Control of Light Pulse Propagation with Only a Few Cold Atoms in a High-Finesse Microcavity

Yukiko Shimizu,* Noritsugu Shiokawa,† Noriaki Yamamoto, Mikio Kozuma,‡ and Takahiro Kuga
Institute of Physics, University of Tokyo, 3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan

L. Deng and E.W. Hagley
National Institute of Standards and Technology, Gaithersburg, Maryland 20899
(Received 5 June 2002; published 15 November 2002)

Propagation of a light pulse through a high-Q optical microcavity containing a few cold atoms ($\overline{N} < 10$) in its cavity mode is investigated experimentally. With less than ten cold rubidium atoms launched into an optical microcavity, up to 170 ns propagation lead time (''superluminal''), and 440 ns propagation delay time (subluminal) are observed. Comparison of the experimental data with numerical simulations as well as future experiments are discussed.

DOI: 10.1103/PhysRevLett.89.233001 PACS numbers: 32.80.Pj, 42.50.Ct

When a well-defined electromagnetic disturbance propagates in a highly dispersive medium, its group velocity can be described by $v_g = c/(n + \omega dn/d\omega)$, where c is the speed of the electromagnetic wave in vacuum, and ω is the wave's angular frequency. This expression of the group velocity indicates that the functional form of the refractive index n and its derivative determine the group velocity at which the wave propagates. In the frequency region where the index changes rapidly [1–8], the group velocity can become very different from the speed of light in vacuum [9], and sometimes may even result in apparent ''superluminal'' propagation [10]. The studies reported thus far on superluminal and subluminal propagation of optical pulses have been all carried out with highly dense atomic systems such as atomic vapor cells at elevated temperatures, and recently with Bose-Einstein condensed alkali vapors. A key element in these studies is that a significantly large number of atoms ($> 10^6$) interact with the probe pulse. Because the refractive index is intrinsically a macroscopic quantity, the statistical ensemble average will lead to the direct proportionality between the refractive index and the total number of the atoms with which the probe pulse interacts as it propagates through the medium. To our knowledge, there has been no study of abnormal wave propagation effects using a high-finesse cavity to enhance the dispersive properties of an individual atom.

When a resonant or near resonant optical field (or even a single photon) propagates through a cavity containing a single atom, the atomic and probe light states become highly entangled. Such an entangled state, also known as a Schrodinger cat state, may be useful for quantum computational processes [11–15]. It has been shown that a well-controlled entangled atom-photon system is also a useful tool to investigate quantum decoherence [16]. The system described in the experiment reported here may therefore also prove to be a useful tool for systematic investigation of quantum decoherence with only a handful of atoms.

The goal of our study is to observe and subsequently analyze the propagation characteristics of a weak Gaussian optical pulse through a high-finesse cavity containing only a few cold atoms ($\overline{N} < 10$). In order to obtain an observable signal of such propagation with a reasonable signal-to-noise ratio, the light pulse must interact with the atoms repeatedly for a sufficiently long period of time (limited only by the storage time of the cavity). To achieve this, one must work in the strong-coupling regime so that relaxation processes due to spontaneous emission do not cause photons to be scattered by the atom into vacuum modes and thereby lost from the cavity during the cavity storage time. Recent progress in high-reflectivity mirror technology and atomic manipulation techniques have provided the means to allow an atom to coherently interact with the cavity mode in the strong-coupling regime [17,18]. Under these conditions, the detection of the real-time motion of single atoms [19–22],

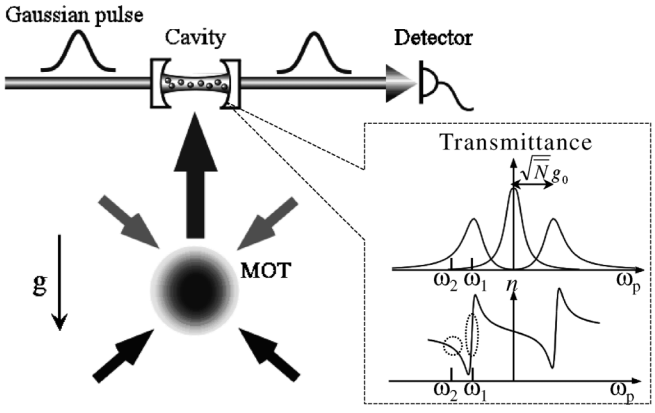

FIG. 1. The experimental setup. The inset shows the transmittance and refractive index for light propagation through the cavity. The transmittance splits due to atom-cavity coherent coupling. The corresponding dispersive property results in abnormal propagation. According to the slope of the dispersion curve, subluminal or superluminal propagation takes place at ω_1 or ω_2.

and the trapping of a single photon have been observed [23–25]. It is therefore natural to use a strongly coupled atom-cavity system to investigate optical pulse propagation when the cavity contains a small number of atoms.

To begin, let us consider the case where a few atoms are located along the optical axis of a microcavity. We denote the decay rate of atomic polarization by γ, the vacuum Rabi frequency by g_0, and the effective intracavity atom number by $\overline{N}$. If $g_0 > \gamma$, i.e., the atoms are strongly coupled to the cavity mode, the vacuum Rabi splitting is enhanced by $\sqrt{\overline{N}}$ [18], and the dispersion properties of the atom-cavity system are modified (inset of Fig. 1). A steep change of dispersion leads to a large variation in the refractive index, leading to a significant change in the group velocity v_g. At frequency ω_1, the index slope is positive and this results in subluminal propagation, e.g., $v_g < c$. On the other hand, at frequency ω_2 the index slope is large and negative, resulting in even a negative group velocity that is commonly referred to as superluminal propagation.

In the experimental setup depicted in Fig. 1, ^{85}Rb atoms are first cooled and trapped with a magneto-optical trap (MOT) comprised of six circularly polarized laser beams in a cubic arrangement [26]. Typically, 10^8 atoms are captured in a few seconds from the background vapor at a pressure of 10^{-9} Torr. We then abruptly extinguish the two laser beams propagating downward, causing the atoms to be launched upward into the optical microcavity located 33 mm above the MOT. The launched atoms are optically pumped to the $F = 3$, $M_F = 3$ state by a laser before they enter the cavity, and the number of atoms in the cavity can be well-controlled by adjusting the loading time of the MOT. We monitor the number of atoms in the MOT by measuring MOT fluorescence. When the fluorescence signal reaches a preset value, the atoms are launched upward. This procedure allows us to control the number of atoms in the cavity from a single atom to a few tens of atoms.

The optical microcavity (length $L_c = 70$ μm) consisting of two concave mirrors has finesse $\mathcal{F} = 2.1 \times 10^5$ and decay constant $\kappa/2\pi = 5$ MHz. The cavity resonant frequency is locked to the $F = 3 \rightarrow F' = 4$ transition throughout the experiments using an FM sideband technique [27]. The beam waist w_0 for the TEM_{00} mode of the cavity is 31 μm, and the atom-field coupling constant (vacuum Rabi frequency) $g_0/2\pi$ is 19.6 MHz for the $F = 3$, $M_F = 3 \rightarrow F' = 4$, $M_F = 4$ transition. Since the decay rate of atomic polarization $\gamma/2\pi$ is 3 MHz, the strong-coupling condition is well satisfied.

We derive the probe light from an extended cavity laser diode whose frequency is precisely controlled using saturated absorption spectroscopy. The spatial mode of probe laser is purified using a single-mode optical fiber, and the intensity at the exit of the fiber is actively stabilized using an acoustic-optic modulator before being sent to the cavity. Before the arrival of the atoms, the probe laser is used to stabilize the cavity. In this stabilization mode, the probe laser intensity is 16 μW. It is then decreased to the pW level, where the average intracavity photon number is 0.4, just before the launched atoms reach the cavity. The transmitted probe light is monitored using a heterodyne detection technique for which the local oscillator is generated by frequency shifting the probe laser by 88 MHz. The temporal change in the amplitude of the 88 MHz beat signal (monitored by a spectrum analyzer with a detection bandwidth of 300 kHz) corresponds to changes in the transmitted probe intensity.

Figure 2 shows a typical probe transmittance signal when both the probe and cavity frequencies are locked to the atomic resonance. Figure 2(a) corresponds to the case where atoms enter the cavity one at a time. When a single atom enters the cavity, the probe transmittance decreases rapidly [19,20] while the atom crosses the cavity mode. In our case, this transit time is 6 μs which is comparable to the probe pulse width (FWHM = 5.6 μs). Because the frequency region in which the steep change in the refractive index occurs is very narrow, ultrashort pulses cannot be used in the investigation of abnormal light pulse propagation. We therefore perform the experiments when the cavity is continuously filled with atoms over a few milliseconds. With a 3 s MOT loading time, the cavity mode is filled with several atoms for 2 ms, a time much longer than the single-atom transit time [Fig. 2(b)].

The intracavity atom number $\overline{N}$ is determined by measuring the probe transmittance as a function of probe detuning from atomic resonance. When atoms are present

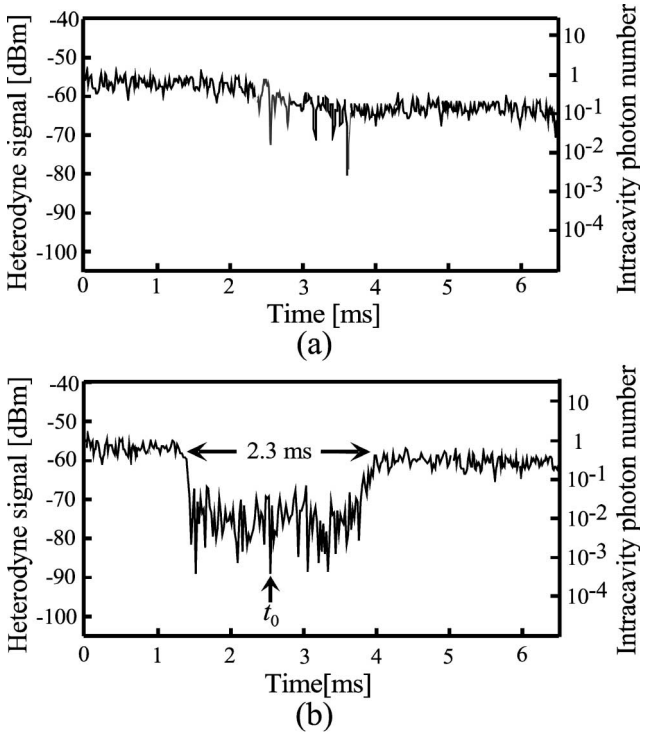

FIG. 2. (a) The transmitted probe signal when atoms enter the cavity one after another. (b) The transmitted probe signal when a group of atoms enters the cavity.

in the cavity, the transmission of probe light at frequency $\omega_p/2\pi$ is given by [18]

$$T = T_0 \left| \frac{\kappa[\gamma + i(\omega_a - \omega_p)]}{(\omega_p - \lambda_+)(\omega_p - \lambda_-)} \right|^2, \quad (1)$$

where T_0 is peak transmittance of the cavity without atoms, $\omega_a/2\pi$ is the atomic transition frequency, and $\lambda_\pm = (\omega_a \pm g) - i(\gamma + \kappa)/2$. When $\overline{N}$ atoms cooperatively interact with the same light field, the Rabi frequency is given by $g \equiv \sqrt{g_0^2\overline{N} - (\gamma - \kappa)^2/4}$ and is well approximated in the present case ($\gamma \approx \kappa$) by $g = g_0\sqrt{\overline{N}}$. Fitting the observed probe transmittance with Eq. (1) can yield a mean value of the number of atoms ($\overline{N} = 6.4$ in the present case).

When several atoms enter the cavity [at t_0 in Fig. 2(b)], we send a Gaussian probe laser pulse at the frequency ω_p into the cavity, and measure the arrival time of the probe pulse after it has traversed the cavity. The delay (advance) in the arrival time of a pulse propagation through the cavity with atoms is defined being referred to the propagation time in free space to be $\Delta t = \mathcal{F}L_c/v_g - L_c/c$. As shown in Fig. 3, actually we measured the time delay (advance) by comparing the arrival time of the light pulse transmitted through the cavity with atoms to that through the empty cavity, $\Delta t_{obs} = \mathcal{F}L_c/v_g - t_c$, where t_c is propagation time through the empty cavity. It should be noted that the empty cavity also induces the delay [8] of

$$t_c - \frac{L_c}{c} = \Delta t - \Delta t_{obs} = \frac{1 - R^2}{(1 - R)^2 + 4R\sin^2(\delta\frac{L_c}{c})}\frac{L_c}{c} - \frac{L_c}{c}, \quad (2)$$

where $\delta = \omega_p - \omega_c$ and R is the reflectivity. R is calculated to be 0.99 985 from the relation of $\mathcal{F}/\pi = \sqrt{R}/(1 - R)^2$.

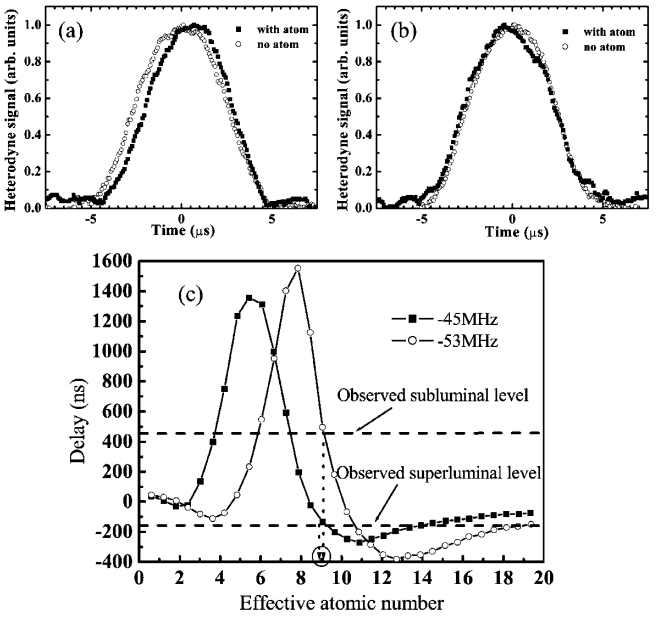

FIG. 3. Transmitted probe pulse profiles observed with heterodyne detection method. Solid square: with atoms in the cavity. Open circle: without atom in the cavity. (a) When the detuning is $\delta/2\pi = -53$ MHz, 440 ns delay is observed. (b) When $\delta/2\pi = -45$ MHz, 170 ns advance time is observed. (c) The delay/advance time as a function of the effective atom number calculated using a Monte Carlo simulation. The intersections between the curves and the horizontal lines (the observed delay or advance time) determine the effective number of atoms in the cavity to be $\overline{N} = 9.4$.

The pulse shapes depicted in Figs. 3(a) and 3(b) are the results of accumulation of about 200 times pulse transmissions, with and without atoms. Because of the nonlinear nature of atom-light interaction in the strong-coupling regime and the inevitable fluctuations of experiments, the pulse shapes show appreciable deformation. We fit the observed pulse shapes with Gaussian functions in order to deduce the delay (advance) times. With this method we obtained the delay (advance) time. The delay of Δt_{obs} of 440 ns at $\delta/2\pi = -53$ MHz [Fig. 3(a)] and the advance (negative delay time) of -170 ns at $\delta/2\pi = -45$ MHz [Fig. 3(b)] are clearly observed.

We estimate the cavity finesse effect using Eq. (2) for the present experimental conditions used for Figs. 3(a) and 3(b) and obtain 0.29 and 0.40 ns, respectively. Since $\Delta t - \Delta t_{obs} \ll \Delta t$ or Δt_{obs}, Δt may be well approximated by Δt_{obs}.

We have performed Monte Carlo simulations of the process to compare the observed results with calculations. We first examine an atom-cavity system with thousands of atoms randomly distributed inside the cavity mode. The effective Rabi frequency $g_0\sqrt{\overline{N}}$ can be calculated by summing the contribution of all atoms [18], giving an expected transmittance signal $T(\overline{N})\exp[-(t - \Delta t(\overline{N}))^2/2\tau^2]$, where $\sqrt{2\ln 2}\tau$ is the half-width of the pulse. We repeated the above procedure 4000 times and then averaged them to obtain the final results of the simulation. Figure 3(c) shows the delay (advance) time Δt as a function of the number of atoms. Both the observed delay (440 ns) and advance ($-$ 170 ns) times give the same effective atom number of 9.4. (Note the intersections of the curves and dotted horizontal lines.)

The number of atoms in the cavity (9.4) estimated from the pulse propagation shows an appreciable disagreement with that estimated from the Rabi splitting (6.4). This is due to incomplete optical pumping of atoms into the $M_F = 3$ state. When the population is distributed among various M_F states, the mean Rabi frequency of a group of atoms becomes smaller than g_0 used in the calculation. For a given Rabi splitting, use of a larger g_0 value in the estimation leads to a smaller atom number.

To further improve the consistencies of the measurements on atom number, we carried out a second set of experiments with the cavity finesse $\mathcal{F} = 7.8 \times 10^4$ ($\kappa/2\pi =$ 13.8 MHz). In these experiments, the optical pumping condition was well optimized and the highly sensitive photon counting detection method was employed. The

delay of 470 ns at $\delta/2\pi = -80$ MHz, and the advance of 20 ns at $\delta/2\pi = -96$ MHz were observed. The Monte Carlo simulation on the assumption that all atoms are pumped into the $F = 3$, $M_F = 3$ state gives the intracavity atom numbers of 15.4 for the subluminal propagation and 16.6 for the superluminal propagation. These values are in fairly good agreement with the atom number of 15.2 estimated from the Rabi splitting measurement.

The above-described method can be extended to the case where only one atom is in the cavity. Our calculation predicts that with properly chosen parameters a single atom can modify the pulse propagation time, causing up to 900 ns of delay and -110 ns of advance at the best condition of our apparatus. The atomic velocity must be sufficiently slow to perform an experiment with a single atom, so that the transit time of the atom through the cavity mode will be much longer than the duration of the Gaussian probe pulse. We are currently working to improve our experimental setup so that single-atom effects can be directly observed.

There are other interesting extensions of our experiments such as the creation of an entangled state between the atom and the transmitted photon (a Schrodinger cat state). Since a single atom can modify the propagation time of the optical pulse, if it were prepared in a superposition state, the light pulse would be split into two propagating parts reflecting the two distinct atomic states. Such an atom-photon entangled state may be used in the field of quantum communication and information technology. It is also possible to investigate the decoherence of an atom-photon entangled state by increasing the atom number interacting with the cavity in a controlled way. In the strong-coupling regime, atoms in the microcavity interact cooperatively with the single-photon field, and the atomic state is well represented by the Dicke state. However, the phase of the first excited Dicke state may change dynamically in time because the atoms in the cavity frequently exchange photons. The more atoms in the cavity may cause the faster phase evolution of the Dicke states.

This work was supported by the Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Corporation, a Grant-In-Aid from the Ministry of Education, Science, and Culture, and JSPS Research Fellowships for young scientists.

*Current address: National Metrology Institute of Japan, AIST, Tsukuba Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563, Japan.
Electronic address: shimizu-yukiko@aist.go.jp
†Current address: Toshiba Corporation, 1 Komukai Toshiba-cho, Saiwai-ku, Kawasaki 212-8582, Japan.
‡Current address: Tokyo Institute of Technology, 2-12-1 Ookayama, Megro-ku, Tokyo 152-8552, Japan.

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