An array of integrated atom-photon junctions

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Abstract

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Photonic chips that integrate optical elements on a single device can process vast amounts of information rapidly. A new branch of this technology involves coupling light to cold atoms or Bose-Einstein condensates (BEC), whose quantum nature provides a basis for new information processing methods. The use of optical waveguides gives the light a small cross section, making coupling to atoms[1, 2] efficient. In this letter we present the first waveguide chip designed to address a BEC along a row of independent junctions, which are separated by only $10\,\mu$m and have large atom-photon coupling. We describe the fully integrated, scalable design and demonstrate 11 junctions working as intended, using a low density cold atom cloud with as little as one atom on average in any one junction. Our device opens new possibilities for engineering quantum states of matter and light on a microscopic scale.

Micro-fabricated chips are widely used to control clouds of ultra-cold atoms and Bose-Einstein condensates [3, 4]. Recently, the idea has been extended to the control of ions [5] and similar possibilities exist for molecules [6]. This atom-chip technology provides a way to miniaturise existing atomic physics devices. In addition, it promises new devices that take advantage of the elementary quantum nature of atoms [7–9], ions [10] and molecules [6, 11], together with photons [12]. Although laser light is an essential tool for preparing, controlling and interrogating the atomic systems on a chip, the integration of optics into atom chips is still in its infancy. Millimetre-sized vapour cells have enabled optical spectroscopy [13], clocks [14] and magnetometry [14] on a chip, and etched mirrors on a silicon wafer have been used to integrate magneto-optical traps [15]. On a scale ten times smaller, several groups have explored how optical fibres, typically $125\,\mu$m in diameter, may be glued [16–18] or otherwise attached [19] to a chip. A pair of these fibres looking into each other can be used to detect an atom cloud and can reach close to single atom sensitivity [17]. When reflective coatings are added, the gap between two fibres [1, 20] or between one fibre and a micro-fabricated mirror [21] becomes a Fabry-Perot resonator. Similarly, a fibre can be coupled to a micro-disk resonator [22, 23]. These devices can achieve strong atom-photon coupling for applications in quantum information processing.

This letter reports a further order of magnitude scale reduction, in which the $125\,\mu$m-diameter optical fibre is replaced by an integrated waveguide only $10\,\mu$m across, with a $4\,\mu$m square core. Since a BEC is typically $\sim 100\,\mu$m long, this size reduction opens the new

possibility of intersecting a BEC with many closely spaced atom-photon junctions of high coupling strength. In our device, illustrated in Figure 1, a trench containing the cold atoms cuts through an array of 12 waveguides spaced by $10\,\mu$m. This design is a significant advance in the way that photons can be coupled to ultracold atoms.

In order to characterise the chip, we have released cold atoms into a junction to measure its sensitivity and to demonstrate the basics of its operation. Every few seconds, ^{87}Rb atoms are cooled and collected from a room-temperature vapour by a Low-Velocity Intense Source (LVIS), then transferred to a magneto-optical trap (MOT) about $4\,$mm from the chip surface, where the atom density is up to 4×10^{-2} atoms$/\mu$m^3 and the temperature is $\sim 100\mu$K. We push this cloud towards the chip just before switching off the MOT light and magnetic field, thereby launching the atoms at $40\,$cm/s into the trench. The light beams from the waveguides diverge only slightly as they cross the trench, with w - the 1/e radius of the field - growing from $2.2\,\mu$m to $2.8\,\mu$m. Since the width of the trench is $L = 16\,\mu$m, any given beam interacts with roughly one to four atoms of the cloud as they pass through. Each atom crosses the light in $\sim 7\,\mu$s, scattering up to 130 photons (the fully saturated rate is $\Gamma/2 = 1.9 \times 10^7\,$s^{-1}).

With low-intensity resonant light in the trench at frequency $\omega = 2\pi \times 385$ THz, and rubidium atoms of number density ρ, we expect the absorbed fraction of the light f to be given by

$$f = \frac{\hbar\omega\Gamma L}{2I_{sat}}\rho = 3.2\,\mu\mathrm{m}^3 \times \rho. \qquad (1)$$

The saturation intensity I_{sat} depends on the polarisation of the atoms and the light, and for our first experiments it is well approximated by $I_{sat} = 22\,$pW$/\mu$m^2 (see Methods section C). Thus, the atoms in our experiment should absorb up to 3% of the light. This is demonstrated experimentally in Fig. 2(a), where two adjacent channels of the chip record the density of atoms versus time at positions $10\,\mu$m apart. Since the cloud is much larger than the channel spacing, the absorption dips recorded by the two junctions are the same. They occur some $10\,$ms after the atoms are launched into the trench and have the expected size and width.

If the intensity in the trench I approaches I_{sat}, the scattering rate begins to saturate and the absorbed fraction decreases according to the relation

$$f(I) = \frac{f(I \to 0)}{1 + I/I_{sat}} \qquad (2)$$

The bleaching of the atoms in this way lets us measure the absolute intensity of the light in

the trench. Figure 2(b) shows the measured decrease of absorption as the detected power is increased, together with a fitted theory curve. The fit relates intensity in the trench to power at the detector and demonstrates that the latter is six times smaller than the power in the trench, as expected (see Methods A). These experiments show that the junction works: the light detects the atoms, the atoms sense the light, and both perform in agreement with theory.

For some applications it will be important to control the polarisation of the light in the trench as well as its intensity. We find that light prepared with positive helicity, ξ^+, and delivered to the chip through one of the optical fibres, still has typically 87% of the power in the ξ^+ mode when it emerges from the corresponding output fibre, provided the fibres are securely held so that they cannot move in the ambient currents of air [24]. This suggests that the light in the trench is polarised, but we were also able to check the polarisation directly, using the atoms themselves as the probe.

Figure 3 shows the absorption of the light versus frequency in the presence of a magnetic field $B = 0.78$ mT parallel to the waveguides. This spectrum indicates the ratio of σ^+ to σ^- power in the trench, where $\sigma^+(\sigma^-)$ means the angular momentum of the light is parallel (antiparallel) to the magnetic field. The light excites the ^{87}Rb D_2 transition $|F = 2, m_F\rangle \rightarrow |F' = 3, m_F'\rangle$, for which the Zeeman shift of $\sigma^\pm$ transitions is $\frac{1}{6}(m_F \pm 4)\mu_B B/h$, where m_F is the projection of atomic angular momentum, and $\mu_B/h = 14$ GHz/T. The strongest excitation with $\sigma^+(\sigma^-)$ light comes from $m_F = +2(-2)$ and is shifted by $+(-)\mu_B B/h$. With ξ^- input light (filled circles) the strong peak is close to $-\mu_B B/h$, indicating that the power in the trench is still mainly of ξ^- polarisation. When we reverse the helicity (open circles) the shift reverses. We conclude that the polarisation in the trench can be controlled by adjusting the input light to have anything up to 90% of the power in pure σ^+ or σ^- polarisation.

In Figure 4 we compare the performance of 11 junctions. Net transmission of light through the chip and fibres was in the range 2-6% as shown in (a). In (b) we compare the atom absorption signals using a large cloud to give equal density in all the junctions. The variability is small and mainly due to fluctuations in atom density between separate channel tests. In order to demonstrate high spatial resolution, we excited a small part of the cloud with resonant light focussed to a 40 μm spot at one end of the trench. Figure 4(c) shows fluorescence signals that closely follow the excitation beam profile. A low level of

background fluorescence is seen in all channels. This may be due to defects that scatter light into the trench and then to the detector via the atoms. The poor performance in fluorescence detection of junctions 2, 5 and 9 may be related to the same phenomenon.

In conclusion, we have fabricated and demonstrated an array of 12 atom-photon junctions, fully integrated on a chip using a scalable design. This device is a major advance over previous interfaces between light and BEC because it provides a way to probe and/or to alter the structure of a BEC at points only $10\,\mu$m apart. To demonstrate this, we have shown that a low density of atoms can be detected, corresponding to less than one atom in the light mode. We have shown, using the atoms themselves, that the polarisation and intensity of the light in the trench can be reliably controlled. The scalability has been tested by connecting a full set of 24 fibres to one of the chips and demonstrating sensitive absorption detection in 11 junctions. High spatial resolution is demonstrated by measuring the profile of a small optically excited atom cloud through observation of its fluorescence. Our next step will be to bring a trapped Bose-Einstein condensate into the trench. These clouds have typical density of 100 atoms/μm^3 and will therefore be opaque at resonance. If off-resonant measurements[25] are used, much less than one photon per atom can be scattered, while retaining sufficient sensitivity to make precise measurements of local density in a single shot as short as 1μs. These atom-photon junctions open new possibilities for engineering the quantum states of matter and light on a microscopic scale.

METHODS

A.   Photonic chip fabrication.

The chip was manufactured by the Centre for Integrated Photonics[26] on a $1\,$mm-thick silicon wafer. A $10\,\mu$m-thick layer of silica, grown by thermal oxidation, formed the lower cladding for the waveguides. A second layer of silica, doped with Germanium and Boron to achieve a 0.75% refractive index contrast, was created by flame hydrolysis deposition. This was etched through a UV-lithography mask to create the waveguide cores. A further $10\,\mu$m silica layer of upper cladding, also deposited by flame hydrolysis, was doped with boron and phosphorus in order to match the refractive index of the lower cladding. A layer of $50\,$nm of chrome and then $100\,$nm of gold provides the reflecting surface needed by the MOT beams.

Finally the central trench was cut by deep reactive ion etching to a depth of $22\,\mu$m through a $16\,\mu\text{m}\times500\,\mu$m rectangular mask formed by UV-lithography. The finished chip was polished on the back to reduce its thickness to $500\,\mu$m. This reduced the distance between the atoms in the trench and the current-carrying wires underneath.

The chip is glued to a sub-chip, containing current-carrying wires. These provide magnetic fields for preparing the BEC and generate the field parallel to the waveguides that is used in the experiments of Fig. 3. The two adjacent channels used in making Figures 2 and 3 were connected by gluing four single-mode fibres (non-polarisation-maintaining) to the polished edges of the chip using Epotek 353ND index-matching adhesive. The entire optical path from fibre input to fibre output had 5% transmission. This was made up of 50% from each of the two vacuum feedthroughs, 60% from each fibre/waveguide interface, 78% at each face of the trench (Fresnel reflection plus roughness) and 83% mode overlap where the expanded beam arrives at the second waveguide. The various interfaces in the optical train form several etalons that modulate the transmission by a few percent as the frequency varies. The cross-talk between the waveguides was less than 10^{-3}.

The data in Figure 4 come from a second chip, with a full set of junctions connected using a commercial strip of 12 fibres attached to v-grooves in a carrier, spaced to match the waveguide positions on the chip. The first and last fibres are positioned so that their couplings are optimised and the whole assembly is held in place using Epotek OG116. This index-matching glue is a better choice than 353ND because it is both UV-curing and bakeable, as required for ultrahigh vacuum. We have connected several chips in this way, and normally find transmissions in the range $20-30\%$, which vary because the fibre cores are not all perfectly centred on the waveguides. The net transmission is ideally 30%, made up of 80% from mode overlap at each fibre and 50% across the trench. The fibre coupling could approach 100% if we were to match the fibre mode size to the $2.16\,\mu$m waveguide mode instead of using standard fibres with a mode of $3.6\,\mu$m. The trench transmission will reach 74% if we can improve the machining to eliminate the roughness of the waveguide ends. Unusually, the particular chip used to make Figure 4 lost one channel during the gluing of the fibres. In addition, this chip was mounted on a subchip which, due to a design flaw, interfered with one of the fibre carriers and reduced the transmission by about a factor 4 below the normal level. For data presented here the photodetector is coupled to the correctly-connected side of the chip. We have also changed the vacuum feedthroughs to

those described by Abraham and Cornell [27], which have 100% transmission.

B. Detection system.

The light is transported by optical fibres to a single-photon counting avalanche photo-diode. The counting rates in these experiments are between 7×10^4 and 1.5×10^7 counts per second, far above the background of $\sim 130\,\mathrm{s}^{-1}$ from dark counts and stray light. At the high end, almost half the counts are lost to the $32\,\mathrm{ns}$ dead time of the detector, which limits the rate. We extended the dynamic range by using calibrated filters to attenuate the light. We checked and confirmed the manufacturer's specified dead-time by measuring the noise as a function of intensity and comparing this with the Poisson statistics appropriate for attenuated laser light.

Our measurements of absorption were taken over a number of shots, ranging from 10 to 600. The APD signal was averaged, then smoothed over a 1–2 ms window as appropriate, before taking the reading at the point in time where the atom density in the trench was at its maximum. For the polarisation measurements the large magnetic field needed time to settle after switching it on, and therefore we delayed the measurement point. Each of these measurements was accompanied by a background measurement without atoms, which we averaged and used to normalise the absorption. The error bars are the 1σ statistical uncertainties of a Poissonian photon source with detector dead time [28].

C. Saturation intensity I_{sat}.

Light is at the saturation intensity I_{sat} when the photon scattering rate from one atom is $\Gamma/4$. Here, Γ is the population decay rate of the upper state and is the same regardless of which magnetic sub-level is excited. Among the D_2 transitions $|F = 2, m_F\rangle \rightarrow |F' = 3, m'_F\rangle$ of ^{87}Rb, the strongest are $m_F = \pm 2 \rightarrow m'_F = \pm 3$ driven by $\sigma^\pm$ light. Both of these have $I_{sat} = 16.7\ \mathrm{pW}/(\mu\mathrm{m})^2$. The relative strengths of the other transitions depend only on the squares of the 3-j symbols $\begin{pmatrix} 3 & 1 & 2 \\ -m'_F & -m'_F + m_F & m_F \end{pmatrix}^2$. A magnetic field is applied along the waveguides, so the light only has $\sigma^\pm$ polarisations and the transitions are restricted to $m'_F = m_F \pm 1$.

For the experiments in Fig. 2, the atoms scatter several photons, even in the most weakly excited sub-level, and this ensures that the cloud is optically pumped. To a good approximation, the resulting population distribution of m_F states is the steady-state of the Einstein rate equations. We calculate the mean scattering rate using that distribution. The calculation is repeated to average over all polarisations of the light because our measurements are an average over many shots, each with random polarisation. Thus, we obtain an effective saturation intensity of $I_{sat} = 22.4$ pW/$(\mu\mathrm{m})^2$.

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Competing Financial Interests: We the authors declare that there are no competing financial interests.

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FIG. 1. **Schematic diagram of the integrated-waveguide atom chip.** A silicon substrate supports a layer of silica cladding, within which 4μm-square doped silica waveguide cores are embedded. There are 12 parallel waveguides (for clarity, only six are shown) spaced at the centre of the chip by 10μm. These flare out at the edges of the chip so that optical fibres can be connected. A 22μm-deep trench cutting across the waveguides is narrow enough (16μm) that 65% of the light entering the trench is collected by the waveguides on the far side in the absence of atoms. An atom in the trench affects the phase and the intensity of the transmitted light. Conversely, the light affects the state of the atom. Thus each waveguide provides a microscopic atom-photon junction. The top layer of the chip is coated with gold to reflect laser light used for cooling the atoms. Current-carrying wires below the chip provide magnetic fields to trap and move the atoms.

FIG. 2. **Absorption of light by atoms in the trench.** (a): Time of flight signals from two adjacent junctions. Upper curve: the photodiode detects 7.8×10^6 counts per second (5 pW). The 2.6 % dip indicates 8×10^{-3} atoms/μm^3, i.e. one atom on average in the illuminated volume, ~ 100 μm^3. Lower curve: the adjacent channel shows the same atom density and transit time because the $10\,\mu$m channel spacing is much less than the cloud size. A smaller photon rate gives lower signal:noise ratio. (b): Measured fraction of light absorbed by atoms versus detected power. The solid theory line takes into account variations of light intensity and optical pumping of atoms (see Methods section C). There are two fitting parameters: atom number density, and the ratio of light power in the trench to that at the APD (setting the power axis scale). The fit tells us that the power in the trench is six times that at the detector, consistent with the known transmission of 65% across trench and 25% through the fibre couplers on the way to the detector. Error bars give 1σ statistical uncertainties for Poissonian light with detector dead time.

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FIG. 3. **Zeeman-split absorption spectrum measures the light polarisation.** D_2 absorption spectrum of ^{87}Rb, measured on the hyperfine component $|F = 2\rangle \to |F' = 3\rangle$ with a magnetic field of 0.78 mT parallel to the waveguides. When pure ξ^- light (filled circles) is coupled into the input fibre the Zeeman shift is almost $-\mu_B B/h$. The line is a theory obtained by summing over all the Zeeman components of the spectrum, fitted to the data with two parameters: the over-all normalisation and the ratio of σ^+ to σ^- intensity. This fit tells us that $(85 \pm 3)\%$ of the power in the trench is still in the ξ^- mode. For ξ^+ light (open circles) the shifts are opposite. The fit to these points gives $(81 \pm 3)\%$ of power in the ξ^+ mode. The experiment was done at sufficiently low light intensity that optical pumping was negligible, allowing the theory to take equal populations of the m_F levels. Error bars give 1σ statistical uncertainties for Poissonian light with detector dead time.

FIG. 4. **Comparison of performance for 11 junctions.** (a): Optical transmission efficiency of the waveguides. Grey bar shows mean and standard deviation. (b): Absorption due to atoms, for densities around 4×10^{-2} atoms/μm^3. Error bars indicate the statistical noise of the light. Some additional variation is due to fluctuations in atom density. Grey bar shows mean and standard deviation. These 11 junctions are working well. (c): Fluorescence. Points show peak detected count rates due to atomic fluorescence, excited by an external, resonant beam focussed to a $1/e$ field radius of 40 μm. The line is a Gaussian profile whose width corresponds to the known beam size, with an added background offset. The junctions act as pixels, spaced by 10 μm, allowing us to measure the profile of the excited atom cloud. Error bars indicate the statistical noise of the light. Some additional variation is due to fluctuations in atom density. Junctions 2,5 and 9 appear to be partially defective, though they work well in transmission and absorption.

16μm

Waveguides

10μm

4μm

Atoms

Trench

Gold
Surface

Silica
Layer

Trench

Silicon
Substrate

Optical
Fibres