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Single-atom detection by micro-cavities

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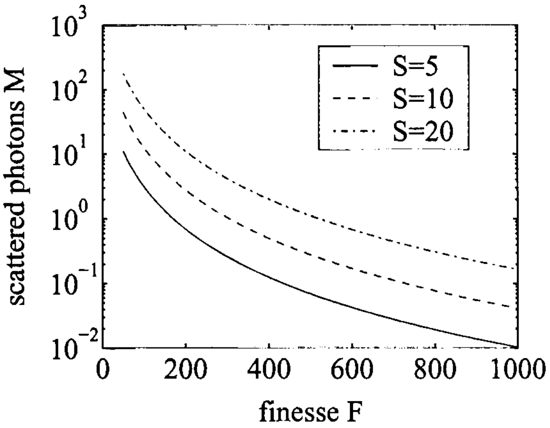
The last few years have seen tremendous progress in the miniaturization of traps for neutral atoms. Several groups have successfully trapped atoms in the magnetic field created by current-carrying wires on top of a glass or silicon substrate (atom chips) [1]. Such traps can in principle be used for scalable quantum information processing. So far, however, optical access to the trapped atoms was mainly limited to free space observation and laser manipulation. We are now investigating possibilities to integrate micro-optics on top of an atom chip by standard fiber technology. In particular we are interested in single-atom detection with minimal spontaneous scattering.



In a first step, we investigate theoretically the properties of a fiber-based standing-wave cavity as an atom detector [2]. The cavity consists of two fiber pieces with Bragg mirrors or reflective coatings on one side of each fiber with the non-reflecting ends facing each other. The gap of several microns between the two fibers is large enough to accommodate an atom micro-trap or guide. In this configuration most of the resonant mode remains in the fibers allowing for tuning and variation of parameters. The cavity is resonantly driven by a laser through one of the mirrors and the transmission through the other mirror is monitored on a photon detector. A drop in the cavity output indicates the presence of an atom in the gap and thus the device works as a single-atom detector. We find that due to the small waist of the cavity mode (typically about 3 μm), already very modest values of the cavity finesse allow for efficient atom detection. As an example, the figure shows the number M of photons which are spontaneously scattered by a single rubidium atom during a measurement time which leads to detection with signal-to-noise ratios of S=5, 10, and 20. We see that a finesse of several hundred is sufficient for atom detection with minimum disturbance of the atom. Similar results were obtained for the case of off-resonant pumping and homodyne detection of the phase shift of the output light induced by the atom.

The short mirrored fiber cavity described above has been realized outside of the vacuum using gold mirrors on 2 cm lengths of fiber. Various issues involving on-chip alignment and tuning are being investigated. Initial studies indicate that thin film heating via a metallic coating on the fiber offers one feasible solution to the tuning. However, effective passive alignment seems to be a difficult problem. Variations of this cavity are possible and we are now looking at experimental realizations of these cavities using a variety of standard fiber optic devices, such as tapered fibers, gradient index (GRIN) lenses, metallic and dielectric coatings, fiber couplers, etc.

One interesting variation we built was a ring cavity out of a 2x2-port fiber coupler where one input and one output fiber are coupled to each other via a small gap. In this case the additional counter-propagating mode creates a range of additional effects. For example we have found that, in contrast to the standing-wave cavity, a ring-cavity is very sensitive to the actual size of the gap, i.e., whether the gap itself together with the slightly reflecting fiber ends forms a resonant or off-resonant micron-sized cavity. This cavity allowed us to measure the loss in the gap as a function of gap size and verify that it behaves as predicted. The finesse of this first effort was limited by internal losses in the coupler, but a finesse of better than 100 seems achievable with better quality couplers.

Another effort was a standing-wave cavity built with two gold-coated GRIN lenses. This has the advantage that the focusing effect of the lenses allows much larger gap sizes (of the order of 100 μm) without excessively large losses. On the other hand, it is much more difficult to obtain single transverse mode operation in such a system. The highest finesse in the GRIN-lens cavity is limited by the reflectivity of the gold coatings and is again of the order of 100.

For improved standing-wave cavities we will need different mirrors such as dielectric coatings or Bragg reflectors, but we now focus on the problem of chip mounting and hope to make the first efforts at atom detection in the near future.

[1] R. Folman et al., Adv. At. Mol. Opt. Phys. **48**, 263 (2002).
[2] P. Horak et al., e-print quant-ph/0210090 (2002).