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► **To cite this version:**

A. Couvert, M. Jeppesen, T. Kawalec, G. Reinaudi, Renaud Mathevet, et al.. A quasi-monomode guided atom-laser from an all-optical Bose-Einstein condensate. 2008. hal-00257245v1

HAL Id: hal-00257245

<https://hal.science/hal-00257245v1>

Preprint submitted on 18 Feb 2008 (v1), last revised 15 Sep 2008 (v2)

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A quasi-monomode guided atom-laser from an all-optical Bose-Einstein condensate

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(Dated: February 19, 2008)

We report the achievement of an optically guided and quasi-monomode atom laser, in all spin projection states ($m_F = -1, 0$ and $+1$) of $F = 1$ in Rubidium 87. The atom laser source is a Bose-Einstein condensate (BEC) in a crossed dipole trap, purified to any one spin projection state by a spin-distillation process applied during the evaporation to BEC. The atom laser is outcoupled by an inhomogeneous magnetic field, applied along the waveguide axis. The mean excitation number in the transverse modes is $\langle n \rangle = 0.65 \pm 0.05$ for $m_F = 0$ and $\langle n \rangle = 0.8 \pm 0.3$ for the low field seeker $m_F = -1$.

PACS numbers: 37.10.Gh, 37.10.Vz, 03.75.Pp

When atoms are coherently extracted from a Bose-Einstein condensate they form an atom laser, a coherent matter wave in which many atoms occupy a single quantum mode. Atom lasers are orders of magnitude brighter than thermal atom beams, and are first and second order coherent [1]. They are of fundamental interest, for example, for studies of atom-light entanglement, quantum correlations of massive particles [2] and quantum transport phenomena [3, 4, 5]. They are of practical interest for matter-wave holography through engineering their phase [6] and for atom interferometry because of their sensitivity to inertial fields [7].

Many prospects for atom lasers depend upon a high degree of control over the internal and external degrees of freedom and over the flux. The control of the output flux in a pulsed or continuous manner has been investigated using different outcoupling schemes: short and intense radiofrequency pulse [8], gravity induced tunneling [9], optical Raman pulses [10], long and weak radiofrequency field [11], and by decreasing the trap depth [12].

The control of their internal state is intimately related to the outcoupling strategy. Atoms are either outcoupled in the magnetically insensitive (to first order) Zeeman state $m_F = 0$ or another Zeeman state, each offering different advantages. Atom lasers in $m_F = 0$ are ideal for precision measurement [13] because of their low magnetic sensitivity. Atoms in other Zeeman states, however, are ideal for measurements of magnetic fields because of their high magnetic sensitivity [14].

The control of the external degrees of freedom has been investigated through the atom laser beam divergence while propagating downwards due to gravity [15]. Inhomogeneous magnetic field have been used to realize atom optical elements [16]. Recently, a guided and quasi-continuous atom laser from a magnetically trap BEC has been reported [17].

In this Letter, we report on a new approach to generate *quasi-monomode* guided atom laser. This method can produce an atom laser in *any* Zeeman state, with a

non-state changing outcoupling scheme which leads to an intrinsically good transverse mode-matching. Therefore, we achieve simultaneously a high degree of control of the internal and external degrees of freedom.

The atom laser is extracted from a Bose Einstein condensate (BEC) produced in a dipole trap, made from a Ytterbium fiber laser (IPG LASER, model YLR-300-

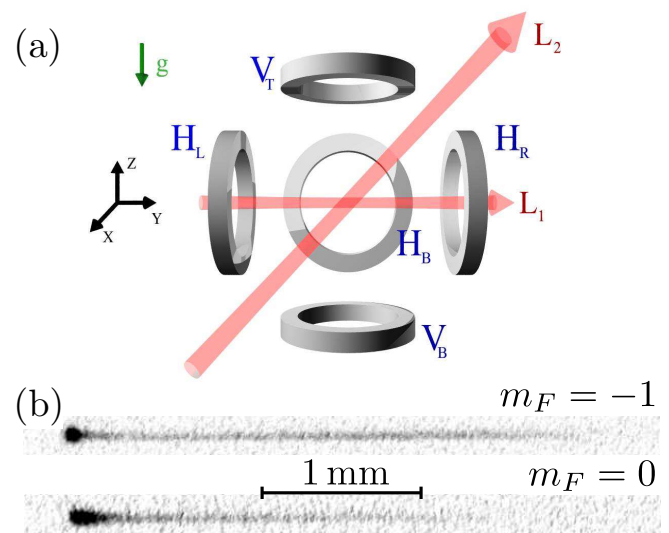


FIG. 1: (color online). (a) Schematic of experiment, showing trapping lasers and magnetic coils. The cross dipole optical trap is formed by two lasers of wavelength $\lambda = 1.07 \mu\text{m}$, one horizontal (L_1) and one at 45° (L_2). The coils are used individually to produce magnetic field gradients: during the evaporation ramp, the top coil V_T is used for production of $m_F = +1$ condensates, the bottom coil V_B for $m_F = -1$, and the off-axis horizontal coil H_B for $m_F = 0$. Atom laser outcoupling is done with either on-axis coil, H_L or H_R . (b) Absorption images for $m_F = -1$ and $m_F = 0$ atom lasers in waveguides, taken after a 15 ms expansion time.

LP) with a central wavelength of 1072 nm and a FWHM linewidth of 4 nm. We have used a crossed beam configuration formed by two focused linearly polarized beams: beam (L_1) is horizontal and has a waist of $w_1 \simeq 40 \mu\text{m}$, and beam (L_2) has a 45 degree angle with respect to the vertical axis and a waist of $w_2 \simeq 150 \mu\text{m}$ (see Fig. 1(a)).

In order to control the laser power P_i ($i = 1, 2$) of each beam, we used the first-order diffracted beam from a water-cooled acousto-optic modulator (AOM), made in fused silica and designed for high power lasers. The selected diffraction order ensures that beam (L_1) and (L_2) have a frequency difference of 80 MHz. We actively stabilized the vertical beam direction, and passively stabilized the horizontal beam direction to less than $50 \mu\text{rad}$ [18].

The experimental sequence begins by collecting around 10^9 atoms of ^{87}Rb , in an elongated magneto-optical trap (MOT), loaded from a Zeeman slower source in less than 2 seconds. The elongated shape of the MOT results from the two-dimensional magnetic field gradient configuration. The dipole trap is on during the MOT loading, with powers $P_1 = 24 \text{ W}$ and $P_2 = 96 \text{ W}$. To maximize the loading of atoms into the dipole trap, the horizontal beam L_1 is overlapped on the long axis of the MOT [19]. In addition, we favor the selection of atoms in the hyperfine level $5S_{1/2}, F = 1$ by removing the repump light in the overlapping region, similar to the dark MOT technique [20]. To evaporate, we reduce the power in each beam by typically two orders of magnitude according to Ref. [21], and we produce spinor condensates of around 10^5 atoms. The entire experimental cycle is less than six seconds.

To analyze the properties of the condensate, we use low-intensity absorption imaging, with a variable time-of-flight (TOF), after switching off the dipole beams. In addition, we can use the Stern and Gerlach effect by applying a magnetic field gradient during the expansion to spatially separate the spin components.

When evaporating with no magnetic field, we produce a condensate with an approximately equal number of atoms in each m_F spin state. To produce the atom laser, we require a BEC of one pure spin state. To do this, we use a single magnetic coil to produce a gradient in the magnetic field amplitude $\nabla|\mathbf{B}|$, and hence a force on the atoms due to the Zeeman effect. At the location of the atoms, this force is almost purely in one direction, along the axis of whichever coil is being used. We use such a force, perpendicular to the guide axis, to produce a spin-polarized BEC of an arbitrary m_F state.

Spin distillation to one m_F state occurs because, when the force is applied during evaporation, the trap is less deep for the other m_F states (see Inset of Fig. 2), and they are evaporated first [12, 22]. For example, to purify $m_F = 0$, we use the horizontal coil H_B (see Fig. 1), which forces the other m_F states out of the trap, attracting the $m_F = +1$ and repelling the $m_F = -1$. To purify $m_F = -1$, we use the bottom coil V_B , which partially cancels the effect of gravity for $m_F = -1$, has little effect on $m_F = 0$, and increases the effect of gravity for

$m_F = +1$. Because atoms in the selected spin state are sympathetically cooled by the others, the evaporation is more efficient, and we can produce condensates with a number of atoms in a given spin state approximately three times greater than when evaporating with no field. We have confirmed that the three spin states are approximately at the same temperature during the entire evaporation. In Fig. 2, we show the evolution of each spin state population in the course of evaporation for a spin distillation to the $m_F = 0$ state. From the slope of the evaporation trajectories in the number of atoms - temperature plot, we infer (using the evaporation model of Ref. [21]) that during the last second of evaporation, the ratio between trap depth and temperature η is 5.1 for $m_F = 0$ and 4.6 for $m_F = \pm 1$, which is further evidence for sympathetic cooling.

We demonstrate in the following that a BEC in a pure spin state held in an optical trap can be coupled to the horizontal arm of the trap in a very controlled manner using magnetic forces along the guide axis. The large Rayleigh length (5 mm for the horizontal beam L_1) of the laser we use for the trap enables us to guide the atom laser over several millimeters (see Fig. 1(b)). The data reported in this article are for $m_F = 0$ and $m_F = -1$ spin state. Similar results have been obtained with $m_F = +1$ state, using the same sequence as for $m_F = -1$ but with the magnetic fields reversed.

After the evaporation is complete, we prepare to outcouple the atom laser by linearly *increasing* over 200 ms the power in the horizontal beam to 200 mW for $m_F = \pm 1$ (resp. 400 mW for $m_F = 0$) and *decreasing* the power in the vertical beam to 1 W for $m_F = \pm 1$ (resp. 800 mW for $m_F = 0$). This is done so that the maximum available magnetic force will be sufficient to outcouple. At the same time, we linearly increase a magnetic gradient along the horizontal guide axis from 0 to 18 G/cm, to reach the threshold of outcoupling. Finally, to outcouple we hold the power in each beam constant and increase the magnetic gradient from 18 G/cm to 22 G/cm over a further 200 ms to generate the beam. For atoms in $m_F = 0$ state, the force exerted by the magnetic field is weaker than the one experienced by atoms in $m_F = \pm 1$ since it relies on the second order Zeeman effect. Nevertheless, we have demonstrated this magnetic outcoupling method for all three spin states.

The role played by the magnetic field is two fold: (i) it lowers the trap depth along the optical guide axis and favors the progressive spilling of atoms, and (ii) it accelerates the atoms coupled into the guide, similar to gravity for standard non guided atom lasers. Note that unlike gravity, we can control and even turn off this inhomogeneous magnetic field at will.

The figure of merit for a guided atom beam is the number of transverse modes that are populated. We cannot measure directly those populations, but we have access to the mean excitation number of the transverse modes $\langle n \rangle$. Using the virial theorem for a non interacting beam [27] in a harmonic guide, one can show that the transverse

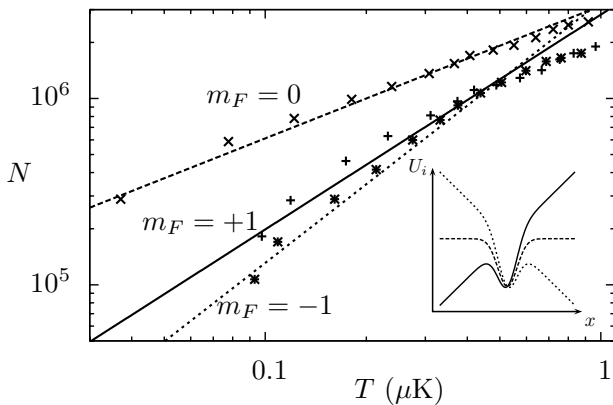


FIG. 2: Spin distillation. Number of atoms in each spin state versus temperature during the evaporation process, showing the sympathetic cooling and purification of $m_F = 0$ down to degeneracy. The purification is due to a horizontal magnetic field gradient, applied during the evaporation ramp. This field induces a force on $m_F = \pm 1$ that reduces the effective depth that they experience (see inset, U_i is the potential experienced by an atom in a m_i Zeeman sublevel ($i = -1, 0, +1$)).

velocity distribution Δv obeys:

$$\frac{1}{2}m(\Delta v)^2 = \frac{\hbar\omega_z}{2} \left(\langle n \rangle + \frac{1}{2} \right). \quad (1)$$

To infer $\langle n \rangle$ requires measurement of Δv and ω_z along the vertical axis. We measure the trap frequency ω_z of the optical guide by observing the center of mass oscillation of an atom cloud prepared at this location. We give a momentum kick to the cloud from the fast switch off (< 1 ms) of the magnetic field used for distillation. Fig. 3(a) shows the Fourier transform of the oscillations from which we infer a trap frequency of $\omega_z = 2\pi \times (245 \pm 10)$ Hz.

The velocity dispersion Δv is inferred from a TOF measurement. We integrate the absorption images along the atom laser propagation direction over one millimeter i.e. on a distance over which the transverse frequency is constant within few percent. The resulting one dimensional profiles are fitted with a Gaussian function to find the width $\Delta x(t_0)$, t_0 being the TOF duration. We then find Δv through the relation $(\Delta x(t_0))^2 = (\Delta x_0)^2 + (\Delta v)^2 t_0^2$. A typical fit and TOF measurement can be seen in the inset of Fig. 3(b).

Using Eq. 1, we find $\langle n \rangle = 0.8 \pm 0.3$ for guided atom laser of atoms in $m_F = -1$, and $\langle n \rangle = 0.65 \pm 0.05$ for $m_F = 0$. Note that, taking into account the two dimensions of the guide, the number of transverse modes populated scales as $\langle n \rangle^2$, this quantity can thus be considered as a measurement of the quality of the transverse mode. From our data, we conclude that this quality is preserved as the beam propagates in the optical guide over several millimeters. We have therefore produced a quasi-monomode guided atom laser for all Zeeman states.

The control of the output flux is also a crucial issue for

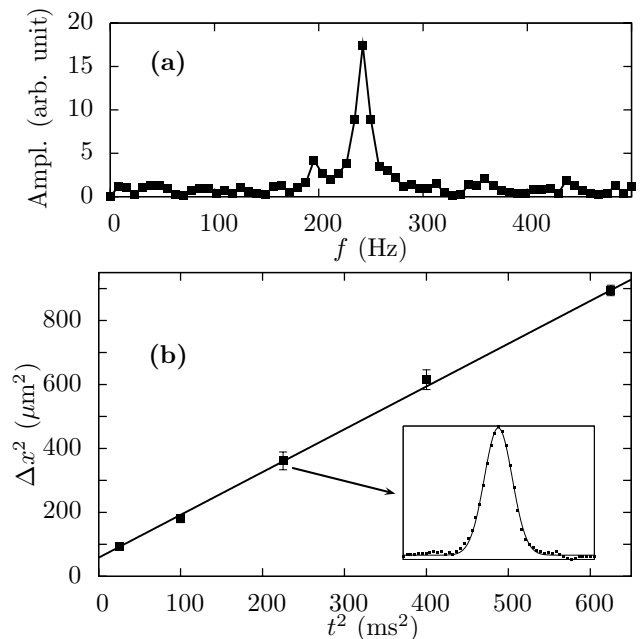


FIG. 3: (a) Fourier transform of atom cloud oscillations in the waveguide. The peak has a frequency of 245 Hz and a width of 10 Hz. (b) Plot of measurements of $(\Delta x(t))^2$ against t^2 for the time of flight expansion of the atom laser, and the straight line fit to the data, from which we infer the velocity dispersion $\Delta v = 1.2$ mm/s. Inset: Example of Gaussian fit to integrated data, for a 15 ms TOF.

applications. Its variation as a function of time can be extracted from the absorption images of Fig. 1(b). Those images are taken after a 15 ms time of flight in absence of any magnetic force. An atom that experiences the mean acceleration \bar{a} ($= \mu_B b / 2m$ for $m_F = -1$ atom) where $b = 20$ G/cm during a time τ , is located after a time-of-flight of duration t_0 at $y - y_0 = \bar{a}\tau^2/2 + \bar{a}\tau t_0$, where y_0 is the point of outcoupling. From the absorption images we have directly access to the mean linear atomic density $n[y]$ along the propagation axis. The flux is thus given by [28]: $\Phi(\tau) = n[y(\tau)](dy/d\tau)$. We have shown in Fig. 4 two examples of the flux as a function of time, deduced from the measured density in the absorption images of a guided atom laser in $m_F = 0$ and in $m_F = -1$. The mean flux is on the order of 5×10^5 atoms/s. For our experimental sequence, the magnetic force is smaller for the $m_F = 0$ state compared to $m_F = -1$ state, and the smaller outcoupling rate yields a nearly constant output flux for $m_F = 0$. During the outcoupling process, the flux is determined by the chemical potential which is equal to the trap depth. Therefore, to have the flux constant and stable over a long time would require precise control of beam power and position, and the magnetic field gradient, over the entire outcoupling. We observe fluctuations of the time at which outcoupling starts, that are on the order of 10 ms.

To overcome this limitation and to remove the residual

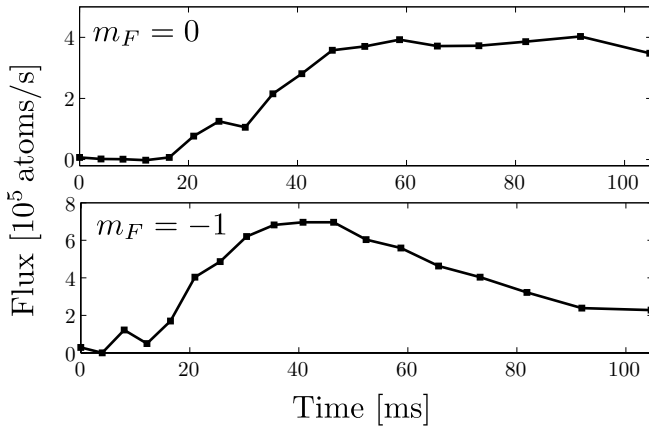


FIG. 4: Flux of atom laser versus time for guided atom laser depicted in Fig. 1(b) in $m_F = 0$ and $m_F = -1$ spin state.

multimode character of the atom laser, we envision two main improvements for future experiments: (i) a position locking scheme for the guide with a bandwidth of a few kHz, and (ii) a more adiabatic outcoupling by shaping the ramp of the magnetic field, which would require a numerical optimization by solving the three-dimensional Gross-Pitaevskii equation.

In conclusion, we have succeeded in smoothly coupling

an optically trapped BEC to a horizontal optical guide with low transverse excitation. The near monomode nature of the atom laser will be important in all applications which use phase engineering such as matter-wave holography [23]. A guided atom laser is an ideal tool to investigate the transmission dynamics of coherent matter waves through different structures. Such studies have their counterpart in electronic transport phenomena, including the generalization to cold atoms of Landauer's theory of conductance [24], the atom-blockade phenomenon [4], non-linear resonant transport [5]. Guided atom lasers in magnetically sensitive states are ideal to combine with magnetic structures, such as on atom-chips [25].

Finally, we emphasize that this work, combined with a continuous replenishing of the optical dipole trap, is a promising strategy to generate a continuous guided atom laser [26].

We thank C. Cohen-Tannoudji for useful comments, and I. Carusotto for fruitful discussions. Support for this research came from the Délégation Générale pour l'Armement (DGA, contract number 05-251487), the Institut Francilien de Recherche sur les Atomes Froids (IFRAF) and the Plan-Pluri Formation (PPF) devoted to the manipulation of cold atoms by powerful lasers. G. R. acknowledges support from the DGA, and M. J. from IFRAF.

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- [27] The outcoupled beam is in the low collisional regime $(n_{LA})^{1/2} \lesssim 0.3$ [3].
- [28] The classical reasoning performed here is justified since the length scales of interest are much larger than the quantum length $\ell = (\hbar^2/m^2\bar{a})^{1/3} < 1 \mu\text{m}$ on which the Airy-like wave function oscillates.