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Single-atom laser

A laser that uses a single atom as its gain medium wa first realized in 1994. This laser uses a low-densit beam of barium atoms traversing a small optical resonator with highly reflective mirrors. Light emission and amplification are achieved via quantized Rabi oscillation.

Every laser consists of two essential component an optical resonator (also called a cavity), typicall formed by two mirrors facing each other; and a gain medium between the mirrors, which generates and amplifies the light. For laser oscillation to occur, the laser gain—the increase in the intensity of light as it passes through the laser medium—must be greate than the loss caused by imperfections in the lase mirrors and other factors.

Comparison with conventional lasers. Appreciatio of the single-atom laser requires an understandin of how a conventional laser operates. Conventional lasers, in which light is amplified by the process of stimulated emission, require a very large number of atoms in the laser medium to provide enough gain to exceed the loss. For example, a helium-neon laser emitting a 1 milliwatt beam may contain 10^{16} neon atoms and about 10 times as many helium atoms Light amplification, due to the neon atoms (active atoms), reaches equilibrium when there are roughly 10^9 photons in the laser cavity. Therefore, tens of millions of atoms are needed to maintain each photon in the resonator. In general, conventional lasers require at least 100,000 active atoms per photon stored in th resonator. The active atoms alternate between tw of the energy states. Light amplification can occu only when the number of the active atoms in th higher-energy, or excited, state exceeds the numbe in the lower-energy state. This condition is called population inversion.

Quantized Rabi oscillation. The single-atom lase uses an alternative method of light amplification based on a process called quantized Rabi oscillation. Rabi oscillation is the periodic exchange of energy between atoms and a single electromagnetic fiel mode. When an atom interacts with only a small number of photons, the Rabi oscillations are quantized—that is, they occur at discrete frequencies determine by the number of photons.

One consequence of quantized Rabi oscillation is that an excited atom can be induced to emit a photon simply by placing it in a very small cavity. If th cavity is resonant—that is, if its dimensions are adjusted so that the photons emitted by the atom can build up inside the cavity—a strong coupling may occur which causes the atom to emit a photon muc more quickly than it would in free space. Th process is called vacuum Rabi oscillation because there are initially no photons in the cavity.

Micromaser and microlaser. A single-atom maser, or micromaser, utilizing the quantized Rabi oscillation was demonstrated in 1984. In this experiment, a beam of Rydberg atoms—atoms in which the outermost electrons are excited to large, circular orbits—flowed one by one into a resonant, superconducting microwave cavity. As the atoms passed through the avity, they emitted photons at an increased rate, consistent with a theory based on quantized Rabi oscillations.

The single-atom laser, or microlaser, is the optical version of the micromaser. Excited two-level barium atoms from an oven stream into a small resonator one by one and emit photons at a wavelength of 791 nanometers (at the upper end of the range of visible wavelengths). The first photon is emitted by vacuum Rabi oscillation, and further amplification occurs through the quantized Rabi oscillation process. As the number of photons in the cavity grows, the probability that a subsequent atom will emit another photon increases, up to some level. The photon buildup continues until the rate of loss from transmission, absorption, and scattering at the mirrors equals the rate of photon emission from the barium atoms. When the average number of atoms in the cavity was 0.4, the atoms emitted about 10^6 photons per second, enough to maintain one photon in the cavity at all times; when the average atom number was increased to 0.7, the output of the laser rose by a factor of 7. This clearly shows a thresholdlike behavior, indicative of laser action.

Prospects. The single-atom laser is a new experimental tool for studying quantum atom-field interactions and laser oscillation. It is a simple system, consisting of a two-level atom and a single-mode cavity, so that rigorous comparison with theory can be made. Due to the quantized Rabi emission process, the single-atom laser is expected to exhibit unusual nonclassical behavior (behavior that can be explained only by quantum-mechanical theory). In contrast to the linear increase in output as the pump rate is increased above threshold in a conventional laser, the single-atom laser is expected to show a second threshold as the number of intracavity atoms is increased to much greater than one.

The emission spectrum of the light emitted by the single-atom laser will also display unconventional features, which may have an impact on the theory of laser spectral lineshapes. The single-atom laser is predicted to be a source of nonclassical light (light with uniquely quantum-mechanical properties). In particular, the photon number distribution in the cavity is expected to exhibit sub-Poisson statistics; that is, the fluctuation in the number of photons in the cavity will be less than for any classical light source, including conventional lasers, a phenomenon called photon antibunching.

Experiments are under way to study the unique, nonclassical features of the single-atom laser. These experiments will measure the second-order intensity correlation function, $g^{(2)}(\tau)$, by studying the emitted photons as a function of time, and the distribution of photons in the cavity. Measuring $g^{(2)}(\tau)$ will allow researchers to study photon bunching and antibunching (features of nonclassical light), while measurement of the intracavity photon distribution will provide a direct measurement of cavity photon statistics.

Another feature to be studied is the operation of the microlaser in the mesoscopic regime, where the number of intracavity atoms exceeds one but is still well below a macroscopic quantity. One of the motivations of microlaser- micromaser research is to investigate the quantum theory of the laser. In a microlaser in which one or a small number of atoms interacts with a single cavity mode in a controlled fashion, it should be possible to observe effects that are averaged out in conventional lasers. A classical field, the type generated in a conventional laser, is reached only if a sufficient amount of randomness is introduced into the system. By altering the randomness of the microlaser, it should be possible to demonstrate the transition between microlaser behavior and that of a conventional laser, and examine how it occurs. In these experiments, the amount of randomness or noise to the system will be gradually increased, either by varying the pump excitation process or the atom-cavity interaction. For example, the flow of excited atoms into the cavity may be modified to increase the variability of times for different atoms to flow through the cavity mode. Similarly, the degree of coupling variation may be modified by allowing different atoms to travel through different parts of the cavity mode. The various atoms will then experience different atom-cavity coupling strengths. In each case, the flux of atoms entering the cavity can also be varied. By studying the increase in photon emission as the pump rate is increased, the transition between microlaser behavior and classical laser behavior can be studied. Measurement of photon statistics and laser linewidth will be used to study the evolution from nonclassical to classical laser behavior.

For background information *see* LASER; MASER; QUANTUM MECHANICS; RYDBERG ATOM; SQUEEZED QUANTUM STATES in the McGraw-Hill Encyclopedia of Science & Technology.

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Bibliography. K. An et al., Microlaser: A laser with one atom in an optical resonator, *Phys. Rev. Lett.*, 73:3375–3378, 1994; M. S. Feld and K. An, The single-atom laser, *Sci. Amer.*, 279(1):56–63, July 1998; D. Meschede, H. Walther, and G. Muller, One-atom maser, *Phys. Rev. Lett.*, 54:551–554, 1985.