

Achieving Peak Brightness in an Atom Laser

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In this Letter we present experimental results and a simple analytic theory on the first continuous (long pulse) Raman atom laser. We analyze the flux and brightness of a generic two state atom laser with an analytic model that shows excellent agreement with our experiments. We show that, for the same source size, the brightness achievable with a Raman atom laser is at least 3 orders of magnitude greater than achievable in any other demonstrated continuously outcoupled atom laser.

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Continuous atomic beams derived from magnetically trapped Bose-Einstein condensates (BECs) bear striking similarities to optical lasers—so much so that the beams are termed atom lasers [1]. Both optical and atom lasers create a coherent output beam of bosons that are photons in the case of an optical laser and de Broglie matter waves in the case of an atom laser. There is a promising future for atom lasers in any application which requires a high brightness atomic source [2,3]. In particular, continuous atom lasers may prove superior to optical or mechanical techniques in precision measurement systems such as inertial and rotation sensors or sensors of magnetic, electric, or gravitational fields and their gradients. To achieve the fundamental levels of sensitivity (quantum limited) and to surpass existing technology, an atom laser must have a high brightness and be shot noise limited over the frequency band being measured. In practice the shot noise limit is difficult to achieve at least for high flux, and it is essential to have a spectrally narrow, classically quiet, low divergence beam with the minimum transverse structure in both phase and amplitude.

Most atom lasers have been produced experimentally using a radio-frequency (rf) coupling between trapped and untrapped magnetic states to produce the atomic beam [4–6]. A number of ground breaking experiments have been made with such a beam, including measurements of the temporal coherence [7], the second order correlation function [8], focusing and trapping in an rf cavity [9], and a dynamic measurement of the atom laser beam density [10]. The divergence properties of the rf atom laser beam have been the subject of a number of recent studies [6,11–14].

In this Letter, we present the first results on a continuously outcoupled Raman atom laser. A Raman outcoupler coherently transfers magnetically trapped condensate atoms to an untrapped state via a multiphoton optical transition. Additionally, the atoms receive a momentum kick equal to the sum of the momentum per photon in the absorption and emission events comprising the optical outcoupling process [15]. Prior to the work presented here, there has been one demonstration of a Raman atom laser by Hagley *et al.* that was performed in pulsed mode

producing a broad-linewidth ($\Delta E \sim 1$ kHz) multispin component beam [16]. A continuous output coupler based on the Bragg effect, a non-state-changing two photon transition, has recently been utilized to demonstrate the formation of the relative phase between BECs in two separate optical traps [17]. Our laser is operated in the weak outcoupling regime producing a single spin component, classically quiet low divergence matter wave output beam with an inferred linewidth that can be a factor of 100 less than that achieved in the work of Hagley *et al.* [18]. The ^{87}Rb Raman atom laser has a flux limit that we calculate to be a factor of 25 higher than that achievable with an rf outcoupled atom laser produced from the same source. As we will show, the output mode has a calculated divergence that can be a factor of at least 7 less in each transverse direction than any continuous (long pulse) atom laser demonstrated to date. For our current experimental conditions, the limit for the beam brightness of a Raman outcoupled atom laser is more than 3 orders of magnitude greater than can be achieved with an rf output coupler.

Our setup for producing BEC, the source for the atom laser, is unchanged from the apparatus used in our previous studies of the rf continuous output coupler [19]. Briefly, we produce an $F = 2$, $m_F = 2$ ^{87}Rb condensate, consisting of approximately 10^5 atoms, via evaporation in a water-cooled quadrupole-Ioffe configuration magnetic trap [20] with a radial trapping frequency of $\omega = 2\pi \times 260$ Hz and an axial trapping frequency $\omega_z = 2\pi \times 20$ Hz. We operate our trap at a bias field of $B_0 = 0.25$ G. The trap runs at 12 A (12 V) generated from a low noise power supply. The low power dissipation, and additional chilled water cooling, suppresses heating related drift of the magnetic trap bias field, allowing precise addressing of the condensate with resonant rf radiation or Raman beams (we measure a drift of significantly less than 0.7 mG over 8 h).

The $F = 2$, $m_F = 2$ atoms in the condensate are coupled to the $m_F = 0$ state using two phase locked lasers. The coupling scheme, based on a combination of linear and circular polarized beams, is shown in Fig. 1(a) [21]. Atoms coupled to the $m_F = 0$ state fall under gravity to produce the atom laser beam also shown in Fig. 1(b). The two

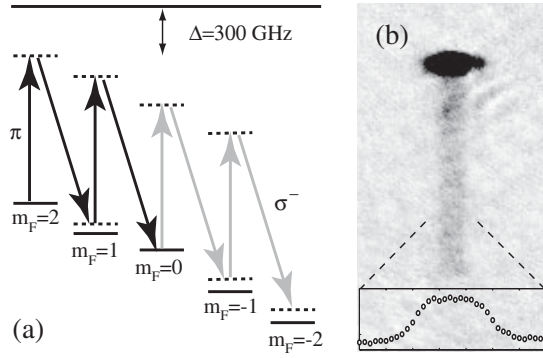


FIG. 1. A continuous Raman output coupler. (a) Transitions from the $5^2S_{1/2} F = 2, m_F = 0$ state to the $F = 2, m_F = 0$ state via the $5^2P_{3/2}$ transition of ^{87}Rb . (b) Absorption image ($0.7 \text{ mm} \times 1.3 \text{ mm}$) of an 8.5 ms continuous Raman atom laser produced with $60 \mu\text{W}$ per 1 mm beam. Inset shows a $200 \mu\text{m}$ slice through the transverse beam profile (longitudinal integration $200 \mu\text{m}$).

optical beams that form the outcoupler are produced from a single 70 mW diode laser, detuned 200 GHz to the red of the $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ optical transition in order to suppress spontaneous emission. This light is split and sent through two separate phase locked acousto-optic modulator (AOMs), each in a double pass configuration. The frequency difference between the AOMs corresponds to the Zeeman plus kinetic energy difference between the initial and final states of the multiphoton Raman transition. The beams are then coupled via a single mode, polarization maintaining optical fiber, directly to the BEC through a collimating lens and wave plate, providing a maximum intensity of 250 mW/cm^2 per beam. The beams intersect at the condensate and are aligned in the plane of the weak axis and gravity and are separated by $\theta = 45$ degrees in the vertical direction. With the laser polarizations chosen appropriately the atoms acquire a momentum kick of $4\hbar k \sin(\theta/2)$ downwards. In Fig. 1(b) we show an absorption image of an atom laser produced with a continuous Raman output coupler. The Raman lasers, each with $60 \mu\text{W}$ in roughly collimated 1 mm beams (7.6 mW/cm^2), were applied to the condensate for 8.5 ms. The magnetic trap was then abruptly turned off and 2 ms later the atoms were imaged. At this low laser power the output shows no density fluctuations, indicating that the optical system used to produce the output coupling is at least stable to a small fraction of the 5 kHz (non-angular) resonant width of the condensate. Increasing the power in the Raman beams, which increases the two photon Rabi frequency, causes density fluctuations in the atom laser beam reminiscent of those we observe for the rf atom laser [19]. We also observe pumping to the antitrapped states. However, up to the maximum power available in the experiment we find that the Raman atom laser *does not* exhibit a bound state [22].

In the following paragraphs, we show that the continuous Raman output coupler has the potential to surpass the

output brightness [23] achievable in an rf atom laser by more than 3 orders of magnitude. The large momentum kick imparted by the Raman lasers (up to $4\hbar k$ or a velocity of $\sim 2.35 \text{ cm/s}$) boosts the output flux and decreases the transverse and longitudinal momentum spread of the atom laser. We first consider the flux from a simple two state model of output coupling (say $|F = 1, m_F = -1\rangle$ to $|F = 1, m_F = 0\rangle$). Applying a weak coupling between magnetically trapped and untrapped states leads to a localized output resonance within the BEC (Fig. 2 inset). Gravity causes the condensate to sag (by g/ω^2 where g is gravity and ω is the angular radial frequency of the magnetic trap) away from the magnetic field minimum, broadening the frequency resonance.

In the limit of continuous weak coupling in typical magnetic traps, the output region forms a roughly planar slice through the condensate perpendicular to gravity [5]. The rate at which atoms are coupled between the fields is given by the angular Rabi frequency, $\Omega = g_F \mu_B B / (2\hbar)$ for rf, where g_F is the g factor, μ_B is the Bohr magneton, B the magnetic field magnitude, and $\Omega = \Omega_1 \Omega_2 / (4\Delta)$ for Raman, where $\Omega_{1,2}$ are the single photon Rabi frequencies and Δ is the detuning from the appropriate resonance. The characteristic frequency width of the coupling is the Rabi frequency. For reasons of mathematical simplicity we arrange the center of the output-coupling resonance to coincide with the center of the condensate. We can then calculate the *characteristic spatial width* of the resonance, Δx , and hence a transit time for atoms to fall out of the resonance. The lower resonant half-width is found by considering the difference in resonant frequencies between the lower edge of the resonance at $x_l = g/\omega^2 + \Delta x_l$ and the center of the resonance at $x_c = g/\omega^2$. The magnetic field at any point in the vertical direction is given by $B = B_0 + 1/2 B'' x^2$ where $B'' = \frac{m\omega^2}{g_F \mu_B}$ and m is the atomic mass, and the resonant frequency is $\omega_{\text{rf}} = g_F \mu_B B / \hbar$. Thus the

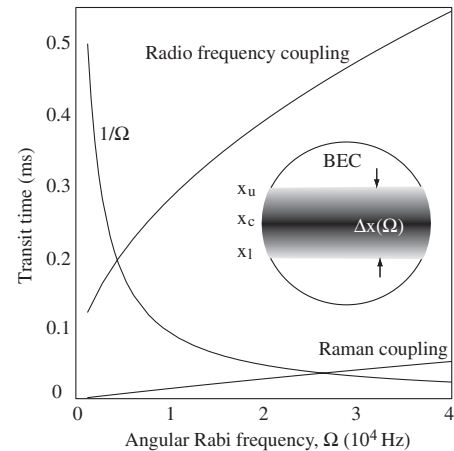


FIG. 2. A comparison of the transit time of atoms through the output-coupling resonance Δx for the rf and Raman output couplers. The inset shows a simple schematic of our model of continuous output coupling.

lower resonant width of the coupling is given by

$$\Delta\omega_{\text{rf}} = \frac{M\omega^2}{2\hbar}(x_l^2 - x_c^2) = \frac{M\omega^2}{2\hbar}\left(\frac{2g\Delta x_l}{\omega^2} + \Delta x_l^2\right). \quad (1)$$

This equation can be solved for the spatial width of the lower half of the output-coupling resonance as

$$\Delta x_l = -\frac{g}{\omega^2} + \sqrt{\frac{g^2}{\omega^4} + \frac{\hbar\Omega}{M\omega^2}} \quad (2)$$

where we have set $\Delta\omega_{\text{rf}}$ to the half-width of the frequency resonance, $\Omega/2$. A similar expression can be derived for the upper half of the resonance to give a total spatial extent of $\Delta x = \Delta x_l + \Delta x_u$.

For an rf atom laser, an output coupled atom is accelerated out of the coupling region only by gravity. The output coupling will remain uncomplicated if the transit time of an atom through the coupling region, $\tau_{\text{grav}} = \sqrt{2\Delta x/g}$, is shorter than the Rabi flopping time [19] leading to a homogeneous output flux in the atom laser beam. If the transit time exceeds the Rabi flopping time the atoms will be coupled back into the trapped Zeeman state (for this two state model) and complex dynamics will occur [19]. Atoms output coupled with a momentum kick, as in the Raman scheme, leave the interaction region more quickly, ($\tau_{\text{kick}} = \sqrt{(v_0/g)^2 + 2\Delta x/g} - v_0/g$ where v_0 is the velocity imparted to the atoms). Hence the homogeneous flux limit will be higher for this type of atom laser. In Fig. 2 we plot the transit times of both an rf and a Raman output coupler as a function of the coupling strength, which is parametrized by the Rabi frequency, Ω . The limit of weak outcoupling is given by the intersection of $1/\Omega$ with the transit time in Fig. 2. The two state rf atom laser satisfies the condition for weak outcoupling and therefore classically quiet operation for $\Omega < 5$ kHz. This result is consistent with the data we recorded in our investigation of flux and classical fluctuations in an rf atom laser. Based on this experimentally verified criterion, a Raman atom laser can be operated in a classically quiet regime at a Rabi frequency of up to 25 kHz, a factor of 5 higher than an rf atom laser.

We can calculate the flux of an atom laser by integrating the condensate density $|\Phi(x, y, z)|^2 = 1/U(\mu - V(x, y, z))$ (within the Thomas-Fermi approximation) over the output-coupling slice, Δx . This allows us to find the total number of atoms within the output-coupling region, $N_{\Delta x}(N, \Omega)$. Here $U = (4\pi\hbar^2 a)/m$ is the interaction strength and a is the s -wave scattering length, $\mu = \frac{1}{2}(15a\hbar^2 m^{1/2} \omega_z \omega^2 N)^{2/5}$ is the chemical potential, with N the total number of atoms in the condensate, and $V(x, y, z) = \frac{m}{2}(\omega^2(x^2 + y^2) + \omega_z^2 z^2)$ is the trapping potential. The output flux of the atom laser can then be approximated by multiplying the number of atoms in the coupling region by the Rabi frequency to give

$$F = N_{\Delta x}(N, \Omega) \Omega. \quad (3)$$

Figure 3 shows the numerical solution of the differential equation $dN/dt = -F$ for the number of atoms remaining in the condensate after 100 ms of rf output coupling as a function of Rabi frequency and is compared with our rf experiments [24]. We obtain excellent agreement *with no free parameters* in our model. A one dimensional model of the same form, with the 1D condensate interaction term fixed by matching 1D and 3D chemical potentials is also in excellent agreement with the experiment. However, the 3D model appears more accurate at higher condensate numbers, while the 1D model matches our data more closely as the condensate atom number decreases. A number of previous attempts to calculate the flux have found large discrepancies between 1D and 3D calculations and between theory and experiment (see, e.g., Ref. [25] and references therein). A previous experiment by Bloch *et al.* on an rf atom laser [5] measured an exponential decay of the condensate number with a rate $1.2(2) \times 10^{-5} \text{ s}/\Omega^2$. Our data gives a value of $3 \times 10^{-5} \text{ s}/\Omega^2$.

From these considerations, we can estimate the *peak* flux of an atom laser and the maximum phase sensitivity in an interferometric measurement. The maximum density obtainable in a ^{87}Rb condensate is clamped at approximately $10^{14} \text{ atoms}/\text{cm}^3$ by three body recombination. Taking Ω to be the maximum allowable for the rf and Raman atom lasers (see Fig. 2) we find a peak flux of $1.4 \times 10^8 \text{ atoms}/\text{s}$ and $4.2 \times 10^9 \text{ atoms}/\text{s}$ respectively. In making this estimate we have assumed realistically weak axial and radial trapping frequencies of 20 Hz. The factor of 5 increase in Rabi frequency translates to a factor of 25 increase in peak flux for the Raman atom laser over the rf atom laser. In a shot noise limited measurement of phase the sensitivity of an interferometric measurement is π/\sqrt{N} per square root of bandwidth, where N is the total atom flux. Using the flux limit given above for Raman outcoupling, the maximum sensitivity of a Raman atom laser based interferometric phase measurement is approximately $10^{-5} \text{ rad}/\sqrt{\text{Hz}}$, a factor of 5 times more sensitive than that achievable with an rf atom laser. It is important to note, however, that the

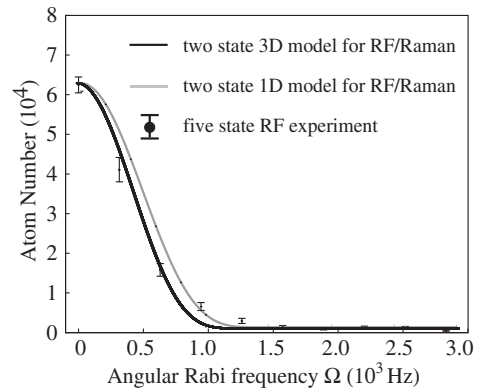


FIG. 3. A comparison of experiment and theory for the output flux of an rf atom laser. Plotted is the number of atoms remaining trapped after 100 ms of continuous output coupling as a function of Rabi frequency.

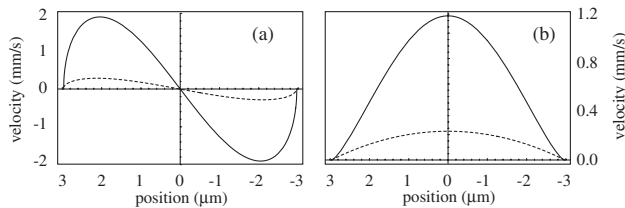


FIG. 4. Velocity distribution of the output coupled atoms after traversing the tightly confining longitudinal and transverse axes of the condensate, from an initial condition corresponding to a planar slice through the center of the condensate. The velocity due to gravity and/or the kick has been subtracted to show only the velocity contribution from the condensate mean field. (a) shows the transverse velocity distribution of the rf (solid) and Raman (dashed) atom laser, (b) the longitudinal distribution. The Raman atom laser is operated with the maximum $4\hbar k$ kick in the direction of gravity. Similar gains occur along the weakly confined transverse direction of the condensate.

Heisenberg limit sets a sensitivity limit of π/N or 2×10^{-10} rad/Hz if we use the peak flux for a ^{87}Rb Raman laser. It is interesting to consider the possibility that very strong squeezing is possible due to high nonlinearities in an atomic system and this may be a path to increasing the sensitivity of atom laser based precision measurement in future experiments.

In addition to increased flux, Raman atom lasers can be expected to gain in brightness over the rf atom laser because of their lower divergence [16]. The repulsive mean-field experienced by the output atoms across the coupling resonance leads to a nonzero longitudinal and transverse velocity width of the atom laser beam as atoms are repelled from the potential hill created by the BEC. The transverse component of this velocity width leads to an undesirable divergence [6] and mode quality [11–14] of the rf atom laser. Following [12], we use a classical trajectories model to estimate the effect of the momentum kick of a Raman atom laser on the transverse and longitudinal velocity widths. The results of this model are presented in Fig. 4 for the longitudinal and transverse velocities at the Thomas-Fermi edge of the condensate for the tightly confining axes of the magnetic trap. The Raman atom laser gains a factor of 245 increase in brightness over the rf system due to a reduction of 7 in both transverse velocity widths and a factor of 5 in the longitudinal width. Because of its dramatically decreased divergence, a continuous Raman atom laser largely negates the issues of beam quality raised in [13,14]. We note that a condensate source of lighter atoms will produce vastly higher homogeneous output flux and lower divergence atomic beam from a Raman output coupler.

It is hard to ignore the dramatic improvements that are offered by Raman output coupling when considering the atom laser as a measurement device. The models for flux and divergence presented in this Letter predict a factor of 5000 increase in brightness for a Raman atom laser over an

rf atom laser produced from the same condensate. A complete experimental characterization of the Raman laser and a detailed comparison with an rf output coupler is required to confirm our models. Furthermore, a study of the effect of the Raman kick on the transverse mode of the atom laser is required. Assuming that we can produce a high brightness source, another practical issue arises. It has been suggested (and indeed demonstrated) by a number of authors that measurements based on a *trapped* condensate will suffer greatly in their precision and accuracy due to mean-field interactions. It is not yet clear how such factors will impact on the utility of the atom laser.

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