Design for an optical cw atom laser

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A new type of optical cw atom laser design is proposed that should operate at high intensity and high coherence and is possibly capable of recording low temperatures. It is based on an “optical-shepherd” technique, in which far-off-resonance blue-detuned swept sheet laser beams are used to make new types of high-density traps, atom waveguides, and other components for achieving very efficient Bose–Einstein condensation and cw atom laser operation. A shepherd-enhanced trap is proposed that should be superior to conventional magneto-optic traps for the initial collection of molasses-cooled atoms. A type of dark-spot optical trap is devised that can cool large numbers of atoms to polarization-gradient temperatures at densities limited only by three-body collisional loss. A scheme is designed to use shepherd beams to capture and recycle essentially all of the escaped atoms in evaporative cooling, thereby increasing the condensate output by several orders of magnitude. Condensate atoms are stored in a shepherd trap, protected from absorbing light, under effectively zero-gravity conditions, and coupled out directly into an optical waveguide. Many experiments and devices may be possible with this cw atom laser.

One of the remaining challenges of ultralow-temperature research with atomic vapors is the achievement of a truly cw atom laser. This problem has resisted solution since the time of the first demonstration of Bose–Einstein condensation (BEC) in 1995 with magneto-optic traps (MOTs) and evaporative cooling from purely magnetic traps (1–2). Crude pulsed atom lasers were made shortly thereafter by using similar magnetic techniques (3–5).

Recent attempts to achieve cw atom lasers by combining magnetic techniques of BEC formation with optical tweezer techniques for transporting and combining condensates succeeded in demonstrating sustained B–E condensates (6, 7). Serious problems still remain to be overcome, mainly having to do with insufficient atoms, before a useful cw atom laser is achieved. Proposed here is a design of a viable cw atom laser with mainly optical techniques. This design uses new types of optical traps and waveguides based on so-called “optical–shepherd” beams, which should be superior to the currently used standard MOTs and magnetic traps. Shepherding involves use of thin reflective blue-detuned sheet beams to make box-like atom traps and waveguide structures to confine and move atoms at controlled velocities. The sheet beams are made by cyclically sweeping Gaussian beams in space at a sufficiently rapid rate so that the beams act as fixed repulsive walls for slow-moving atoms. The sweeping shepherd beams can be controlled electronically by using well known beam-scanning technology, as discussed later. With shepherd beams one can make complex optical structures with strikingly new capabilities, such as high-density dark-spot optical traps and the ability to capture and recycle evaporatively cooled atoms, essentially canceling the effect of gravity on atoms. This capability leads to the design of a powerful, highly coherent, optical cw atom laser operating at very low temperatures.

Advantages of Optical Trapping and Cooling Techniques

Insight into the problems of making a cw atom laser and how to solve them can be gained by examining the history of optical trapping and comparing the relative advantages of optical and magnetic trapping and cooling techniques.

The discovery of stable optical trapping of neutral particles (8) and the understanding of the properties of the basic optical scattering and dipole forces on neutral particles and atoms (9–11) date back to the 1970s. By 1980 the basic principles of optical atom trapping and cooling were well understood (11–13), and the foundations of “atom optics” were laid (14). A key concept in proposed optical dipole force traps and shepherding was detuning far from resonance to avoid saturation and scattering force heating (11, 13).

The first demonstration of optical molasses cooling of atoms was made in 1985 (15), followed by the first optical dipole trapping of ~1,000 sodium atoms in 1986 (16). Soon thereafter the first MOTs were introduced. These hybrid magnetic scattering force traps initially confined >107 atoms (17, 18). At this point work on optical dipole traps essentially ceased while MOT-type traps and, later, dark-spot MOTs became the workhorse traps for collecting and cooling large numbers of atoms to Doppler and subDoppler temperatures (19–21).

In the late 1980s many new applications of ultracold atoms were pursued and searches began for methods to reach the high densities and low temperatures needed to achieve BEC (20, 22). Achievement of BEC in 1995 (1, 23) led to an explosion of interest in the physics of these novel quantum systems and their applications (24, 25). Experiments with B–E condensates also brought a further appreciation of some of the many advantages of optical dipole traps and optical manipulation techniques over magnetic techniques. With optical traps, one can confine all hyperfine states, both low- and high-field seekers (26). This ability made sophisticated experiments in spintronics possible (27) in dipole traps using condensates transferred from large-volume magnetic traps (28). With dipole traps the trapping parameters are independent of externally applied magnetic fields. This property made possible the first observations of Feshbach resonances (29, 30). It was shown that evaporative cooling was possible in dipole traps (31) and efforts were made to reach BEC in all-optical traps (31), but the original densities were too low. Finally, in 2001, Barrett et al. (32) succeeded in demonstrating BEC in all-optical traps, although the final number of condensate atoms was small. More recently, Granada et al. (33) used an all-optical technique to produce a degenerate Fermi gas.

The optical shepherd techniques described here have evolved from the original work in atom optics on the focusing and defocusing of atoms by laser beams (14), and, more recent experiments, on atom guiding in TEM01* mode beams (34), trapping of atoms with a donut-mode beam (35), and experiments with “atom-optics billiards” (36). Relevant experiments were also performed involving the trapping of macroscopic particles in spatial arrays and in a “light-cage” by scanning a pair of computer-controlled galvo mirrors (37, 38).

Fig. 1 shows a cross-sectional sketch of the proposed cw atom laser in 87Rb, fabricated from shepherd beams. The first step in achieving BEC is the collection of atoms in a molasses-cooled trap. This usually involves capturing atoms from an atomic vapor source in a MOT, which simultaneously traps and molasses cools atoms. Here, we enhance performance of the MOT by the...
addition of a cubic, blue-detuned shepherd trap \( \approx (1.4 \text{ cm})^3 \) surrounding the spherical MOT volume, as shown. Atoms in a standard MOT feel a linearly decreasing trapping force as the radius decreases, whereas the average shepherding force is highly localized and can be larger than the MOT force and actually increases with decreasing distance from the origin because of the increase in light intensity as the shepherd beams shrink. These considerations imply an ability to collect all the atoms of the MOT and compress them at higher speeds to higher densities by shrinking the repulsive walls of the shepherd-type trap. One concludes, therefore, that shepherd enhanced MOTs should be superior to conventional MOTs as a source of cold atoms.

Looking at the number of Rb atoms typically collected in a MOT, one conservatively expects, by using shepherding, to surround \( \approx 3 \times 10^7 \) atoms cooled to a temperature approaching \( T_D \approx 140 \mu \text{K} \) in a volume of \( \approx (1.4 \text{ cm})^3 \), in \( \approx 2 \text{ s} \) or less, at \( \approx 10^{-6} \) Torr (35). Next, the shepherd beams surrounding \( V_6 \) are rapidly collapsed, as indicated by dotted lines, compressing the molasses-cooled atoms into the volume \( V_1 \). For a volume of \( V_1 \approx 350 \mu \text{m} \times 350 \mu \text{m} \times 9 \text{ mm} \) and \( 3 \times 10^7 \) atoms, we have a density of \( 2.7 \times 10^{10} \) atoms per cm\(^3\).

To take full advantage of the shepherd beam’s ability to rapidly compress atoms in the MOT volume we have to prevent atom pileup as the shepherd pushes the slow-moving atoms diffusing in molasses. By chopping the MOT molasses beams as the shepherd beams advance, one can periodically undamp the atoms and keep the density uniform. Compression times of a few tenths of a second are anticipated to reach volume \( V_1 \).

It should be stressed that the figure of merit for an atom source is not just the maximum number of atoms that can be collected, but rather the maximum number of atoms per s that can be collected.

Because the conditions are not optimal for producing BEC at the typical vapor-source pressures of \( \approx 10^{-5} \text{--} 10^{-4} \) Torr, it is desirable to adopt a double-dipole trap arrangement that separates and optimizes the initial process of trapping thermal-source atoms from the final condensation process at pressures of \( \approx 10^{-9} \text{--} 10^{-11} \) Torr, or even lower. With this scheme atoms are transported along the 350-\( \mu \text{m} \)-square waveguide of Fig. 1, as a unit, in a fraction of a second, by using a pair of pusher shepherd beams. This transport is analogous to the standard double-MOT procedure (39, 40). However, instead of the long, losy magnetic atom guides commonly used to isolate high- and low-vacuum chambers, one can use a simple, \( \approx 250-\mu \text{m} \) pinhole in a thin antireflection-coated septum between the chambers and the shepherd waveguide to reach high-vacuum conditions at a distance of only \( \approx 1 \text{ cm} \) into the high-vacuum region, with no loss of atoms.

### Cooling Stages Leading to cw Atom Laser in High Vacuum

Once in the high-vacuum chamber, cooling follows several distinct stages leading to BEC and a highly efficient optical cw atom laser: (i) molasses cooling of input atoms moving through \( V_1 \) to \( V_2 \); (ii) polarization gradient cooling (PGC) of atoms in volume, \( V_{\text{PGC}} \), and their compression into \( V_3 \); (iii) preevaporative cooling from \( V_3 \) into the \( V_{\text{PGC}} \) chamber, followed by evaporative cooling from \( V_3 \) into the \( V_{\text{evap}} \) chamber to form a B–E condensate in \( V_5 \) (included in the cooling step are atoms fed back to \( V_3 \) from the previous evaporation cycle); and (iv) the feeding of condensed atoms from \( V_5 \), through \( V_5 \) and \( V_4 \) to the laser storage volume \( V_3 \) and the coupling out of cw laser atoms.

In the first stage (i) of high-vacuum cooling, the \( \approx 3 \times 10^7 \) atoms collected in \( V_1 \) from the vapor source are pushed through the molasses volume \( V_1 \) at a constant density of \( \approx 10^{11} \) atoms per cm\(^3\) and cooled to a temperature approaching the Doppler limit temperature of Rb, \( T_D \approx 143 \mu \text{K} \).

In the second stage (ii), the \( \approx 5 \times 10^7 \) atoms are advanced, maintaining the same density of \( \approx 10^{11} \) atoms per cm\(^3\), into volume \( V_2 \) located at the entrance of the \( V_{\text{PGC}} \) all-optical shepherd trap. The \( V_{\text{PGC}} \) trap is used to cool the atoms in the PGC volume \( V_{\text{PGC}} \) to temperatures of \( \approx 10\text{--}20 \mu \text{K} \), as seen by Barrett et al. (32) and Granada et al. (33) and compress them to densities of \( \approx 10^{14} \) atoms per cm\(^3\), in preparation for subsequent evaporative cooling. Included in this second cooling stage, however, is also a large number of atoms, \( \approx 10^9 \text{--} 10^{10} \), which have been collected in \( V_{\text{PGC}} \) and \( V_{\text{evap}} \) and fed back to \( V_3 \) from the previous evaporation cycle. The handling of such a large number of atoms presents a problem. Experience with MOT cooling at densities in excess of \( \approx 10^{11} \) atoms per ml shows that difficulties arise from reabsorption of spontaneously emitted fluorescence (19, 40, 41). Use of a “dark-spot” MOT (19), with a dark core of atoms, reduced absorption, and increased the density of cooled atoms by an order of magnitude.

In this proposal, as shown in Fig. 1, one starts with six PGC beams surrounding the 300-\( \mu \text{m} \times 1.3 \text{ cm} \times 1.3 \text{ cm} \) \( V_{\text{PGC}} \) volume. An optical dark-spot trap \( V_2 \) is formed by sweeping a focused \( w_0 = 55-\mu \text{m} \)-diameter red-detuned CO\(_2\) laser beam transversely over a width of 330 \( \mu \text{m} \) inside the \( V_{\text{PGC}} \) volume. Atoms in \( V_{\text{PGC}} \) are combined with atoms from \( V_{\text{evap}} \) and \( V_2 \) for cooling and compression by turning off the trap wall \( W_1 \) of \( V_2 \) and gradually lowering the potential of wall \( W_2 \) of \( V_{\text{evap}} \). This process is done while keeping the average atomic density in the cooling volume at \( \approx 10^{11} \) atoms per cm\(^3\). The atoms in \( V_{\text{PGC}} \) are quickly cooled to their minimum PGC temperature and should start to diffuse.

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**Fig. 1.** Improved cw optical atom laser design. This design features a double-vacuum chamber separated by a septum, a separate molasses and PGC region, and a recirculating evaporative cooling chamber; all in an optical waveguide.
into the deep-red-detuned dipole storage trap $V_3$, where they are collected at high density. A final stage in this filling process involves shrinking the surrounding shepherd walls of $V_{\text{evap}}$ and $V_{\text{PGC}}$ to collect all of the remaining atoms and feed them into the red-detuned dipole trap $V_2$. Although not driven by shepherd beams, similar filling behavior into a red-detuned optical trap was observed in the experiments of Barrett et al. (32) and Thomas and collaborators (33). Barrett et al. (32) were able to transfer PGC-cooled Rb atoms into their dipole trap, achieving the high density of $\sim 10^{10}$ atoms per cm$^3$. They offer several explanations for this successful behavior: the damping of atoms in the tails of the red-detuned dipole potential; the formation of an effective dark-spot MOT due to the Stark shift of the red-detuned trap; and, possibly, the existence of some blue-detuned Sisyphus cooling (42). An important aspect of the buildup of high density in the red-detuned trap is the thermalization of atoms captured in the fringes of the trap by two-body collisions. Any atoms that gain energy in such collisions and leave the trap are recooled in the PGC volume by the PGC molasses beams and eventually returned to the red trap.

Here, as an additional aid to the CO$_2$ trap-filling process, one may resort to chopping of the cw PGC beams at a rapid rate. With the trapping beam turned on, and the damping beams turned off, atoms move freely and are drawn into the CO$_2$ trap and move more rapidly toward the focus, where they can thermalize. With the cooling on and the trap on, the atoms are damped down to PGC temperature, where they only can move diffusively everywhere except near the red-trap focus, where they are Stark-shifted out of resonance. As the process continues, the atoms follow this alternating free motion toward the focus and the diffusive damping motion. Finally, all the atoms collect in the red trap, with the help of the shrinking shepherd beams. This chopping technique is somewhat reminiscent of the first optical trapping experiment (16).

The principal reason optical dark-spot cooling is superior to dark-spot cooling in MOTs is that the optical dark-spot is a true trap that prevents PGC-cooled atoms from reentering the PGC volume.

Stamper-Kurn et al. (28) were also able to transfer a sodium condensate directly from a large-volume, low-density magnetic trap into a high-density, compact red-detuned dipole trap. Densities as high as $2 \times 10^{10}$ atoms per cm$^3$ were observed.

The dimensions of the red-detuned CO$_2$ trap were selected to give a final density in the $10^{12}$–$10^{14}$ range. With an assumed trap $U/kT_{\text{atoms}} = 160 \mu$K/20 $\mu$K $= 8$, it is estimated that $\sim 7.5 \times 10^8$ atoms are compressed in $V_2$ to a density of $7 \times 10^{13}$ atoms per cm$^3$. Compression times of a second or less should be sufficient to reach this density at PGC temperatures. At this point the PGC molasses beams are turned off.

The third stage (iii) in producing a cw atom laser, the evaporative cooling stage, involves a large departure from conventional practice. In previous work on evaporative cooling to BEC with magnetic traps and optical traps, one evaporated the high-energy component of trapped atoms into free space, thereby cooling the remaining atoms in the trap (1, 2). For example, for Rb atoms in magnetic traps, many groups have started with $\sim 2 \times 10^7$ to $5 \times 10^9$ atoms and ended up with condensates having $10^4$ to $2 \times 10^5$ atoms at temperatures in ranging from 100 to 500 nK after cooling times of 20–45 s. Typically, 100–1,000 or more atoms are evaporated away and lost for every cold condensate atom remaining in the magnetic trap. This is a very inefficient process.

In this proposal involving atom feedback with shepherd beams, starting with a modest source of $3 \times 10^9$ atoms at the input from $V_2$, assuming a moderate feedback ratio $r = 0.99$, corresponding to 900 atoms fed back for every condensed atom that remains in $V_3$, one expects to collect and recirculate $\sim 3 \times 10^9$ atoms internally. The feedback effectively increases the source by a factor of 100. Under equilibrium conditions, this result implies an output yield of $\sim 3 \times 10^8$ condensate atoms in the final volume $V_3$ per evaporation cycle, assuming no other losses. This calculation may not be totally realistic with high densities of $\sim 10^{13}$–$10^{14}$ atoms per cm$^3$ in $V_2$, $V_3$, and $V_2$, because of some loss from three-body recombinations.

One can analyze the feedback and buildup of internally circulating atoms, $N_m$, in $V_2$ after $m$ cycles as a geometric series, $N_m = \Sigma a r^m$ from $n = 0$ to $n = m - 1$. To see the correctness of this formula, one can rewrite $N_m = a + \Sigma a r^m$ from $n = 1$ to $n = m - 1$. This equation says that the number of atoms in the $m$th cycle is made up of “a” from the input plus the fraction $r$ times the population in the $(m-1)$th cycle. After a large number of cycles, $N_m$ approaches $N_m = a/(1 - r)$, whereas a number of atoms $(1 - r) N_m = a$ is effectively lost to the output and recombination. This formally accounts for all of the atoms. However, it cannot determine the division of the so-called “lost” atoms between the output of condensed atoms and recombinations, without additional data.

To recapitulate numerically, for a case with no recombination loss, having an input of $a = 3 \times 10^8$ atoms and $r = 0.99$, one gets $N_m = 100 = 3 \times 10^8$ atoms and an equilibrium condensate output of $3 \times 10^7$ atoms. For a case including recombination loss, $a = 3 \times 10^8$ and an assumed $r = 0.96$, one gets recirculating atoms $N_m = a/(1 - r) = 25a = 7.5 \times 10^8$ atoms and a total of $3 \times 10^7$ atoms divided between condensate atoms and atoms lost to recombination. Experimental results for evaporative cooling from a magnetic trap of fixed volume show that the temperature falls approximately linearly with the number of evaporated cycles (41, 43). Thus, if one wants a final temperature $T = 0.15$ $\mu$K, starting from $7.5 \times 10^8$ atoms at $20 \mu$K, this calls for a final number of atoms $(7.5 \times 10^8)/(20 \mu K/0.15 \mu K) = 5.6 \times 10^8$. This, in turn, implies a loss of atoms due to three-body recombination of $3 \times 10^7 - 5.6 \times 10^8 \approx 2.4 \times 10^7$ atoms.

With optical cooling from a shepherd trap, where one can optimally adjust the density and trap proportions during evaporation, one expects to achieve even lower temperatures. Thomas and colleagues previously indicated that evaporation from optical traps has advantages over that from magnetic traps (33). Considering the experimental results of Burnett et al. (32), one anticipates reaching temperatures of 0.10 $\mu$K or less after approximately 2 s of evaporation time. Ultimately, it is the loss of atoms that limits the lowest achievable temperatures by using evaporative cooling. One simply runs out of atoms.

In practice, one performs the optical evaporative cooling in two stages. In the first stage one preevaporates from the $V_2$ red-detuned CO$_2$ laser trap back into $V_{\text{PGC}}$, starting at $\sim 7.5 \times 10^8$ atoms and $T_{\text{atoms}} = 20 \mu$K. Conservatively, assuming performance comparable with magnetic evaporation, one should be able to cool down to $T_{\text{atoms}} = 2.7 \mu$K, ending up with $\sim 1 \times 10^8$ atoms. As one reduces the $V_2$ potential in preevaporation, one reduces the transverse sweep of the CO$_2$ trapping beam to help maintain optimum density. The escaping atoms leaving $V_2$ trampoline over the lower surface of $V_{\text{PGC}}$ and very few return to interfere with the evaporative process.

Next, the potential and width of the CO$_2$ trap are increased and the remaining $\sim 1 \times 10^8$ atoms are lifted into the $V_{\text{evap}}$ chamber, where they are surrounded by $V_3$, a box-like 4880 Å blue-shepherd trap in preparation for the second step of forced evaporative cooling down to BEC. The dimensions and potential of the box-like $V_3$ trap are chosen to enclose essentially all the $1 \times 10^8$ atoms at the same density and, therefore, temperature, as in $V_2$ after preevaporation.

Gravitational forces often play a considerable role in the dynamics of ultracold atoms. With a box-like blue-detuned shepherd trap, the possibility exists of buildup of excessively high densities at the lower repulsive wall. One can avoid such difficulties by simply canceling gravity within the 4880 Å sheep-
herd trap by fabricating a blue shepherd intensity ramp with a constant upward gradient force equaling gravity. The gravity ramp keeps the density uniform within $V_3$ during evaporative cooling and subsequent condensate manipulation. Gravity ramps are likely to find other important applications, using ultralow-temperature atoms and condensates.

In the second stage of forced evaporative cooling, starting from the 4880 Å blue-detuned $V_3$ trap with $1 \times 10^8$ atoms and $T = 2.7 \, \mu K$, one ends up with a condensate of $5.6 \times 10^6$ atoms at a temperature of $T = 0.15 \, \mu K$ or less. The dimensions of $V_{evap}$ are chosen to be large enough so that very few of the evaporating atoms return to $V_3$ and $V_2$ and interfere with the production of the condensate. This is due to the small volume of $V_3$ relative to $V_{evap}$ and also the long time of flight for evaporated atoms to reach the outer walls and return.

A matter of further interest is the time it takes for the cw atom laser to reach full output after being turned on. The analysis above shows that for $r = 0.96$ it takes $\approx 64$ feedback cycles to reach 93% of $N_e$, the equilibrium output. If each cycle is $\approx 5$ s long, this implies a startup time of 320 s or $\approx 5$ min.

The last step (iv) in making a cw atom laser involves guiding the condensate a distance $<2$ mm from its source in $V_3$ into the final storage volume $V_4$ from which it is continuously coupled out. This, however, must be done under effectively dark conditions, free of any destructive resonant or near-resonant light from other parts of the optical structure. The guiding of the condensate can be done with appropriate $\pm y$ and $\pm z$ beams. An opaque light shield protects the condensate in $V_4$ and $V_3$, from resonance light coming from the molasses and PGC volumes during subsequent cycles.

One sees, in step iv, that use of shepherding with all-optical traps gives a solution to the problem of effectively sustaining a condensate in the dark that is superior to the one used by Chikkatur et al. (6).

If the final storage volume $V_4$ contains five times the number of atoms of $V_4$, for example, then the maximum change in the number of atoms in $V_4$ during any cycle will be much less than 20%. One can essentially eliminate all fluctuations with a simple feedback setup. By sensing the fluctuations in output and controlling the number of atoms being vented from the storage volume by a separate venting port, one can stabilize the output at the expense of a small loss in output. A stabilized condensate such as this in $V_4$, with minimal perturbations, should have high spatial and temporal coherence (6). Atoms can be coupled out of $V_4$ by adjusting the output sheet beam potential. They can then go directly into the shepherd waveguide at a rate equal to the average rate of atoms being fed in from $V_4$. For the case of $5.6 \times 10^6$ atoms entering $V_4$ per cycle and a total estimated cycle time of $\approx 5$ s one expects a cw output flux of $5.6 \times 10^4$ atoms every 5 s, or $\approx 1.1 \times 10^5$ atoms every s. The breakdown of the total $\approx 5$ s cycle time is: $\approx 2$ s to collect source atoms and transfer them to $V_5$ plus $\approx 1$ s for preevaporation and transfer to $V_5$, and $\approx 2$ s of evaporation time to reach $V_3$ and $V_2$. One anticipates a final temperature of 0.1 $\mu K$ or less, as indicated above. Picokelvin temperatures are conceivable if one accepts lower output flux.

It has been pointed out for red-detuned optical trapping that an additional heating source exists because of fluctuations in the power and pointing direction of the trapping beam (44). Beam fluctuational heating should be much reduced for blue box-like shepherd traps, as in $V_4$, because atoms in such traps interact with the repulsive light walls at much lower light intensities and for only a fraction of the time. Laser noise introduced by mechanically driven moving lenses (7) should be much reduced by using electronically driven shepherd beams.

Possible Applications

A viable cw atom laser would result in novel designs for precision interferometers and devices, such as gyroscopes, gravimeters, and high-precision atomic clocks. In addition, they could be used as a superior source for the sympathetic cooling of other atomic vapors and in two-component Fermi mixtures (43, 44). Observation of the very-low-temperature Cooper-pairing transition (33, 44) may also be possible with the proposed very-low-temperature cw optical laser.

It becomes possible to study the Josephson effect in waveguide-confined B–E condensates that are the exact analog of the DC and AC Josephson effect (45). Applications are also conceivable to optical computing involving arrays of atoms in optical lattices in atom waveguides.

Finally, the atom laser itself could serve as an ideal experimental tool for detailed studies of the processes of atom collection from the vapor, PGC rates at high density with dark-spot traps, and controlled optical evaporative cooling at high densities and very low temperatures.

Apparatus

Fig. 24 shows the scheme for making a thin, moveable, repulsive light mirror from a single blue-detuned laser beam. A blue-detuned beam strikes a computer-controlled gimbaled mirror, M, for example, located at the focus, $O_a$, of a thin lens, L, and is rotated at a uniform angular rate by a saw-tooth drive in voltage having an amplitude, $a_v$, thus forming a scanned sheet mirror beam. If the mirror M is moved downward off axis in the focal plane, the rays of the sheet beam are then tipped upward. One can repeatedly translate the sheet mirror in a direction perpendicular to the plane of the mirror by rotating the mirror M about an orthogonal $\varphi$ axis with an $a_v$ voltage waveform, as shown in Fig. 2B. Using two orthogonal pairs of scanned sheet mirror beams, we can form an optical waveguide for atoms having an adjustable rectangular cross section, as shown in Fig. 3. Samples of atoms can be translated along such an optical waveguide by advancing a pair of sheet mirror beams while the beams are held at constant separation, as mentioned above.

The beam-sweeping elements just described can be fabricated by using either microelectro-mechanical mirror-type devices...
(MEMs), or acousto-optic deflectors (AODs), or galvo mirrors. Microelectromechanical mirror-type devices and acousto-optic deflectors act as electronically controlled gimbaled mirrors and can deflect in θ and φ directions. Galvo mirrors are single deflectors and must be used in pairs in conjunction with cylindrical lenses to give deflections in orthogonal directions. The relevant beam-deflection design parameters are the angular amplitude and the frequency responses of the different scanners. Beam-steering techniques are well developed.

Implementation of the atom laser of Fig. 1 should be fairly straightforward with these elements. Fig. 4A shows how one feeds an essentially parallel Gaussian beam into lens L1 to generate a focused beam of diameter, 2ω0, in the z direction, which is then swept. Fig. 4B is a perspective sketch of the entire atom laser apparatus, showing the location of all the most important Lx, Ly, and Lz lenses of varying aperture and focal length. With the Lx lenses pointing in the x direction, one can project the xz waveguide surfaces and xy sheet beam surfaces of the structure. The Ly lenses pointing in the y direction form the yz waveguide surfaces and also xy sheet beam surfaces.

The laser beam parameters needed to fabricate different parts of the apparatus vary according to the local geometry and temperature of the guided atoms. The following basic equations can be used to determine the optical potential, U, the saturation parameter, p, and the fraction of time that an atom spends in the excited state.

\[ U = \frac{\hbar}{2(v - \nu_0)\ln(1 + p)} \]

\[ p(v) = \frac{I_0}{I_{sat}}\left[\left(\frac{\gamma_n}{4}\right)/(v - \nu_0)^2\right] \]

\[ f = \frac{1}{2} \left[\frac{p}{1 + p}\right] \]

For a single Gaussian beam of the form \( I(r) = I_0 \exp(-2r^2/\omega_0^2) \), one determines these parameters in terms of the total power, \( P_0 \), the spot size, \( \omega_0 \), and the detuning from resonance \((v - \nu_0)\). The intensity \( I_0 \) on the beam axis is \( 2P_0/\pi\omega_0^2 \). \( I_{sat} \) and \( \gamma_n \) are the saturation intensity and line width of the atomic transition. See refs. 9, 11, and 13.

For a shepherded Gaussian beam swept uniformly over a total distance, \( L_{tot} \), large compared with \( \omega_0 \), the peak intensity \( I_0 = (2P_0/\pi\omega_0^2)\left[\pi/2\right]^{1/2} \omega_0/L_{tot} \).

Initially, atoms are collected from the vapor in the relatively high-pressure regions \( V_0 \) and \( V_1 \) of a (1.4 cm³) shepherded MOT, using a pair of swept 250-mW Ti:sapphire beams with \( \omega_0 = 50 \mu m \) and saturation parameter \( p = 0.1 \), giving a blue-detuned peak wall potential of \( U_0 = 14 h\gamma_n/2 \). The same shepherd beams guide the molasses-cooled atoms through volumes \( V_1 \) and into \( V_2 \) in the low-pressure region.

One sees in Fig. 1 that an atom leak may occur because of the shadow cast by the thin septum dividing the high- and low-pressure chambers. This can be avoided by launching two pairs of additional \( L \) beams (not shown in Fig. 4B) at an angle into the shadow region to bridge the waveguide gap.

Resonance fluorescence from atoms in the \( V_0 \), \( V_1 \), \( V_1 \), and \( V_2 \) can cause heating of previously evaporated atoms being held in \( V_{PGC} \) and \( V_{evap} \) by far-off-resonance shepherd beams from the earlier cooling cycle. To prevent such heating and possible atom loss, once a new collection cycle is started, one switches from the far-off-resonance \( V_{PGC} \) and \( V_{evap} \) shepherd traps to PGC-cooled near-resonance traps, having the same shepherd beam parameters as used for \( V_1 \), \( V_1 \), \( V_0 \), and \( V_2 \).

The CO2 red-detuned trap \( V_2 \) used to collect PGC-cooled atoms at \( \approx 20 \mu K \) is formed from a 125-W beam with \( \omega_0 = 55 \mu m \), swept over a width of \( \approx 330 \mu m \), giving a trap depth of \( U_0 = 8 \times 20 \mu K = \)

\[ \frac{\hbar}{2(v - \nu_0)\ln(1 + p)} \]

\[ \frac{I_0}{I_{sat}}\left[\left(\frac{\gamma_n}{4}\right)/(v - \nu_0)^2\right] \]

\[ \frac{1}{2} \left[\frac{p}{1 + p}\right] \]

For a single Gaussian beam of the form \( I(r) = I_0 \exp(-2r^2/\omega_0^2) \), one determines these parameters in terms of the total power, \( P_0 \), the spot size, \( \omega_0 \), and the detuning from resonance \((v - \nu_0)\). The intensity \( I_0 \) on the beam axis is \( 2P_0/\pi\omega_0^2 \). \( I_{sat} \) and \( \gamma_n \) are the saturation intensity and line width of the atomic transition. See refs. 9, 11, and 13.

For a shepherded Gaussian beam swept uniformly over a total distance, \( L_{tot} \), large compared with \( \omega_0 \), the peak intensity \( I_0 = (2P_0/\pi\omega_0^2)\left[\pi/2\right]^{1/2} \omega_0/L_{tot} \).

Initially, atoms are collected from the vapor in the relatively high-pressure regions \( V_0 \) and \( V_1 \) of a (1.4 cm³) shepherded MOT, using a pair of swept 250-mW Ti:sapphire laser beams with \( \omega_0 = 50 \mu m \) and saturation parameter \( p = 0.1 \), giving a blue-detuned peak wall potential of \( U_0 = 14 h\gamma_n/2 \). The same shepherd beams guide the molasses-cooled atoms through volumes \( V_1 \) and into \( V_2 \) in the low-pressure region.

One sees in Fig. 1 that an atom leak may occur because of the shadow cast by the thin septum dividing the high- and low-pressure chambers. This can be avoided by launching two pairs of additional \( L \) beams (not shown in Fig. 4B) at an angle into the shadow region to bridge the waveguide gap.

Resonance fluorescence from atoms in the \( V_0 \), \( V_1 \), \( V_1 \), and \( V_2 \) can cause heating of previously evaporated atoms being held in \( V_{PGC} \) and \( V_{evap} \) by far-off-resonance shepherd beams from the earlier cooling cycle. To prevent such heating and possible atom loss, once a new collection cycle is started, one switches from the far-off-resonance \( V_{PGC} \) and \( V_{evap} \) shepherd traps to PGC-cooled near-resonance traps, having the same shepherd beam parameters as used for \( V_0 \), \( V_1 \), \( V_1 \), and \( V_2 \).

The CO2 red-detuned trap \( V_2 \) used to collect PGC-cooled atoms at \( \approx 20 \mu K \) is formed from a 125-W beam with \( \omega_0 = 55 \mu m \), swept over a width of \( \approx 330 \mu m \), giving a trap depth of \( U_0 = 8 \times 20 \mu K = \)
160 μK. This trap confines all 7.5 × 10^8 atoms up to the average velocity within dimensions of 30 μm × 360 μm × 990 μm at an average density of about 7.0 × 10^13 atoms per cm^3.

During the subsequent preevaporation step, atoms escaping from V_2 trap are then readjusted for transfer to V_3 and subsequent forced evaporative cooling. A CO_2 power of ~20 W and a swept width of ~100 μm give a V_3 trap depth of U_0 = 90 μK and an average density of ~3.4 × 10^13 atoms per ml. The CO_2 trap is then raised to V_{evap} and placed ~75 μm above the wall dividing V_{PGC} and V_{evap}. As a way of reducing the 4880 Å power requirements for the V_3 blue trap and gravity ramp, one can first reduce the axial length of the atom cloud in the CO_2 trap from ~1,000 μm to ~500 μm by using the yz sheet beams before fully forming the 4880 Å V_3 trap and ramp. It takes ~4 W of power divided between +y and +z beams with w_0 = 3.9 μm to get an initial V_3 trap potential U_0 = 8 × 2.7 μK = 22 μK. Atoms in V_3 are maintained at uniform density by an antigravity ramp made from a +y swept 4880 Å beam of ~750 μW with w_0 = 3.9 μW.

Forced evaporation and volume compression to optimum density results in a BEC in V_3, of dimensions 40 μm × 100 μm × 38 μm, with an estimated 5.6 × 10^6 atoms at a temperature of ~0.1 μK. The evaporated atoms leaving V_3 trap are then swept 4880 Å to a plane perpendicular to the MOT axis at 45° to the y coordinate axes. The remaining two orthogonal beam pairs lie in a plane perpendicular to the MOT axis at 45° to the x axis. The three mutually orthogonal molasses beam pairs can be conveniently oriented at the so-called (1,1,1) angle of ~35° to the z axis and rotated in azimuth to avoid other obstructing lenses. The same considerations apply to the PGC beams.

**Conclusion**

The discussion above indicates that a cw atom laser, as proposed here, should be possible by using present-day technology. Such a laser should have high spatial and temporal coherence, high intensity, and low temperature. The experimental achievement of such a cw atom laser would be a truly revolutionary development in BEC research and application.