the focus due to the optical dipole force. Due to the low energy of the condensate, a few milliwatts of laser power at 980 nm were sufficient. The observed heating rate of about 100 nK/s, probably due to spatial and intensity fluctuations of the IR laser beam, was low enough to keep condensates for more than 10 seconds.

The new features of the optical trap were exploited in several studies:

1. Reversible formation of Bose-Einstein condensates. Optical traps allow precise spatial (micrometer) and temporal (microseconds) manipulation of Bose-Einstein condensates. This should allow the realization of box-shaped traps, atom guides, and optical lattices. We have used the spatial resolution afforded by optical traps to create a new "dimple" trap in which BEC was created adiabatically and thus reversibly.[2]
2. Observation of Feshbach resonances in a Bose-Einstein condensate. Optical traps have a new external degree of freedom: they can be operated at arbitrary external magnetic fields. We have used this feature for the observation of Feshbach resonances, which occur at certain magnetic fields and allow the "tuning" of atomic interactions.[3] Such resonances occur in sodium only for strong-field seeking states that cannot be confined magnetically.
3. Spinor Bose-Einstein condensates. Optical traps offer a new internal degree of freedom: the orientation of the atom's magnetic moment. This resulted in the generation of spinor condensates, condensates that populate all three hyperfine states of the F = 1 state of sodium and possess a three-component vectorial order parameter.[4] The phase diagram, the dynamics and metastability of spinor condensates depend crucially on spin-dependent interactions that were shown to be anti-ferromagnetic for sodium.

These developments were accompanied by rapid progress in the field of BEC: BEC was observed in atomic hydrogen (MIT), Bose condensates in standing waves were studied (NIST and Yale), surprising results in two-component condensates were found (JILA), and many new experiments were able to generate Bose-Einstein condensates.

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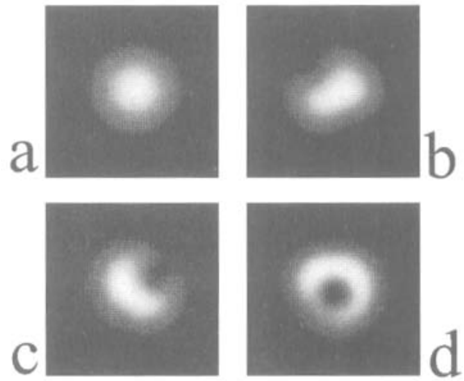
Optically Induced Coherent Rotation and Vortex Creation in Trapped Bose-Einstein Condensates

Karl-Peter Marzlin and Weiping Zhang, School of Mathematics, Physics, Computing, and Electronics, Macquarie Univ., Sydney, Australia.

The research on trapped ultracold atomic gases has become one of the most exciting areas in physics since the experimental realization of Bose-Einstein condensation (BEC) in magnetic traps (for a recent review see Ref. 1). One aspect of particular current interest is whether such gaseous atomic BEC also exhibit superfluid properties as in liquid helium.



Marzlin Figure 1. Numerical simulation of the creation of a vortex state in an anharmonic trap. The modulus squared of the collective wavefunction is shown at different times (a: 0 ms, b: 87 ms, c: 142 ms, and d: 247 ms).

The superfluidity in helium is characterized by the exsistence of persistent currents, which are associated with the formation of quantized vortices. A quantized vortex represents an energy eigenstate in which all atoms have a definite orbital anglar momentum and rotate collectively around some line. In helium, quantized vortices are easily generated by rotating the container of the fluid. However, in dilute trapped BECs, a direct rotation is impossible and other means are required to generate vortex states.

Recently we have shown how state-of-the-art atom optic techniques can be applied to create vortex states. Two different schemes based on light-induced torques were proposed to achieve this goal. The first scheme applies four largely detuned running laser beams whose phases and angles are chosen so that they produce a rotating homogeneous force acting on the BEC.[2] It turns out that this force does not create a pure vortex state if the BEC is harmonically trapped. Instead the BEC begins to rotate as a whole around the trap center, thereby preserving its shape. However, if the BEC is trapped in an anharmonic potential, an almost pure vortex state can be produced.[3] An explanation of this behavior can be given by considering the energy levels of the different trap potentials. A numerical simulation (see Fig. 1) of the creation of a vortex state in a quartic trap [$V(x) \propto x^4$] can be found at www.physics.mq.edu.au.

To circumvent the restriction to anharmonic traps we proposed a second scheme that uses Laguerre-Gaussian laser beams to rotate the BEC.[4] Such beams themselves carry an orbital angular momentum that can be transferred to the condensed atoms by using a Raman transition between two hyperfine states. The BEC is then transferred from the center-of-mass ground state and the original hyperfine state to a vortex state in the second hyperfine state. By appropriately modulating the frequencies of the laser beams to compensate the collision-induced frequency-shift of the BEC, the transfer from the ground to the vortex state can be very efficient.

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Quantum Electro-optic Control

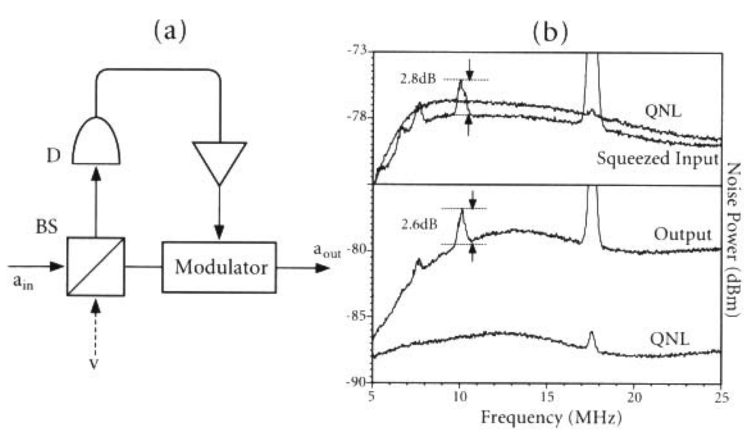
T.C. Ralph, P.K. Lam, E.H. Huntington, B.C. Buchler, D.E. McClelland, and H.-A. Bachor, Dept. of Physics, The Australian National Univ., Canberra, Australia.

The quantum optical uncertainty principle places restrictions on the accuracy with which the intensity and phase of light can be determined.[1] This in turn places quantum limits on the applications of light in high sensitivity measurements, communications, and information storage. These limits can be avoided under certain circumstances. For example, squeezed light gives improved measurement sensitivity for one observable, say, intensity with the penalty that the other observable, here phase, is less sensitive. Similarly, a quantum non-demolition (QND) device can enable a non-destructive measurement of one observable to be made at the expense of reduced information about the other.

We have recently demonstrated a new tool in the manipulation and control of light at the quantum limit,[2] whose simplicity and efficiency make it attractive for applications. The device is an electro-optic feedforward loop (see Fig. 1a). Splitting an input beam (a) at a beam splitter (*BS*) introduces quantum vacuum noise (v) onto the reflected and transmitted beams, which reduces the signal-to-noise of any information carried by the input beam. However, by detecting the reflected beam and feeding it forward, with a particular positive gain, the quantum noise can be exactly cancelled on the transmitted beam (a_{out}). In this simple form, the feedforward loop acts as a noiseless signal amplifier. The size of the signals on the output are increased by the feedforward gain without reducing signal-to-noise. This is a major improvement over linear optical amplifiers (such as laser amplifiers), which must reduce signal-to-noise for quantum limited signals.

The versatility of the feedforward loop and squeezed light can both be increased by combining them. We have shown that very fragile information carried on squeezed light can be made robust to losses by amplifying it with the feedforward loop[2] (see Fig. 1b). Also, if the output of the feedforward loop is mixed with a squeezed light source, an efficient and practical type of QND measurement can be made.[3] Although our demonstrations have been of noiseless amplification of intensity signals, the principle can also be applied to phase signals.

A phenomenon of much fundamental interest is quantum teleportation.[4, 5] Quantum limited information of *both* observables is "teleported" via a direct classical channel and an indirect quantum channel. The feedforward loop can achieve teleportation by using an intensity squeezed input for a and a low intensity phase squeezed beam for v. The sender beam, which is to be teleported, is mixed with the reflected beam and the intensity and phase fluctuations are measured. Both observables are then fed-forward to the transmitted beam where, remarkably, the choice of the correct gain results in the reconstruction—in both observables—of the sender beam.



Ralph Figure 1. (a) Schematic of feedforward loop. (b) Low noise amplification of squeezed light. The upper trace shows the noise spectrum of the squeezed input beam, carrying a small signal, and the quantum noise limit (QNL). The lower trace shows the output beam has been significantly amplified relative to the QNL, but there has been very little loss of signal-to-noise.

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SIGNAL PROCESSING

Control of Broad-area Optical Devices: Patterns to Order

Graeme K. Harkness, Gian-Luca Oppo, and Willie J. Firth, Dept. of Physics and Applied Physics, Univ. of Strathclyde, Glasgow, Scotland, U.K.

Nonlinear physical systems can have multiple output states compatible with a single input state. This enables them to be used to store, process, and transmit information. Applications typically require the selection of a particular desired state out of this multiplicity, for example, the Gaussian mode in a laser. Often the desired state is, or becomes, unstable—as when a laser passes from single- to multi-mode operation. In 1998, several experiments[1–3] have shown how Fourier-space filtering can persuade optical systems to produce otherwise unstable patterns. Persuade, rather than force, because with appropriate design, the system self-organizes in such a way that little or no energy is lost in the filter.[4] This is exciting because optical systems could, in principle, be similarly persuaded to display unstable states representing images or information rather than simple patterns.

The 1998 control experiments concern optical systems that display spontaneous patterns, such as stripes,