physics in action

Single atoms light up in microlaser

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THE last decade has witnessed a tremendous technological effort towards building smaller and smaller lasers. One of the motivations is the need for miniaturized light sources for telecommunications. For this reason it is important to understand the basic properties of a laser that is so small that only a few atoms contribute to the lasing process.

Now Kyungwon An, James Childs, Ramachandra Dasari and Michael Feld from the Massachusetts Institute of Technology (MIT) in the US have built a laser in which no more than one atom is lasing at a given time (K An *et al.* 1994 *Phys. Rev. Lett.* 73 3375).

The MIT group's "one-atom laser" has been designed to study fundamental questions in cavity quantum electrodynamics, not in telecommunications, although similar physical principles are at work in both applications. The microscopic nature of the new laser is confirmed by its output power, which is less than 3 pW. The "microlaser" operates at near-visible wavelengths (791 nm) and extends previous work by Herbert Walther and co-workers at the University of Munich at microwave frequencies. The Munich group demonstrated the first one-atom microwave laser (or micromaser) in 1985.

How does this novel one-atom laser work? To understand the radiation properties of atoms in a laser cavity, let us first consider atoms in free space. An atom prepared in an excited state only remains in that state for a very short time, typically a few nanoseconds, before decaying via spontaneous emission. For many years the "natural lifetime" of an excited state was believed to depend only on the properties of the atom.

In the early 1970s, however, experiments with dye molecules placed in front of mirrors showed that the lifetime of an atomic state also depends on the atom's environment. From a classical viewpoint this is by no means surprising because a radiating atom can be considered as an oscillating dipole that interacts with its mirror image if placed close to a reflecting surface. This can lead to strong enhancement or suppression of the radiated power, a fact well known to the electrical engineers who design antennae.

However, atoms follow the laws of quantum mechanics and can only "see" the mirror by emitting a photon. But if the spontaneous emission of photons is suppressed, how does the atom see the mirror? The answer is that the atom "knows" about the mirror because it reacts to the ever-present fluctuations of the electromagnetic vacuum. Close to a reflecting wall, these fluctuations differ from their free-space value. Indeed, if an excited atom is placed between two mirrors that are spaced such that the cavity is resonant with the atomic transition, the atom sees enhanced vacuum fluctuations. Therefore it emits energy much faster than in free space. Moreover, the photon is emitted in a direction defined by the cavity, not in a completely random direction as happens in free space. The enhancement of the vacuum field is particularly large in a small cavity (i.e. when the mirrors are close together).

The MIT experiment is a technological masterpiece. It uses two mirrors, each with a 10 cm radius of curvature, placed 1 mm apart to form the cavity. The mirror separation, and hence the resonance frequency of the cavity, is controlled by a piezoelectric transducer. The mirrors must also be highly reflecting. The MIT group uses "supermirrors" with reflectivities of 0.999996 – a single photon emitted into such a cavity is typically stored for 840 ns before it escapes.

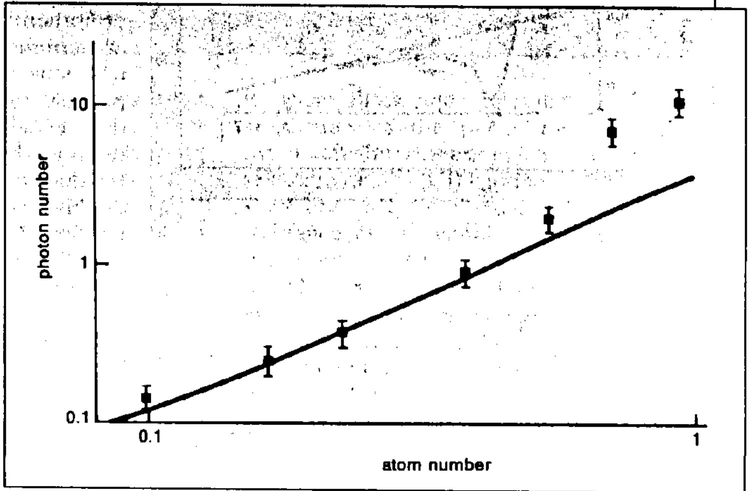
The laser medium consists of barium atoms that are produced in an atomic beam oven some 40 cm from the cavity. Before they enter the cavity a continuous-wave Ti:sapphire laser pumps the atoms into an excited state, which has a long free-space lifetime of 3 μs. The power of the pump laser is chosen to produce a special π-pulse, which guarantees that all the atoms are excited. Since the atoms have a velocity of about 320 m s^{-1}, they are still excited when they reach the cavity.

It is only inside the supercavity that the enhanced vacuum fluctuations between the mirrors can "trigger" the atom to emit a photon of wavelength 791 nm into the resonator. Given an initially empty cavity and a short transit time of 250 ns, the chance of photon emission is 25%. Therefore four atoms are needed on average to deposit a "first" photon inside the cavity. This first photon is stored in the cavity, and stimulates the next atom that enters the resonator to emit a "second" photon (with 50% chance) and so on. In this way a cavity field builds up. Due to mirror transmission and loss, a steady state is established with an average intracavity photon number between 0.14 and 11.0 for an average of 0.1 to 1.0 atoms between the mirrors (figure).

The results agree with a theoretical model except for the case of about one intracavity atom. This discrepancy is probably due to the growing influence of collective atom-field interactions. One of the amazing properties of the one-atom laser is that the plot of the output power versus pump power shows no distinctive threshold, unlike macroscopic (or many-atom) lasers.

One advantage of the one-atom laser compared with its microwave counterpart is that visible photons can be observed directly while microwave photons are difficult to detect. However, it is much more difficult to build and control a cavity at optical wavelengths, which is why the micromaser was developed first.

The new microlaser opens up new possibilities to measure, for example, the photon statistics of the light emitted, which is expected to be non-classical under certain conditions. Indirect evidence of quantum fluctuations reduced below the standard shot-noise level was found some years ago in the Munich micromaser experiments. Furthermore, photon number states without any intensity fluctuations have not been produced so far. It might even be possible to measure the cavity field in a way that does not disturb its quantum properties (a quantum non-demolition measurement). Indeed, with slightly longer atom–field interaction times and better mirrors, one-atom lasers will open the door to a variety of exciting experiments in the optical domain. □



Average number of photons inside the cavity (which is proportional to output power) versus average atom number (proportional to pump power) in the MIT microlaser. Note the absence of a distinctive threshold.