Microlaser: A laser with One Atom in an Optical Resonator

Kyungwon An, James J. Childs, Ramachandra R. Dasari, and Michael S. Feld
George R. Harrison Spectroscopy Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 1 August 1994)

We have demonstrated laser oscillation with one atom in an optical resonator. In our experiment a beam of ^{138}Ba atoms traverses a single-mode cavity with a finesse of 8×10^5. The atoms are excited by a π pulse from the $^1S_0$ ground state to the $^3P_1(m = 0)$ excited state before they enter the cavity. Laser oscillation at 791 nm ($^3P_1 \rightarrow {}^1S_0$) has been observed, with the mean number of atoms inside the mode ranging from 0.1 to 1.0, resulting in the mean number of photons inside the cavity changing from 0.14 to 11. The results are in good agreement with a fully quantized micromaser theory adapted to our experiment.

PACS numbers: 42.50.–p, 42.55.–f

One of the simplest but most interesting problems in quantum optics is the interaction of a single atom with a single quantized mode of the electromagnetic field. This problem, treated by Jaynes and Cummings many years ago [1], has an exact solution if irreversible processes which give rise to damping, such as atomic spontaneous emission and decay of the field mode, are negligible. The atom and the field then exchange an energy quantum in a manner characteristic of coupled oscillators. The rate of energy exchange, determined by the atom-field coupling strength, can be appreciable even for a vacuum field. This coupling has been observed in the line shape splitting for a weakly excited absorbing atom [2].

The atom-cavity interaction process, often referred to as cavity quantum electrodynamics, has been studied extensively in both theory and experiment. One of the best systems to study cavity QED has been the micromaser, a one-atom maser [3]. This system has made possible the study of quantum collapse and revival [4] and nonclassical atom statistics [5]. A large number of proposals have been put forward on such subjects as linewidth measurement of the micromaser [6], number state generation [7], quantum nondemolition measurements [8], squeezing [9], and trap states [10], but most of these experiments have yet to be realized. In addition, there has been great anticipation to realize a microlaser, the counterpart device in the optical regime. This experimental tool would greatly broaden the scope of the study of cavity QED. A microlaser would allow detection of photons, as well as atoms, whereas only atoms can be probed in the microwave regime. Photon counting detectors with efficiencies of up to 80% [11] are now available, making study of the photon statistics in the microlaser quite promising. Furthermore, a linewidth measurement would be straightforward, while it is yet to be done in the micromaser, where a complicated Ramsey-fringe-type configuration is required [12].

One major obstacle in the development of a microlaser has been the technical difficulty in fabricating a very high-Q cavity in the optical regime. Recently, supercavity technology has reached the point where a cavity with finesse of 10^6 or even higher [13] can be assembled. Our research builds upon this recent breakthrough. We have developed a working microlaser and report our first results below. The system undergoes laser oscillation with an average of less than one atom, yielding an average photon number in the cavity much greater than unity.

The components of our experiment are two-level atoms, a high-Q single-mode cavity resonant with the atom, a light source to excite the atom into the upper energy level, and photon-counting detectors (Fig. 1). A two-level atom from an atomic beam is excited to the upper energy level by a pump laser just before it enters the cavity with no photon inside. Once inside the cavity, the atom undergoes a downward transition due to vacuum Rabi oscillation at frequency g_0, emitting a photon into the cavity mode. The next excited atom, interacting with the photon in the mode, experiences a larger Rabi frequency, contributing a second photon to the field, and so on. This leads to an equilibrium situation in which, despite the dynamical atom-field interaction, the number of photons remains

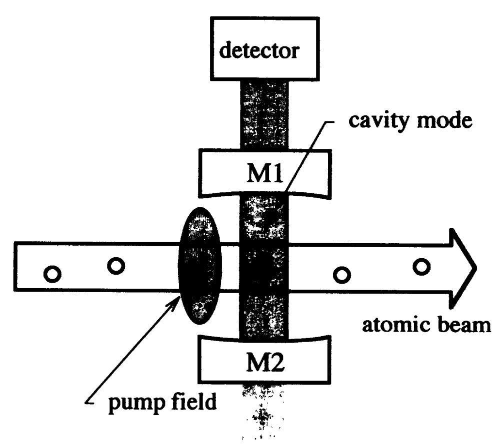

FIG. 1. Schematic of a microlaser experiment.

constant, and the small energy loss due to cavity decay and atomic spontaneous decay is exactly balanced by the mean energy transfer from the excited atom to the field mode.

In our experiment laser oscillation was obtained on the $^3P_1(m = 0) \rightarrow {}^1S_0$ transition of ^{138}Ba. The transition wavelength is 791 nm and the radiative linewidth is about 50 kHz [14]. In the experiment naturally abundant barium metal, of which 72% is ^{138}Ba, was evaporated in an atomic beam oven. The temperature of the oven was varied around 550 °C, resulting in an rms thermal velocity of 320 m/s and an atomic density of 4×10^5 atoms/cm^3, inside a single-mode cavity located 43 cm from the oven aperture. To calibrate the density, we used the fluorescence from the $^1P_1 \leftrightarrow {}^1S_0$ transition of ^{138}Ba atoms ($\lambda = 553$ nm) in the cavity mode. A 340 μm aperture was placed in front of the cavity to confine the atomic beam transversely.

The atoms were excited from the $^1S_0$ ground state to the $^3P_1(m = 0)$ excited state by means of a cw Ti:sapphire pump laser (Coherent model 899-29) just before the entrance to the cavity. The waist and intensity of the pump beam were adjusted so that the velocity group of atoms with the most probable speed were subjected to a π pulse, thereby achieving maximum population in the upper state. The waist along the atomic beam was measured to be 30 μm, with corresponding transit time (broadening) of 190 ns (4 MHz). A dc magnetic "keeper" field of about 10 G was applied parallel to the pump field polarization, which was along the atomic beam, in order to insure that only $\Delta m = 0$ transitions could occur.

The pump laser had a frequency stability of 300 kHz relative to its low-Q reference cavity. However, the frequency of the reference cavity was found to drift by 2–3 MHz over a period of tens of milliseconds. Such performance was not acceptable for the required stability of the pumping process. In order to eliminate the frequency jitter and lock the frequency to the atomic transition, an FM locking technique [15] employing a separate barium vapor cell in a Lamb-dip configuration was used. A dispersion-type FM error signal then replaced the error signal from the laser reference cavity. With this technique we achieved about 40 kHz rms short-term jitter superimposed on 300 kHz rms long-term jitter oscillating at 660 Hz. This slow jitter seems to originate mechanically from a galvo-driven tipping plate in the laser. No further efforts were made to compensate the slow jitter, because at this level the frequency uncertainty is far less than the transit-time broadening.

The resonator used in the experiment was composed of two supercavity mirrors [16]. The mirrors, with radius of curvature of 10 cm, were separated by 1 mm on a mount with a piezoelectric transducer between the mirrors in order to allow frequency tuning of the cavity through the atomic resonance. The finesse of the cavity was measured using a ring-down technique [13] to be 8×10^5, corresponding to a linewidth of 190 kHz. The free spectral range and the transverse mode separation were 150 and 6.8 GHz, respectively, so excitation of a single TEM_{00} mode was easily ensured. The waist of the mode was 42 μm. The geometry of the cavity and the atomic dipole moment determine g_0 to be 340 kHz, therefore satisfying the strong-coupling condition for one atom. The mirror mount was carefully designed to minimize mechanical vibrations. In its free-running state the cavity frequency drifted slowly, at a rate of about 1 MHz/s, with a short-term stability of better than 50 kHz rms. When the system was aligned, active stabilization using a sideband locking technique locked the cavity frequency to that of the pump laser with about 100 kHz offset. This locking laser beam, split off from the pump laser, was chopped by an acousto-optic modulator in a double-pass configuration free of frequency shift in such a way that the output signal of the microlaser was measured only when the locking laser was blocked.

A silicon avalanche photodiode with a thermoelectric cooler (EG&G model C30902S-TC) was used in the photon-counting mode to detect the output of the microlaser. When the detector was cooled to −20 °C, the counting efficiency measured on a photon counter was 36%. With a passive quenching circuit [17], the detector starts to saturate at around 10^4 counts/s, yielding a 10% reduction in registered counts. When the output signal was larger than that level, neutral density filters were used to attenuate the signal.

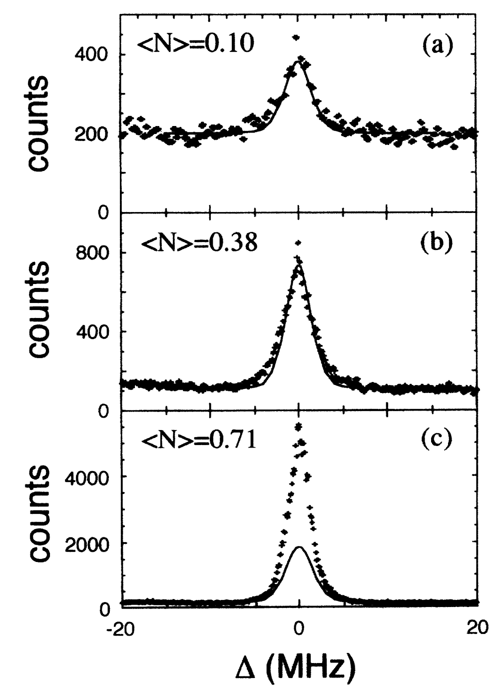

FIG. 2. Signal counts as a function of the cavity-atom frequency detuning, with an average of (a) 0.10, (b) 0.38, and (c) 0.71 atom. The counting time per point was 25 ms for (a) and 12.4 ms for (b) and (c). The solid line is the prediction of the one-atom quantized field model described in the text.

In a typical experimental run, we adjusted the position and the incident angle of the pump laser and the angle between the atomic beam and the cavity axis with the active cavity locking engaged, while maximizing the output signal. Once the system was aligned, we disengaged the cavity locking and let the cavity drift slowly through the atomic transition. The cavity transmission of the locking laser was still monitored to mark the instant when the cavity becomes resonant with the sidebands, as well as the central peak of the spectrum of the frequency-modulated locking laser at 25 MHz. These frequency stamps were used to calibrate the frequency axis of the measured signal. We found the cavity drift to be quite uniform over the 50 MHz scan range, with linearity error less than 400 kHz.

Figure 2 shows the signal output from the microlaser as a function of cavity-atom detuning. The mean number of atoms in the cavity mode was varied: (a) 0.10, (b) 0.38, and (c) 0.71 atom. The uncertainty in the number of atoms is 50%, due to accumulated systematic errors in the fluorescence calibration. From the peak values of these curves, we can find the average number of photons in the cavity mode, as shown in Fig. 3.

In order to interpret the results quantitatively, we used a quantized field model developed by Filipowicz *et al.* [18]. The model assumes that the atoms are all completely inverted by the pumping process. This assumption greatly simplifies the calculation, since only the diagonal elements of the field density operator are

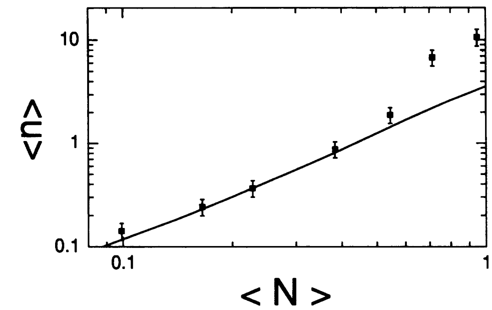

FIG. 3. Average number of photons in the cavity mode, $\langle n \rangle$, as a function of the average number of atoms in the mode, $\langle N \rangle$, when $\Delta = 0$. The solid line is based on our model described in the text.

nonzero, resulting in a simple recursion relation for the photon distribution function. In our experiment, however, atoms with a Maxwell-Boltzmann velocity distribution are excited by a laser beam, which is optimized for π excitation for atoms with the most probable speed. Therefore, slower and faster atoms enter the resonator in coherent superposition states. In this case the off-diagonal elements of the field density operator are as important as the diagonal elements. Consequently, the micromaser theory does not give a good fit. We have hence derived a recursion relation for the matrix elements of the field density operator, $\rho^F_{n,m}$:

$$\begin{aligned}\left[1 + \tfrac{1}{2}\Gamma_c \Delta t(n+m)\right]\rho^F_{n,m} = {}& \rho^F_{n,m}\{N_a[C_n C_m + S^\delta_n S^\delta_m - i(C_n S^\delta_m - C_m S^\delta_n)] \\ & + (1-N_a)[C_{n-1}C_{m-1} + S^\delta_{n-1}S^\delta_{m-1} + i(C_{n-1}S^\delta_{m-1} - C_{m-1}S^\delta_{n-1})]\} \\ & + \rho^F_{n+1,m+1}\left[(1-N_a)S^\kappa_n S^\kappa_m + \Gamma_c \Delta t \sqrt{(n+1)(m+1)}\right] + \rho^F_{n-1,m-1}N_a S^\kappa_{n-1}S^\kappa_{m-1} \\ & + [\rho^F_{n,m-1}(C_{n-1} - iS^\delta_{n-1})S^\kappa_{m-1} + \rho^F_{n-1,m}S^\kappa_{n-1}(C_{m-1} + iS^\delta_{m-1}) \\ & - \rho^F_{n,m+1}(C_n + iS^\delta_n)S^\kappa_m - \rho^F_{n+1,m}S^\kappa_n(C_m - iS^\delta_m)]\sqrt{N_a(1-N_a)}\,, \qquad (1)\end{aligned}$$

where Γ_c is the decay rate of the cavity, N_a is the excited state population of the atom created by the pump field, and

$$C_n = \cos\left[\tfrac{1}{2}(\kappa_n^2 + \Delta^2)^{1/2} t_{\rm int}\right], \qquad (2a)$$

$$S^\delta_n = \frac{\Delta}{\sqrt{\kappa_n^2 + \Delta^2}} \sin\left[\tfrac{1}{2}(\kappa_n^2 + \Delta^2)^{1/2}\, t_{\rm int}\right], \qquad (2b)$$

$$S^\kappa_n = \frac{\kappa_n}{\sqrt{\kappa_n^2 + \Delta^2}} \sin\left[\tfrac{1}{2}(\kappa_n^2 + \Delta^2)^{1/2}\, t_{\rm int}\right], \qquad (2c)$$

$$\kappa_n = 2g_0\sqrt{n+1}\,, \qquad (2d)$$

$$t_{\rm int} = \frac{w_m\sqrt{\pi}}{v}\,, \qquad (2e)$$

with Δ the cavity-atom detuning, w_m the mode waist of the cavity field, and v the velocity of the atom. In deriving this relation we assume that the atoms enter the cavity according to a Poisson process with a mean time interval Δt.

We solved the recursion relation numerically for given experimental parameters, and then averaged the results over the Maxwell-Boltzmann velocity distribution. The solid lines in Figs. 2 and 3 are the theoretical predictions. We find good agreement between theory and experiment for the mean number of atoms up to 0.6. It is clear that the one-atom quantum model fails even for an average of one atom, indicating that collective atom-field interactions play an important role in this case.

In conclusion, we have realized a one-atom laser. The mean number of photons inside the cavity mode was measured to be in good agreement with the prediction of the one-atom quantum mechanical model. Addition of higher-Q supercavity mirrors, a redesigned resonator and improved stabilization should lead to a significant increase in the mean photon number. Addition of a velocity selector in our atomic beam will enable precise control of the initial atomic state. This will enable us to study in detail the Rabi dynamics of the atom-field interaction process. Measurements of linewidth/line shape and photon statistics in this improved microlaser system should provide important tests of cavity QED predictions.

The authors would like to thank Professor D. J. Heinzen and Professor J. E. Thomas for valuable discussions and R. Lalezari for fabricating the supercavity mirrors used in the experiment. This work is supported by NSF Grant No. PHY-9112421 and No. CHE-9304251.

[1] E.T. Jaynes and F.W. Cummings, Proc. IEEE **51**, 89 (1963).
[2] R.J. Thompson, G. Rempe, and H.J. Kimble, Phys. Rev. Lett. **64**, 2499 (1990).
[3] D. Meschede, H. Walther, and G. Muller, Phys. Rev. Lett. **54**, 551 (1985).
[4] G. Rempe, H. Walther, and N. Klein, Phys. Rev. Lett. **58**, 353 (1987).
[5] G. Rempe, M.O. Scully, and H. Walther, Phys. Scr. **T34**, 5 (1991).
[6] S. Qamar and M.S. Zubairy, Phys. Rev. A **44**, 7804 (1991); M.O. Scully, H. Walther, G.S. Agarwal, T. Quang, and W. Schleich, Phys. Rev. A **44**, 5992 (1991); N. Lu, Phys. Rev. A **47**, 1347 (1993); T. Quang, G.S. Agarwal, J. Bergou, M.O. Scully, and H. Walther, Phys. Rev. A **48**, 803 (1993); K. Vogel, W.P. Schleich, M.O. Scully, and H. Walther, Phys. Rev. A **48**, 813 (1993).
[7] J. Krause, M.O. Scully, and H. Walther, Phys. Rev. A **36**, 4547 (1987).
[8] M. Brune, S. Haroche, V. Lefevre, J.M. Raimond, and N. Zagury, Phys. Rev. Lett. **65**, 976 (1990).
[9] P. Meystre and M.S. Zubairy, Phys. Lett. **89A**, 390 (1982); A. Heidmann, J.M. Raimond, and S. Reynaud, Phys. Rev. Lett. **54**, 326 (1985); J.R. Kuklinski and J.L. Madajczyk, Phys. Rev. A **37**, 3175 (1988).
[10] P. Filipowicz, J. Javanainen, and P. Meystre, J. Opt. Soc. Am. B **3**, 906 (1986).
[11] P.G. Kwiat, A.M. Steinberg, R.Y. Chiao, P.H. Eberhard, and M.D. Petroff, Phys. Rev. A **48**, R867 (1993).
[12] J. Krause, M.O. Scully, T. Walther, and H. Walther, Phys. Rev. A **39**, 1915 (1989).
[13] G. Rempe, R.J. Thompson, and H.J. Kimble, Opt. Lett. **17**, 363 (1992).
[14] A.A. Radzig and B.M. Smirnov, *Reference Data on Atoms, Molecules, and Ions, Chemical Physics 31* (Springer-Verlag, New York, Berlin, 1985), pp. 219, 229.
[15] G.C. Bjorklund, Opt. Lett. **5**, 15 (1980); J.L. Hall, L. Hollberg, T. Baer, and H.G. Robinson, Appl. Opt. Lett. **39**, 680 (1981); W.P. Drever, J.L. Hall, F.V. Kowalski, J. Hough, G.M. Ford, A.J. Munley, and H. Ward, Appl. Phys. B **31**, 97 (1983).
[16] R. Lalezari (private communication).
[17] H. Dautet (private communication).
[18] P. Filipowicz, J. Javanaine, and P. Meystre, Phys. Rev. A **34**, 3077 (1986).

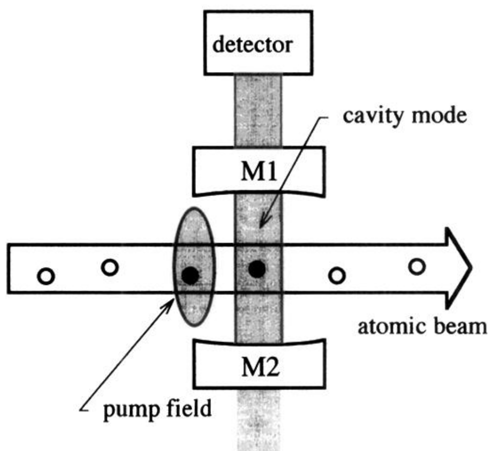

FIG. 1.   Schematic of a microlaser experiment.