Amplification of Light and Atoms in a Bose-Einstein Condensate

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A Bose-Einstein condensate illuminated by a single off-resonant laser beam ("dressed condensate") shows a high gain for matter waves and light. We have characterized the optical and atom-optical properties of the dressed condensate by injecting light or atoms, illuminating the key role of long-lived matter wave gratings produced by the condensate at rest and recoiling atoms. The narrow bandwidth for optical gain gave rise to an extremely slow group velocity of an amplified light pulse ($\sim$1 m/s).

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The field of atom optics is based on profound analogies between electromagnetic waves and matter waves. Both light and atoms can be amplified by bosonic stimulation, and this has led to the optical laser and the atom laser, respectively. Recently, Bose-Einstein condensates illuminated by an off-resonant laser beam ("dressed condensates") were used to realize phase-coherent amplification of matter waves [1,2]. The amplification process involved the scattering of a condensate atom and a laser photon into an atom in a recoil mode and a scattered photon. This four-wave mixing process between two electromagnetic fields and two Schrödinger fields became a self-amplifying process above a threshold laser intensity, leading to matter wave gain. However, the symmetry between light and atoms indicates that a dressed condensate should not only amplify injected atoms, but also injected light.

In this paper, we focus on the optical properties of a dressed condensate above and below the threshold for the matter wave amplification. The optical gain below the threshold has a narrow bandwidth due to the long coherence time of a condensate. This resulted in an extremely slow group velocity for the amplified light. Above the threshold, we observed nonlinear behavior in the optical gain. This is due to the buildup of a macroscopic matter wave grating inside the condensate and was observed *in situ* by a pump-probe measurement.

Figure 1a shows the basic light scattering process. An atom scatters a photon from the laser beam (called "dressing beam") into another mode and receives the corresponding recoil momentum and energy. Injection of atoms or light turns this *spontaneous* process into a *stimulated* process. If atoms are injected, they form a matter wave grating (an interference pattern with the condensate at rest) and this grating diffracts light. The diffraction transfers recoil momentum and energy to the atoms, which results in a growth of the grating and therefore the number of atoms in the recoil mode—this is the intuitive picture for atom gain. If probe light is injected, it forms a moving standing wave with the dressing beam, and this light grating diffracts atoms. This diffraction transfers photons into the probe beam mode, resulting in optical gain.

For low dressing beam intensity, the probe beam gain is due to the two-photon gain of individual atoms (Fig. 1b). By introducing the dressed atom picture [3], the optical gain can be understood as the gain of a fully inverted two-level system (Fig. 1c). The atoms in the condensate and the photons in the dressing beam form a dressed condensate, corresponding to the upper state ($|1'\rangle$). The lower state is the recoil state of atoms ($|2\rangle$) and the dressed condensate can "decay" to the lower state by emitting a photon into the probe beam mode. A fully inverted two-level system with dipole coupling would have a gain cross section of $6\pi\lambda\!\!\!^{-2}$ for radiation with wavelength $\lambda[= (2\pi)\lambda\!\!\!^{-}]$. For the Raman-type system in Fig. 1b, the gain is reduced by the excited state fraction, R_D/Γ (where R_D is the Rayleigh scattering rate for the dressing beam and Γ is the linewidth of the single-photon atomic resonance) and increased by Γ/Γ_2, the ratio of the linewidths of the single-photon and two-photon Bragg resonances. Thus the expected cross section for gain is

$$\sigma_{\mathrm{gain}} = 6\pi\lambda\!\!\!^{-2}\,\frac{R_D}{\Gamma_2}\,, \tag{1}$$

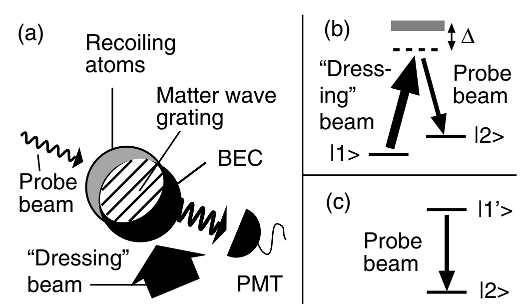

FIG. 1. Amplification of light and atoms by off-resonant light scattering. (a) The fundamental process is the absorption of a photon from the "dressing" beam by an atom in the condensate (state $|1\rangle$), which is transferred to a recoil state (state $|2\rangle$) by emitting a photon into the probe field. The intensity in the probe light field was monitored by a photomultiplier. (b) The two-photon Raman-type transition between two motional states ($|1\rangle, |2\rangle$) gives rise to a narrow resonance. (c) The dressed condensate is the upper state ($|1'\rangle$) of a two-level system, and decays to the lower state (recoil state of atoms, $|2\rangle$) by emitting a photon.

which is proportional to the intensity of the dressing beam. A Bose–Einstein condensate has a very narrow two-photon resonance width Γ_2 of only a few kHz. The residual linewidth stems from the loss of overlap between the two motional states and from the inhomogeneous density distribution [4].

A gain with narrow bandwidth causes a slow group velocity of light. The gain represents the imaginary part of the complex index of refraction. A sharp peak in the gain implies a steep dispersive shape for the real part of the index of refraction $n(\omega)$. This results in a small value of the group velocity v_g

$$v_g = \frac{c}{n + \omega \frac{dn}{d\omega}}, \qquad (2)$$

and in large pulse delays. More precisely, a narrow-band gain feature with gain g and width γ leads to an amplified pulse with a delay time of $\tau_D = (\ln g)/\gamma$.

For the experimental study of optical properties of a dressed condensate, elongated Bose–Einstein condensates consisting of several million sodium atoms in the $F = 1$, $m_F = -1$ state were prepared in a magnetic trap [5]. The condensate was illuminated ("dressed") with a single laser beam that was red-detuned by 1.7 GHz from the $3S_{1/2}, F = 1 \rightarrow 3P_{3/2}, F = 0, 1, 2$ transition. Both the dressing beam and the probe beam were in the plane perpendicular to the long axis of the condensate, and intersected at an angle of 135°. The probe beam was red-detuned from the dressing beam by 91 kHz, which was determined to be the resonance frequency for the two-photon Bragg transition. This small frequency difference between the two light beams was realized by deriving both beams from a common source, and then passing them through two separate acousto-optical modulators that were driven with separate frequency synthesizers. The probe beam, which propagated parallel to the axis of imaging, was a few millimeters in diameter and much larger than the condensate, which was 20 μm in diameter and 200 μm in length. In order to block all the light that did not pass through the condensate, a 25 μm $\times$ 100 μm slit was placed at an intermediate imaging plane where the condensate was 2 times magnified. The light transmitted by the slit was recorded with a photomultiplier. The polarization of each beam was set parallel to the long axis of the condensate to suppress superradiance to other recoil modes [6].

The main results of this paper are shown in Figs. 2 and 3. In order to measure the gain of the dressed condensate, we used long square probe pulses during which the dressing beam was switched off (Fig. 2). At the lowest probe intensity, the depletion of atoms in the condensate was negligible and a clear step at the switch off was observed, corresponding to a gain of ~2.8. The initial rise time ~100 μs is the coherence time of the dressed condensate.

The square pulse response observed in Fig. 2a already indicates long pulse delays. The distortion of the pulse is due to the large frequency bandwidth contained in the square pulse. This was avoided by modifying the pulse shape to be Gaussian, but keeping the peak intensity of the probe beam at the same level. Figure 3a shows that such pulses were delayed by about 20 μs across the 20 μm wide condensate corresponding to a group velocity of 1 m/s. This is, to the best of our knowledge, 1 order of magnitude smaller than any other value published thus far [7].

At high probe laser power we observed Rabi oscillations in the transmitted probe light (Fig. 2). Note that all the traces were normalized by the probe beam intensity, and the oscillatory trace at the bottom was obtained at the highest probe beam intensity. They reflect simple two-level

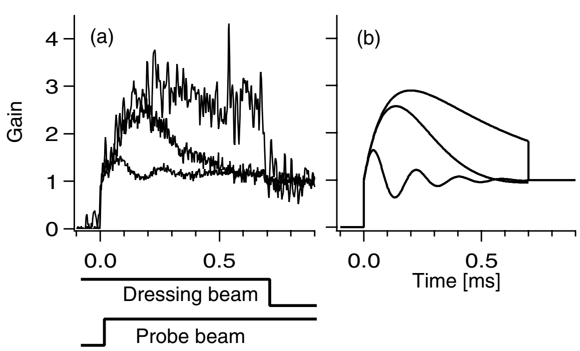

FIG. 2. Gain and temporal behavior of light pulses propagating through a dressed condensate. (a) Observed probe pulse output from a dressed condensate. The probe light intensities were 5.7 mW/cm^2 (bottom), 1.5 mW/cm^2 (middle), 0.10 mW/cm^2 (top), while the dressing beam intensity was 5 mW/cm^2, which was just below the threshold for superradiance. The plotted signals were normalized by the incident probe intensity and show the gain for the probe light. (b) Calculated probe light output for the experimental parameters in (a). Rabi oscillations develop into steady-state gain as the intensity of the probe light is reduced.

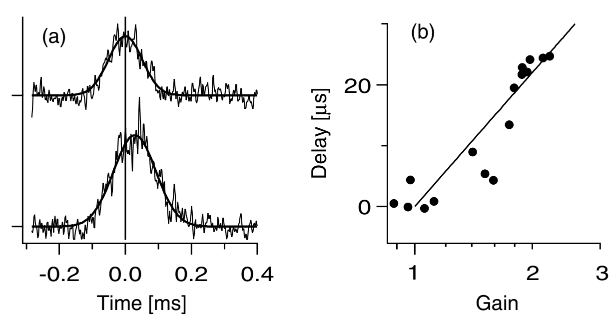

FIG. 3. Pulse delay due to light amplification. (a) About 20 μs delay was observed when a Gaussian pulse of about 140 μs width and 0.11 mW/cm^2 peak intensity was sent through the dressed condensate (bottom trace). The top trace is a reference taken without the dressed condensate. Solid curves are Gaussian fits to guide the eyes. (b) The observed delay τ_D was proportional to $(\ln g)$, where g is the observed gain.

Rabi oscillations of atoms between states $|1\rangle$ and $|2\rangle$ (Fig. 1b) driven by the two-photon Bragg coupling.

The transition from Rabi oscillations to steady-state gain can be described by optical Bloch equations. The two-level system $|1\rangle$ and $|2\rangle$ is coupled with the two-photon Rabi frequency $\Omega = \Omega_D \Omega_p / 2\Delta$ where $\Omega_D(\Omega_p)$ is the Rabi frequency of the dressing (probe) beam and Δ is the detuning of the beams from the atomic resonance. The Bloch equations for atoms at the two-photon resonance take the following simple form:

$$\dot{v} = -\frac{\Gamma_2}{2} v - \Omega w , \tag{3}$$

$$\dot{w} = \Omega v , \tag{4}$$

where $v = 2\,\mathrm{Im}(\rho_{12})$ represents the amplitude of the matter wave grating (ρ_{ij} is the atomic density matrix) and $w = \rho_{22} - \rho_{11}$ is the population difference between the two states.

Figure 2b shows the calculated probe output for a step function input. Assuming constant Ω (valid for small optical gain), the solutions of the optical Bloch equations show either Rabi oscillation ($\Omega \gg \Gamma_2/2$) or damped behavior ($\Omega \ll \Gamma_2/2$). By reducing the probe power, the Rabi oscillations slow down, and a (quasi-)steady-state gain is obtained in the limit that they are slower than the damping time. It is in this regime that the perturbative treatment with the complex index of refraction applies. Note that for longer times ($\gg \Gamma_2/\Omega^2$) the condensate becomes depleted.

For large optical gain, the Rabi frequency Ω increases during the pulse and the above treatment is no longer valid. The population transfer to the recoil state ($\dot{w}$) results in an increase of the number of the probe beam photons inside the condensate volume: $\dot{n_p} = c(n_p^0 - n_p)/l + N_0 \dot{w}/2$, where l is the length of the condensate with N_0 atoms and $c n_p^0 / l$ is the input photon flux. This equation neglects propagation effects of the light by replacing the nonuniform electric field by an average value [8]. Replacing the photon number by the Rabi frequency $\Omega^2 = R_D 6\pi \lambda\!\!\!^{-2} c n_p / V$ (V is the volume of the condensate), we obtain

$$\dot{\Omega} = \frac{c}{l}\left(\Omega^0 - \Omega + \frac{G}{2} v\right), \tag{5}$$

where Ω^0 is the two-photon Rabi frequency due to the input probe beam and the dressing beam, and G is defined by $G = N_0 R_D 6\pi \lambda\!\!\!^{-2} / 2A$ (A is the cross section of the condensate perpendicular to the probe beam). The coupled equations (3) and (5) between the light and matter wave grating are analogous to the optical laser, where the atomic polarization and the electric field inside the cavity are coupled. However, the roles of atoms and light are reversed: in the optical laser, the cavity lifetime is usually longer than the coherence time of the atomic polarization, whereas in our case the extremely long coherence time of the condensate dominates.

Adiabatically eliminating the light [$\dot{\Omega} = 0$ in Eq. (5)] and neglecting condensate depletion ($w = -1$), we are led to

$$\dot{v} = \frac{G - \Gamma_2}{2} v + \Omega^0. \tag{6}$$

Above the threshold for superradiance ($G \geq \Gamma_2$), the matter wave grating builds up exponentially. Below the threshold, it relaxes with a time constant of $2/(\Gamma_2 - G)$, providing a gain for the probe light field of

$$1 + \frac{G}{\Gamma_2 - G} = 1 + \frac{n_0 \sigma_{\mathrm{gain}} l}{2} \frac{\Gamma_2}{\Gamma_2 - G}, \tag{7}$$

where n_0 is the condensate density. In the low intensity limit, Eq. (7) reproduces the two-photon gain discussed above [Eq. (1)]. Equation (7) shows that the effect of the coupled equations is to replace the two-photon linewidth Γ_2 in Eq. (1) by the "dynamic" coherence decay rate $\Gamma_2 - G$. The expansion of the optical gain $1 + G/(\Gamma_2 - G) = 1 + (G/\Gamma_2) + (G/\Gamma_2)^2 + \ldots$ shows the transition from (linear) single-atom gain to (nonlinear) collective gain. At the onset of superradiance, the optical gain diverges.

We studied this transition by first creating a matter wave grating with a Bragg pulse (using the dressing and probe beams), and then observing its time evolution by monitoring the diffracted dressing beam.

The grating showed a simple decay at lower dressing beam intensities (Fig. 4a) [9]. At higher intensities, collective gain started to compensate the loss, and at intensities above a threshold, net amplification was observed. The initial growth rate (Fig. 4b) followed the linear dependence on the intensity of the dressing beam [$\propto (G - \Gamma_2)$] predicted by Eq. (6) and Refs. [6,10]. The net growth of the matter wave grating corresponds to atom amplification which was studied previously by observing an increase in the number of recoiling atoms in time-of-flight images [1]. Here we have monitored the dynamics of amplification *in situ* by observing light instead of atoms.

Extrapolating the decay rate in Fig. 4b to zero intensity of the dressing beam, we obtained the decay time of the matter wave grating Γ_2 of 100 μs, in fair agreement with the linewidth of the Bragg excitation process observed previously [4].

Recent demonstrations of slow group velocities for light focused on electromagnetically induced transparency in a three-level lambda system [7]. This system features a narrow dip in a broad absorption feature. In our system, the broad absorption line is missing. Since the propagation of resonant laser pulses is mainly determined by the narrow feature, both systems show analogous behavior. In the past, "superluminal" pulse propagation was observed in noninverted, absorptive two-level systems [11]. Our scheme realizes the opposite case of gain and slow pulse propagation [12].

The dressed condensate studied in this paper is a clean, model system for discussing optical and atom-optical

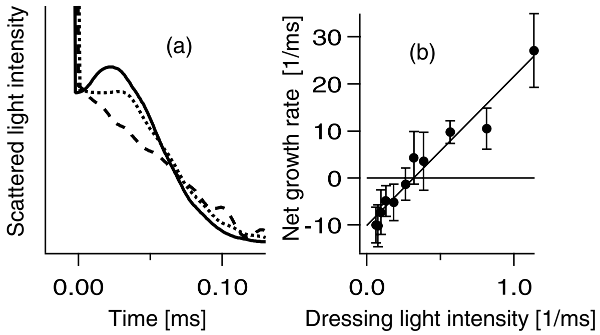

FIG. 4. Pump-probe spectroscopy of a matter wave grating inside the condensate. (a) First, approximately 5% of atoms were transferred to the recoil state by a 100 μs long Bragg pulse. Then the dynamics of the matter wave grating was observed *in situ* by illuminating the grating with off-resonant light and monitoring the diffracted light intensity. All traces were normalized to the same diffracted light intensity at $t = 0$. The dressing beam intensity was 2.9 mW/cm^2 (bottom), 5.7 mW/cm^2 (middle), and 13 mW/cm^2 (top). (b) The initial growth rate of the grating vs light intensity shows the threshold for net gain. The intensity of the dressing beam is given in units of the single-atom Rayleigh scattering rate.

properties. The optical amplification can be described as a reflection of the dressing light by a matter wave grating. The initial delay time in the amplification of optical pulses is the time necessary to build up the (quasi-)steady-state matter wave grating. The trailing edge of the transmitted light pulse reflects the slow decay of quasiparticles. Thus, the slow speed of light is simply related to the buildup and decay of quasiparticles which we were able to monitor directly.

The optical gain studied above clearly showed the transition from single-atom gain to collective gain. Previously, recoil related gain based on single-atom phenomena (recoil induced resonances) was observed in cold cesium atoms [13]. Collective gain due to the formation of a density grating was discussed as a possible gain mechanism for lasing action [14] (named CARL—coherent atomic recoil laser) and pursued experimentally [15] with ambiguous results (see [16] and the discussion in [17]). Our experiments clearly identify the two regimes and their relationship.

Our observation of the decay of the matter wave grating can be regarded as pump-probe spectroscopy of quasiparticles in the condensate. The seeding Bragg pulse created the condensate excitations in the free-particle regime. By controlling the angle between the laser beams, one can also excite phononlike quasiparticles [18]. Thus, the pump-probe scheme presented here could be directly applied to the study of their lifetimes.

In conclusion, we have characterized the optical and atom-optical properties of a dressed condensate. The simple process of Rayleigh scattering gave rise to a rich variety of phenomena including steady-state gain, Rabi oscillations, collective gain, and slow group velocities. We have also introduced a pump-probe technique to study the lifetime of quasiparticles in a condensate.

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