The wonders of the microlaser

A group at MIT has managed to build and operate a laser that functions as such even when the average number of photons in the optical cavity is less than one.

EVERYBODY, of course, now knows how a laser functions. Its essentials are an optical cavity, which can be traversed repeatedly by radiation of an appropriate frequency and in a predetermined mode. The optical performance of the instrument depends on the degree to which modes (of optical vibration within the cavity) other than that desired are suppressed by the geometry of the cavity and on the avoidance of energy loss, as in reflection at the walls. The more effectively the losses are constrained, the more often a coherent light beam will traverse the cavity and, so, the more accurately determined will be the frequency.

But the optical cavity is only half of a laser. The other indispensable part is an original source of radiation whose frequency is approximately that for which the cavity is designed which, typically, is a supply of atoms in an excited state. Ideally, de-excitation of these atoms generates photons with a fixed frequency which, in traversing the cavity, stimulate the emission of coherent photons from other (excited) atoms, thereby generating the coherent oscillation of radiation within the cavity, part of which can be bled off into a usable laser beam. The intensity of the beam is determined by the rate at which excited atoms can be supplied, but its optical properties are largely determined by the quality of the cavity. There are obvious trade-offs between usable intensity and the quality of the beam.

That is a simplified version of what all the textbooks now say. Much of the interest in the development of lasers in the past three decades is the diversity of the uses to which they can be put. At one extreme, they are high-intensity sources of radiation much drooled over by those concerned with ballistic missile defences; at the other, they are frequency standards capable of remarkable accuracy. For applications of the first kind, design effort is lavished on the radiation source; for those of the second kind, the cavity naturally gets the attention.

In the second connection, the 'one-atom laser' now makes its appearance. At first sight, such a device sounds a contradiction in terms. If, as is seriously intended, there is only a single excited atom in the optical cavity, how can excited atoms act in concert to reinforce a radiation beam oscillating within the cavity? But a little thought will show that the contradiction is not as glaring as it seems. If the performance of the cavity part of the laser is almost ideal, the oscillating radiation package within the cavity will retain the properties it is designed to have with only an occasional reminder, in the form of an authentic photon from a single atom, of what the frequency is meant to be.

At this stage, the Massachusetts Institute of Technology (MIT) group responsible for the new laser, called a 'microlaser', are less concerned with the development of frequency standards than with testing the elementary predictions of quantum electrodynamics (QED) that, in an accurately designed optical cavity, only modes of vibration determined by the geometry will be accessible to photons. The authors of this new development are Kyungwon An, James J. Childs, Ramachandra R. Dasari and Michael S. Feld (*Phys. Rev. Lett.* **73**, 3375–3378; 1994). Their first working version of a microlaser is clearly only a model for better things to come.

How does it work? The first need is for a 'supercavity', in this case fashioned from two convex mirror surfaces (with radius of curvature of 10 cm) separated by roughly 1 mm and held apart by a piezoelectric spacer that can be used to tune the resonant frequency of the cavity in real time, on a timescale of a few hundred nanoseconds.

The atoms occasionally injected into the cavity are atoms of ^{138}Ba (the naturally predominant isotope of barium) prepared as an atomic beam (by heating barium metal in a furnace with a narrow aperture) where they can be conveniently put into an excited state by means of a pumping laser. The effectiveness of the arrangement hangs crucially on the precision of the frequency of the laser that excites ^{138}Ba atoms before they reach the cavity. The MIT group says that, by means of an optical frequency-locking arrangement, they can control the frequency of the exciting laser (at least for periods of the order of milliseconds) to within 40 kHz which, for radiation with a wavelength of 791 nm, amounts to a variation of 1 part in 10^{10} in frequency. This precision is needed to ensure a steady supply of excited ^{138}Ba atoms.

At this early stage, the interest of the microlaser now described is largely that it can be built and operated more or less as intended. It is a technical *tour de force* whose importance is entirely belied by the modest language in which it is described. Astonishingly, the group responsible has found incontrovertible evidence of laser function when the atomic beam is so stopped down that the average number of barium atoms in the cavity is only 0.1. With a more plentiful supply of barium, amounting to an average presence in the cavity of 0.71 atoms, the laser signal is actually stronger and sharper than calculated.

There seems no doubt that the instrument functions as a means of exciting in the cavity only the particular mode of oscillation for which it is devised, and essentially at the frequency of the 791 nm barium transition. Indeed, the authors show a plot of the number of photons in the oscillating cavity as a function of the average number of barium atoms it contains. With an average of 1 atom within the cavity, the number of oscillating photons is merely 10. With half an atom (on the average) in the cavity, there is (on the average) just one oscillating photon in the cavity.

The authors write laconically of the improvements of the experiment they now plan. The atomic beam they have used consists of the raw output of the furnace in which barium is heated, which means that the velocity of the atoms follows a Maxwell distribution; velocity selection must give better control of the initial state of the excited ^{138}Ba atoms. Even better mirrors will yield a superior supercavity, which in turn should mean that fewer ^{138}Ba atoms will excite single photons in predetermined states of oscillation.

The immediate objective is, for the time being, pure physics: to provide direct tests of what QED has to say about the interactions between atoms capable of radiating photons and the quantum states of the electrodynamic vacuum. While the success of QED is now so celebrated that doubts of its correctness are non-existent, it will be good to see it all confirmed. Indeed, there will no doubt be some brave soul who will seek to use such techniques for telling whether photons occupying the same quantum state in a resonant optical cavity interact with each other, subtly changing the average energy of occupancy.

There are other possibilities, not the least of which is the long-standing goal of telling whether it is possible to circumvent the limitations of quantum measurement for photons, perhaps even of measuring the number of photons in a quantum state in a resonating oscillator without changing the number of photons in that state. Several ingenious ways of doing this have been proposed, but none of them has so far been adequately tested.

But these are still early days. As with other novel devices, there is no telling what, in the long run, will become of the microlaser. Meanwhile, it is a piece of sheer cleverness that deserves applause. **John Maddox**