MIT TECH TALK
VOLUME 39 ▪ NUMBER 12
WEDNESDAY ▪ NOVEMBER 16, 1994

Single-atom laser technique developed

Researchers at MIT's George R. Harrison Spectroscopy Laboratory have successfully operated a laser using a single, isolated atom. The long-sought development marks the first time that laser oscillation has been achieved with only one atom in the laser resonator.

The new device, which the researchers call a microlaser, constitutes a fundamental advance in laser physics and the field of cavity quantum electrodynamics (QED), the study of how atomic systems radiate in an enclosed laser resonator.

"This development has been long sought, and it is expected to lead to further fundamental advances in our knowledge of light and its interaction with atoms," said Dr. Michael S. Feld, director of the laboratory and a professor in the Department of Physics.

The research is the PhD thesis project of Kyungwon An, a student from Seoul, South Korea. It is supervised by Professor Feld. Other members of the team are Dr. Ramachandra Dasari, assistant director of the Spectroscopy Laboratory and a principal research scientist in the Department of Physics, and James J. Childs of Reading, MA, also a physics PhD student. The research is supported by the National Science Foundation and was performed at the Spectroscopy Laboratory's Laser Research Facility.

A report on the achievement is scheduled for publication in the November 21 issue of Physical Review Letters.

The laser—a device that converts input power into a very narrow, intense beam of coherent visible or infrared light—can be delicate enough for use in eye surgery or robust enough to slice through metals in industrial applications. The input power excites the atoms of an optical resonator to a higher energy level and the resonator forces the excited atoms to radiate in phase, producing the coherent light beam.

Atomic physicists have long recognized the importance of studying the laser emission process with a single, isolated atom. Over the past few years many research groups have been pursuing this goal, but up to now it was not clear whether such a device could be built.

Present lasers use amplifying media composed of many billions of atoms or molecules to achieve the enormous photon multiplication required for coherent light generation. A photon is a massless particle which in the electromagnetic field carries energy, momentum and angular momentum. Such a large number is required to overcome the low emission efficiency per atom of a conventional laser gain medium and the photon losses of existing laser resonators. Because the many atoms of a conventional laser interact with each other as they emit photons, fundamental features of the atom-photon interac-

(continued on page 2)

Single-atom laser technique invented

(continued from page 1)

tion process are lost.

The MIT researchers realized that the key to developing a single-atom laser was to employ a laser resonator with extremely efficient photon storage capability and to select an atomic transition with appreciable strength and yet negligible spontaneous emission. Use of a single atom is then actually helpful, because an isolated atom is free of unwanted perturbations from neighboring atoms, and can then emit photons at the theoretical upper limit of efficiency.

The MIT scientists chose an atomic barium transition at a wavelength of 791 nm. For increased photon storage, a new type of laser resonator called a supercavity was used, composed of two precisely aligned, ultra-high reflectivity mirrors. In this type of resonator the capability for storing photons is 10,000 times greater than in a conventional laser resonator, during which time they are reflected back and forth about one million times.

The new laser device is composed of two supercavity mirrors separated by one millimeter, with a beam of atomic barium flowing through the gap between the mirrors. The barium atoms are raised to an excited state before they enter the resonator, and the flux of atoms is kept small enough to insure that one atom or less is inside the resonator at any moment.

Photon emission is determined by Rabi oscillation, a quantum mechanical process in which an atom emits and reabsorbs a photon in a periodic fashion, the rate of which depends on the number of photons present. Laser operation is initiated when a barium atom traversing the cavity emits a photon into the empty resonator. As successive atoms flow into the resonator, photons are emitted with greater and greater likelihood, leading to an equilibrium state with many photons inside the resonator. Unlike an ordinary laser, a steady state is never reached, and even in this equilibrium state the system continues to undergo atom-photon Rabi oscillations. Laser light is coupled out of the resonator through the mirrors, which are provided with a tiny amount of transmission. With an average of one atom inside the resonator, the researchers measure an emission rate of more than 10 million laser photons per second, from which they estimate that about 11 photons are stored in the resonator.

The researchers had to overcome several technical obstacles to make the experiment work. A laser supercavity exhibits resonant behavior over a very narrow spectral range, making it difficult to keep the laser cavity resonant with the atomic transition. Unless this is done, Rabi oscillations cannot occur and photons will not be emitted. To insure atom-cavity resonance, an extremely stable resonator was developed which kept the mirror spacing fixed to less than a billionth of a centimeter. It was also necessary to insure that the pump laser, which excites the barium atoms before they enter the resonator, was kept in resonance with the atomic transition. Finally, a high-efficiency detection scheme employing an avalanche photodiode was used to achieve a counting efficiency of 36 percent, which is far superior to the efficiency of conventional photomultipliers at this wavelength.

The microlaser is of great theoretical interest to the field of cavity QED, which studies the interaction between atoms and the electromagnetic field mode of a resonant cavity. The initial quantum description of a two-level atom resonantly interacting with a single mode resonator was published by Jaynes and Cummings in 1963, and many theoretical descriptions have appeared since.

From a modern perspective, Professor Feld said, the atom and field mode can be viewed "as two oscillators strongly interacting with each other with coupling frequency, g, called the vacuum Rabi oscillation frequency because it is determined by the fundamental properties of the vacuum. This interaction is analogous to the motion of a pendulum. If the atom is weakly excited, the pendulum undergoes small-angle oscillation, swinging back and forth at frequency g. This indicates that atom-field energy exchange occurs at frequency g, and the atomic lineshape can then exhibit two peaks separated by 2g, a phenomenon called normal mode splitting."

This two-peaked structure was recently measured by a Caltech research group, and is under further study at MIT.

In contrast, in the microlaser the atom is fully excited when it enters the cavity, Professor Feld said. In this case the pendulum swings around and around in a circular path, indicating that the atom undergoes multiple Rabi oscillations, successively emitting and reabsorbing a resonator photon as it makes transitions between ground and excited states.

Initially no photons are present in the resonator and the atom-photon exchange rate is g, but this rate increases as the number of photons builds up. Thus, the microlaser and normal mode oscillation manifest extreme opposite regimes of strongly coupled atom-field behavior.

FEATURES OF INTEREST

The MIT researchers have already discovered some surprising features of microlaser operation. One interesting finding is that when the average number of atoms in the cavity is increased above one, the intensity of the emerging photon beam is surprisingly large, and cannot be interpolated from single atom theory. This may stimulate development of improved theories which take into account the simultaneous interaction of more than one atom with the resonator field.

The microlaser is expected to exhibit many other interesting features. Various theoretical predictions of the fundamental linewidth of microlaser light have been made, and linewidth measurements now in progress at MIT should provide an experimental test of these.

In addition, the photon statistics of the microlaser field should be entirely different from those of a conventional laser. "Conventional laser fields are well described by the laws of classical electromagnetism," Professor Feld said. "Because their emission is determined by many interacting atoms, quantum effects average out. In contrast, microlaser photons are expected to exhibit non-classical statistical properties."

A very important feature of the microlaser is its ability to generate "non-classical photons at a large rate, typically tens of millions per second, despite the small number of photons, typically 10, in the resonator. Thus, the microlaser has the potential to become an important source of non-classical light for probing matter. These and other interesting features will be the subject of the continuing experiments at MIT," he said.