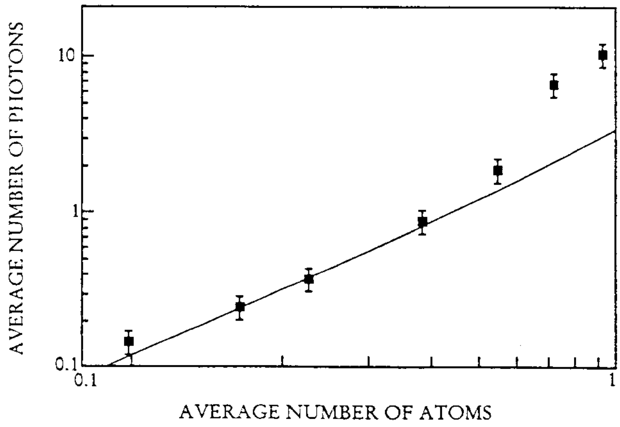
Cavity Lases When Occupied, on Average, by Less Than One Atom



Number of photons at equilibrium versus the number of atoms in the high-Q cavity of a single-atom laser as an atomic beam passes through. Photons leaking from the mirrored ends of the cavity constitute the laser beam. Solid curve is the prediction of a one-atom quantized field model. (Adapted from ref. 1.)

A conventional laser cavity contains many excited atoms, each contributing to the radiation field through stimulated emission. Stripped to its bare essentials a laser would be a single atom interacting with a single mode of the electromagnetic field. A group at MIT recently built a laser that was very close to this minimal configuration.[1]

The "single-atom laser" built at MIT by Kyungwon An, James J. Childs, Ramachandra R. Dasari and Michael S. Feld consists of a cavity through which a beam of excited two-level atoms passes. The researchers found that the radiation field could be maintained in the cavity even when the beam density was so small that the cavity was occupied on average by one atom or less. Designed by An for his PhD thesis, the laser is patterned after the single-atom maser developed in 1985 by Dieter Meschede and Herbert Walther (both from the Max Planck Institute for Quantum Optics in Garching, Germany) together with Günther Müller (University of Wuppertal, Germany).[2]

Although building the single-atom maser, or micromaser, was in itself quite a feat, constructing its optical cousin posed substantial additional challenges. The much shorter wavelengths required quite a different design, with an ultrahigh Q, single-mode cavity strongly coupled to a two-level atom. (Q, which is defined as the ratio of the photon frequency to the linewidth of the cavity, measures how effectively a cavity can store energy.) To strengthen the atom–field coupling, the electromagnetic field mode had to be confined to a small volume by proper design of the cavity geometry. And the researchers had to find an atom with a sufficiently long free-space lifetime to assure adequate time for interaction.

While the microlaser relies on the same physical principles as the micromaser, it offers additional capabilities, such as the ability to observe directly—and count—the photons emitted by the cavity. Measurements on a microwave cavity are much less direct, because it's difficult to detect a single photon in the microwave region (the energy is too low).

Vacuum Rabi oscillations

At the heart of the design of a micromaser or microlaser is the interaction of a single atom with a quantized mode of the electromagnetic field. (See the article by Serge Haroche and Daniel Kleppner in Physics Today, January 1989, page 24.) Quantum electrodynamics predicts that an atom will interact even with the vacuum field. When an excited two-level atom is in a cavity tuned to the frequency of the atomic transition, the quantized modes of the vacuum field are altered by the cavity. The altered atom–field interaction can affect the spontaneous emission rate. In a low-Q cavity, spontaneous emission is irreversible, with effectively a continuum of vacuum states available to the radiating photon, but in a high-Q cavity, such emission becomes reversible. The excited atom can then exchange energy with the cavity field at quantized frequencies, which are proportional to a characteristic rate known as the vacuum Rabi frequency.

Associated with the Rabi oscillation in the time domain is a frequency splitting of the normal-mode spectrum for the atom–cavity system. Three years ago at Caltech, Rob Thompson (now at the National Institute of Standards and Technology in Gaithersburg, Maryland), Gerhard Rempe and Jeffrey Kimble reported directly measuring the vacuum Rabi splitting.[3]

The atom–field coupling is named after I. I. Rabi because he developed a semiclassical theory for the strong interaction of a two-level quantum system with an electromagnetic field at radio frequencies. In the 1960s Edwin T. Jaynes (now at Washington University, Saint Louis, Missouri) and Frederick W. Cummings (now at the University of California, Riverside) gave a fully quantum theory, including a quantized electromagnetic field.[4]

The micromaser and microlaser exploit the phenomenon of quantized Rabi oscillations. In such a system one passes a beam of two-level atoms, raised to their excited state, through a cavity that is tuned to the frequency of the atomic transition. As each atom traverses the cavity, it will tend to give up a photon to the cavity via interaction with the cavity field. The emitted photon will intensify the interaction of the cavity with the next atom that flows through, so that the next atom is even more likely to make the transition to its ground state, leaving behind a second photon. In this way the photon field of the cavity builds up. At some point it reaches an equilibrium with a fixed average number of photons in the cavity; any additional photons added to the field just compensate for the losses from the cavity. The MIT experimenters estimate that at equilibrium, with their microlaser emitting photons at the rate of 10 million per second (about equal to the flow rate of atoms through the cavity), an average of 11 photons were stored in the cavity.

The microlaser

The optical cavity at the heart of the MIT microlaser consists of two concave mirrors facing one another across a separation of 1 millimeter, each with a radius of curvature equal to 10 centimeters. The sides are open, and the beam enters on the side, traversing the cavity perpendicular to the mirror axes. The MIT group had to build a very high-Q cavity, or equivalently, one with a high