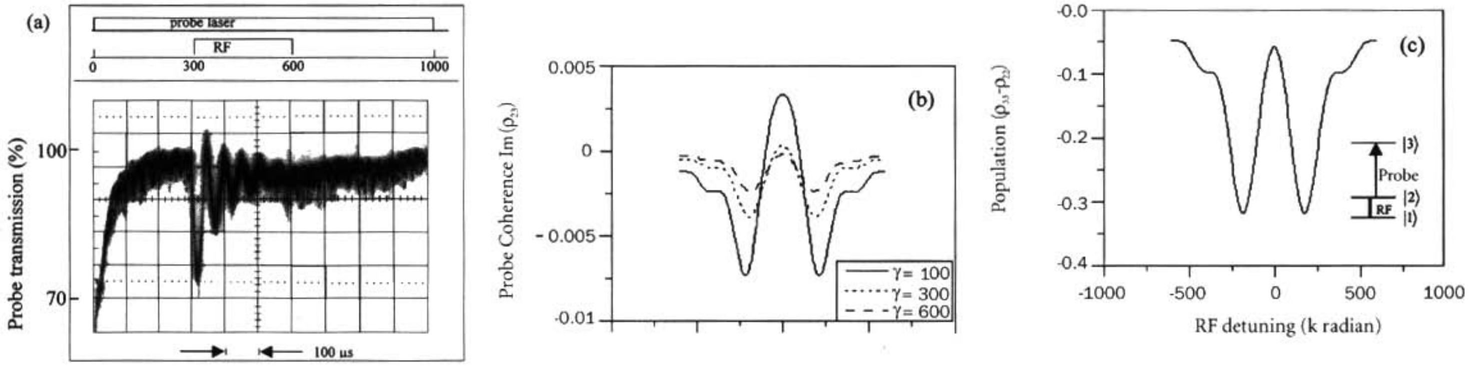

Ham Figure 1. (a) Probe transmission versus time with a RF pulse. Theoretical calculation of optical gain without population inversion. (b) Probe coherence Im(ρ_{23}) and (c) population difference for the probe transition versus RF detuning $\Omega_{RF} = 1.8 \times 10^5$ radians. Refer to Reference 5 for further information.

for many applications such as nonlinear optical processes and lasers without inversion.[2] Especially, EIT observations in solid media trigger intensive research for the potential applications in solids.[3] Recently enhanced four-wave mixing generation and optical memory owing to EIT have been demonstrated in a rare-earth-doped solid.[4] The difficulties of EIT observation in solids are, for example, a very weak oscillator strength, a fast coherence decay time, and an intrinsically broadened inhomogeneous width. In this paper, we present a recent observation of RF-induced optical gain owing to EIT in a solid.[5] We analyze this optical gain and show that the gain is possible without population inversion if certain conditions are satisfied.

In the experiment, we used a rare-earth Pr^{3+} doped Y$_2$SiO$_5$ having ground hyperfine states. For a ladder-type interaction configuration, we chose two ground hyperfine states for the RF transition, and an excited state for the probe transition. Figure 1a shows the experimental data for the optical gain with the RF field at 6 K. As seen in Figure 1a, the probe depletes the ground state population by nearly 100% until the RF pulse is applied. When the RF pulse area reaches π, it inverts the population on the ground states, so that the probe experiences absorption again. Here, it should be noted that the RF Rabi frequency is calculated to be 28 kHz from the oscillation period in the probe absorption spectrum, which is similar to the inhomogeneous width of the 10.2 MHz RF transition. The probe absorption with the RF π-pulse is reduced by ~10%. This absorption reduction is owing to EIT and easily tested by varying the RF power. At the same time, the probe excites the ground state. Hence, there could be population inversion on the probe transition at the end of the RF 2π-pulse. Figures 1b and 1c, however, show that the optical gain is always possible without population inversion if the RF Rabi frequency Ω_{RF} is bigger than the optical homogeneous width γ. The optical homogeneous width in the sample is ~20 kHz. Therefore, we conclude, that the observed optical gain is owing to EIT and enhanced by the RF Rabi flopping. The RF induced optical gain is important for the applications of lasers without population inversion in solids. Either by increasing the RF Rabi frequency or by decreasing the laser jitter, RF induced optical gain should be obtained even without population inversion.

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Optical Confinement of Bose-Einstein Condensates

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Three years after the first observations of Bose-Einstein condensation (BEC) in dilute atomic gases this new field is still bustling with increasing activities. Until recently, all studies of BEC had been performed in magnetic traps. These traps, in combination with RF-induced evaporation, are ideal for cooling and trapping atoms at very low temperature and might develop into workhorses for nanokelvin atomic physics.

However, magnetic traps have severe limitations. They require large scale inhomogeneous magnetic fields that might interfere with applications in precision atom optics. Also, magnetic traps cannot trap atoms in (non-magnetic) m = 0 states, which are preferable for atomic clocks and other precision experiments, thus limiting the use of trapped condensates for metrology.

These limitations have led us to the development of an all-optical trap for Bose-Einstein condensates.[1] We first created Bose-Einstein condensates in a magnetic trap using evaporative cooling, and then transferred them into an optical trap formed by a single focused far-off resonant laser beam, which attracts the atoms to 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

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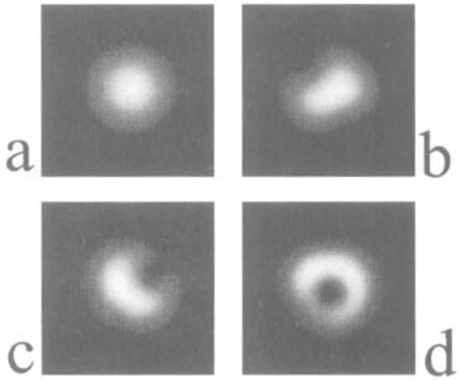
The research on trapped ultracold atomic gases has become one of the most exciting areas in physics since the experimental realization of Bose-Einstein condensation (BEC) in magnetic traps (for a recent review see Ref. 1). One aspect of particular current interest is whether such gaseous atomic BEC also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