Fiber Optics for Quantum Computers

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Abstract: We describe schemes for the integration of miniature optical components onto Atom Chips, for the manipulation and detection of ultra-cold atoms. Our intention is to build detectors sensitive enough to accurately detect single atoms. Two approaches are discussed: simple fluorescence detection and the use of a resonant cavity. Theory predicts that cavities with $\Im$>100 should be sufficient to obtain signal to noise ratios high enough to detect single atoms. The first micro cavities were demonstrated using mirrors formed by cleaved fiber ends coated with a stick-on dielectric coating to give $\Im$ ~100. A more successful approach involves the full integration of the mirrors and fibers by using Bragg gratings written into the fiber core: it has been possible to form gap cavities with $\Im$ ~ 150.

1. Introduction

The field of quantum optics is fast moving and the physical implementation of the theories being developed pushes the boundaries of our present technologies. One of the most exciting areas of research in this field is that of quantum computation. Quantum phenomena such as entanglement are exploited to exponentially increase computing speed in order to tackle calculations of such complexity that they would take years on a conventional computer.

Many groups all over the world are working to overcome the technical challenges involved in developing schemes for quantum information processing. The requirements for a good quantum information system are long coherence times, scalability and robustness. Schemes in development include trapped ions in miniature RF traps, trapped atoms in optical cavities, Rydberg atoms in microwave cavities and semi-conductor quantum dots amongst others [1].

Our particular interest is in ultra cold alkali metal atoms. The field of cooling and trapping atoms is quite mature: laser cooling of atoms was first reported in 1975 [2]. Various forms of trap have been employed to allow manipulation of the cooled atoms including the magneto-optic trap, the magnetic trap and the optical dipole trap. Perhaps the most significant landmark in the history of cold atom trapping is the production of BEC [3, 4] and the recent development of the a*tom chip* [5] opens up new vistas. On an atom chip the large magnetic coils usually required to generate the necessary trapping fields have been replaced by lithographically etched wires of micron dimensions. Miniaturization means that atom chips can provide potentials which tightly confine atoms making it possible to consider the implementation of quantum logic operations.

The design of atom chips is constantly improving and various innovations have enabled the demonstration of atom conveyor belts, atom “lasers” amongst others [6, 7]. The immediate challenge still to overcome is the reliable detection of individual atoms on a chip. We propose that this could be done using micro-fabricated cavities integrated onto the chip. To this end we have designed a fiber-optic system to detect atomic fluorescence and are developing fiber optic micro-cavities.

2. Detecting Single Atoms on a Chip using Micro-Optical Components

We have designed a very simple device comprising two fibers (figure 1) to detect fluorescence emitted by an atom. Light launched into the tapered lens fiber (TLF) is focussed to a spot of ω_0= 2.1 ± 0.2 μm at a distance of ~20 ± 2 μm from the fiber tip. Assuming that the light in the TLF is resonant with an atomic transition, an atom placed at the fiber focus will fluoresce, randomly emitting photons into a solid angle of 4π. The collection fiber is multi-mode to make the system tolerant of minor misalignment and the motion of the atom within the focus of the laser beam. The collection efficiency of the system is 2%.

Light exerts a force on an atom when photons are scattered. This force can be calculated as:

$$F_{scattering} = \frac{s}{(1+s+\delta^2)}\frac{\hbar k\Gamma}{2} \tag{1}$$

where s is the saturation parameter (the ratio of incident light intensity to that intensity required to saturate the atomic transition), Γ is the atomic linewidth, $\hbar$ is planks constant divided by 2π, k is the atom’s wave vector and δ is twice the ratio of the laser detuning to the atomic linewidth. The scattering force pushes atoms in the direction of laser beam propagation and is of greatest magnitude when the incident radiation is on resonance. It can be calculated that for on resonance light the atom placed at the laser beam will stay there only for a few μs.

This combined with the low collection efficiency means that we would expect a vanishingly small signal from the atom.

In order to improve our chances of seeing a single atom there are two choices: increase the time for which the atom can interact strongly with the laser radiation or increase the number of interactions between the atom and each photon. The first of these solutions can be achieved using dipole trapping of the atom while the second requires the atom to interact with a resonant cavity.

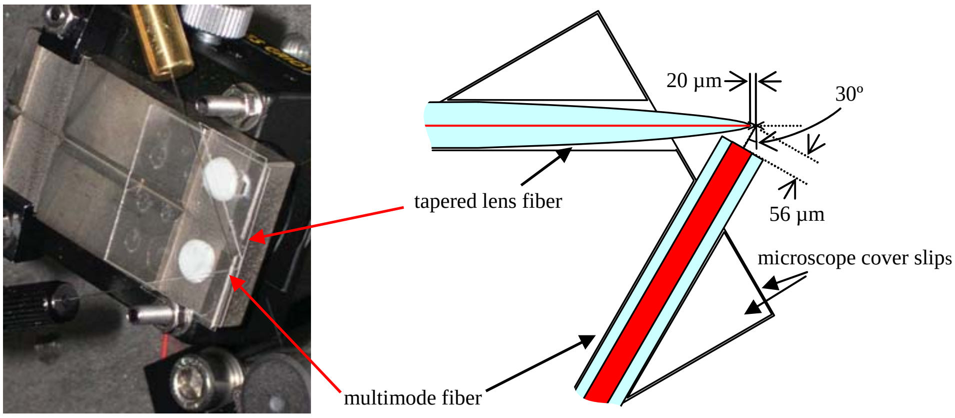

Fig.1. On the left is a photograph of the prototype atom detector described in the text and on the right is a schematic diagram of this set up.

2.1 The Optical Dipole Trap

In addition to the scattering force, there is a second force acting on an atom in a light field: the optical dipole force. The optical dipole force can be calculated as:

$$F_{dipole} = \frac{\delta}{2(1+s+\delta^2)}\frac{\hbar}{2}s' \qquad (2)$$

where s' is the space derivative of the saturation parameter. The nature of the optical dipole force means that it can be used to trap atoms. From equation two it is clear that atoms will be attracted to regions of high light intensity provided the light is red-detuned from a suitable atomic transition. By adjusting laser power and detuning deep optical traps for atoms can be produced [8-10].

Using our TLF it can be shown that trap depths of μK can be produced using laser detunings of ~500 Γ at powers of ~1 mW. Present calculations indicate that we might expect interaction times of 17 ms which enables us to collect ~3000 photons.

2.2 Resonant Cavities

The problem of a two state atom coupled near resonantly to a cavity is a well studied which makes the system attractive for our purposes [11]. The principal behind the detection of single atoms in such cavities can be explained as follows: if we have an optical cavity of resonant frequency ω_C into which we couple a probe light of frequency ω_P then, when $\omega_C = \omega_P$ a transmission maxima will be observed, if an atom with a resonance at $\omega_A = \omega_C$ then enters the cavity this transmission is reduced due to absorption of intra-cavity photons by the atom. It is this loss in transition which could be observed. How sensitive the cavity is to the presence of an atom depends upon the atom-cavity coupling, g and the cavity loss, κ. In order to maximize our signal it is necessary to reach what is known as the strong coupling regime:

$$\frac{g^2}{\Gamma\kappa} = 2\frac{\sigma_a}{A}n_{rt} >> 1 \qquad (4)$$

where σ_a is the atomic absorption cross section, A the cavity mode cross section at the position of the atom and n_{rt} is the average number of round trips which a photon makes before decay. A high atom-cavity coupling can be achieved by using small cavity mode volume (small intra-cavity mode waist). Cavity losses can be reduced by using high reflectivity cavity mirrors (this ensures high finesse: intra-cavity photons make many round trips and interact many times with the atom). In the case of micro cavities it is convenient to make use of the small waist sizes of fiber optic components to maximize g.

Our cavities are non-focussing, thus we necessarily make a compromise between trying to achieve the smallest possible cavity waist and diffraction losses. The finesse of the cavities is limited principally by the mirror reflectivity: gold gives an upper limit on reflectivity of 98% while dielectric coatings might enable us to reach reflectivities in excess if 99%. The best option is to use of Bragg gratings written into the core of the optical fibers which should give us reflectivities greater than 99% with the advantages of full integration and repeatability.

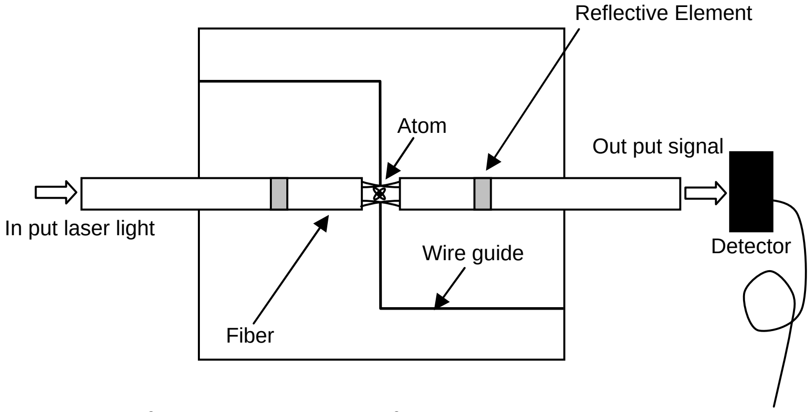

Fig. 2. A schematic diagram of a possible arrangement for on-chip atom detection.

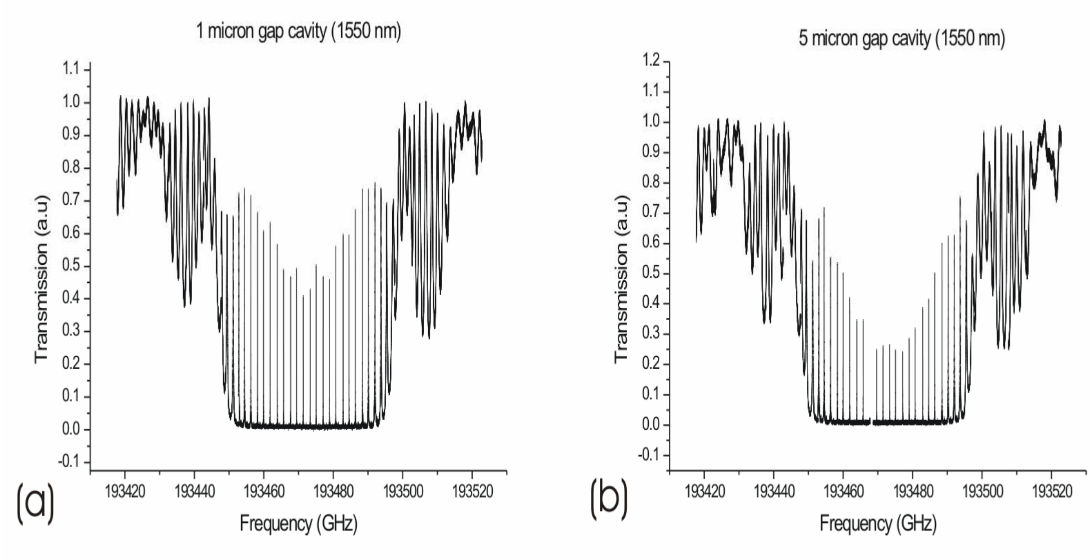

Fig. 3. (a) and (b) show the spectral responses of two gap cavities made using FBG mirrors. Typically cavity lengths are of the order of ~cm while the air gap is <5μm.

Theoretical evaluation of the cavities under development [12] shows that to obtain signal to noise ratios sufficiently high to detect individual atoms only requires cavity finesses of the order of F=100. This is experimentally realistic and has been achieved using mirrors with dielectric coatings. Bragg grating mirrors have yielding gap cavities with finesses of the order of 150.

3. References

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