way of cavity transmission is determined by three factors: the coupling rate between the induced atomic dipole and the resonant mode of the cavity (g_0), the atomic dipole decay rate (γ) and the field decay rate of the cavity (κ).

Although these initial microcavity devices only have a finesse of $F = 280$, the small mode volume of the Fabry–Pérot cavities (about 2,000 μm^3) still enables detection of fewer than one atom in the cavity. Atom detection is performed by sending a weak (1 pW) probe beam through the single-mode fibre end of the cavity and measuring the back-reflected signal from the cavity incident on a single-photon detector. Owing to the large coupling strength of the atomic dipole to the cavity mode, the presence, on average, of even a single atom in the cavity is heralded by a measurable increase in the resonant reflected signal level. This is due to the efficient scattering of intracavity light back into the fibre by the atom, and its interference with the light reflected by the cavity mirrors.

In addition to studying the atom–cavity resonant response, the Imperial College team also measure the enhanced fluorescence properties of atoms as they travel through the cavity. The Purcell effect — which enhances the rate of spontaneous emission from atoms into the cavity mode, and thus the directionality of atomic fluorescence — scales inversely with the cavity volume. For the devices studied in ref. 4, roughly 50% of the atomic fluorescence is directed into the cavity mode, resulting in a burst of fluorescence detected through the mirror of the single-mode fibre as optically excited atoms pass through the cavity. This should be compared with the roughly 0.01% of atomic emission that would be collected by the single-mode fibre in the absence of the cavity.

With further improvements in cavity finesse, the team hopes to improve both the sensitivity of their atom detection and the efficiency of the cavity-enhanced atomic fluorescence into their fibre-optic waveguides. Attaining finesse values approaching $F = 5{,}000$ for their system[5] would enable the tracking of individual atoms as they make their way through the cavity. It would also raise the excitation transfer efficiency above 90% from atom to cavity through atomic fluorescence. Although the scale of the devices under investigation at present is rather modest (an array of only two cavities were demonstrated), there is good reason to expect that this architecture could be scaled up to include a much larger number of devices. The authors are already well on their way to developing electrostatically actuated micromechanical versions of the silicon end mirrors[6], and the precise alignment and fabrication of optical-fibre arrays is already a commodity in the photonics industry. A further challenge will be the integration of the cavity arrays with atom chips capable of manipulating and trapping atoms near a microchip surface. Recent work along these lines[7] has resulted in an all-fibre-based Fabry–Pérot cavity, which can be loaded by sending atoms along a magnetic

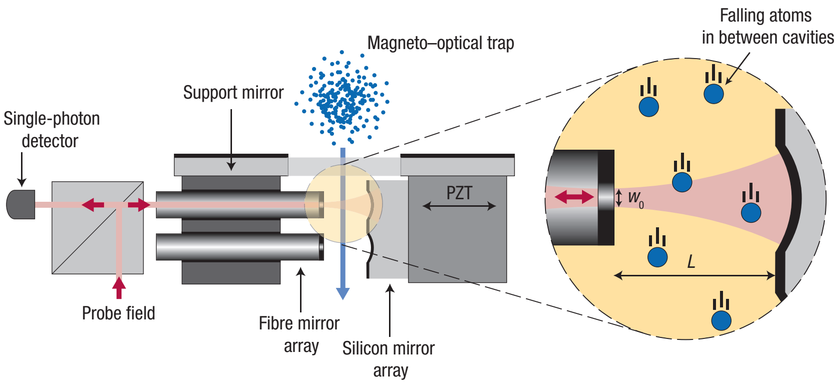

Figure 2 Schematic of the cavity apparatus demonstrated by the Imperial College research team[4]. The mirrors of an array of Fabry–Pérot cavities are formed on one side by planar ends of single-mode fibres, and on the other side by a series of smoothly etched curves in the surface of a silicon wafer. A hole in the support mirror allows ^{85}Rb atoms, cooled to a temperature of about 30 μK in a magneto–optical trap, to enter the microcavity array. The falling atoms are then detected by applying a weak optical probe through one of the optical fibres and measuring the back-reflected signal. An optical beam perpendicular to the cavity array may also be used to excite intracavity atoms, with the resulting fluorescence efficiently captured by the optical-fibre end mirrors. The cavity length, L, is 130 μm, and the minimum cavity-mode waist diameter, w_0, is 4.6 μm.

guide formed from on-chip microwires. Other chip-scale cavity geometries are also being explored, including microdisk[8] and microtoroid[9] resonators, which can be fibre-coupled with extremely high efficiencies using drawn fibre taper waveguides. In contrast to the open cavity geometries of the Fabry–Pérot, the whispering-gallery-mode microdisk and microtoroid cavities would require atoms to be trapped close to the surface of the resonator, in the evanescent field of the cavity mode.

In a broader context, the miniaturization and integration of atomic, electronic and photonic systems is also important for the realization of chip-scale precision measuring devices and sensors[10]. Similarly, the ability to integrate highly coherent media, such as atomic gases, into a chip-scale format greatly expands the possibilities for optical devices and systems. Whether for quantum or classical applications, it is quite amazing to think that microchips of the future may involve clouds of atoms being transported within miniature circuits controlled by electrical and optical signals.

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LIGHT AND MOTION

Cavities learn to adapt

When tiny optical cavities are coupled together on the nanoscale, optical forces can dominate. A new proposal from researchers at the Massachusetts Institute of Technology provides a way of harnessing these forces, leading to microcavities that can mechanically adapt their geometry.

Mihaela Dinu
is at Alcatel-Lucent's Bell Laboratories, 791 Holmdel-Keyport Road, Holmdel, New Jersey 07733, USA.
e-mail: mdinu@alcatel-lucent.com

Controlling the properties of light using mechanical devices is standard practice in the laboratory. Conversely, light has been used to generate mechanical forces that can then be exerted on dielectric materials. Closing the loop on the interplay between mechanical devices and their control of light, Peter Rakich and colleagues propose a method of trapping and controlling optical resonances through the use of opto–mechanical potentials (page 658 of this issue[1]). This intriguing concept could lead to a new class of reconfigurable optical devices.

The idea that light radiation can exert mechanical action, or pressure, has a long history (see for example the historical timeline in ref. 2). The radiation pressure of light was first rigorously derived by Maxwell[3] and measured experimentally at the beginning of the twentieth century by Lebedev[4], and Nichols and Hull[2]. In more recent times, following the pioneering work by Ashkin[5], dipole forces exerted by light fields on dielectrics have been used to trap and control macroscopic particles and to cool atoms to very low temperatures.

Optical tweezers, used for the accurate movement and placement of micrometre-sized particles, typically require careful tight focusing of one or more light beams, relying on an external optical system to achieve this. But suppose that instead the optical system could be mechanically reconfigured by exploiting the forces produced by the input optical beams themselves, thereby controlling the optical output. This type of control would be equivalent to that offered by optical microelectromechanical system (MEMS) devices, which are routinely used for switching, routing or spectrally shaping light beams[6]. This is the concept described in the article by Rakich and co-workers[1],