This thesis exploits the possibilities of optical evanescent fields as tools to manipulate cold atoms. An evanescent wave (EW) appears when a light wave undergoes total internal reflection at the surface of a dielectric. At the vacuum side of this surface an optical field exists that decays exponentially on a length scale comparable to the optical wavelength. There are many applications of EWs in combination with cold atoms. It can be used as a mirror for cold atoms. Scattering evanescent photons can lead to further cooling of the atoms. A combination of more EWs can lead to low-dimensional traps for cold atoms. Finally, they enable us to probe atoms in close proximity to a dielectric surface. Our samples of cold atoms are prepared using conventional laser-cooling techniques. This chapter will briefly review the major developments in the field of cold atoms, focussing in particular on the interaction of cold atoms with evanescent fields.
1.1 Laser cooling

The development of laser-cooling techniques in the 1980s quickly resulted in atomic samples with high phase-space densities and adopted quantum degeneracy as a goal. In particular the development of the magneto-optical trap that was proposed by Dalibard (according to [1]) and realized by Chu and co-workers [2] was a major breakthrough. This system provides an easy way to collect several millions of atoms and cool them to temperatures of less than a milli-Kelvin. Even lower temperatures can be achieved by applying techniques like polarization-gradient cooling. Both techniques are currently employed in hundreds of experiments worldwide. They are used to collect and cool numerous gaseous atomic species to relatively high densities and low temperatures. In 1997 S. Chu, C. Cohen-Tannoudji, and W. Phillips were awarded the Nobel prize for development of methods to cool and trap atoms with laser light [1, 3, 4]. The phase-space density that can be achieved by these techniques is ultimately limited by re-absorption of the spontaneously emitted secondary photons.

Far off-resonant dipole potentials created by far-detuned laser beams are very well suited to act as conservative traps for atoms. The scattering rate can be made arbitrarily small when sufficient laser power is available, as will be discussed in chapter 2. Since laser beams can be focussed, and multiple beams can be crossed, it is possible to create traps of almost any geometry. However, trapping atoms in these traps does not result in an increase of the phase-space density.

More advanced laser-cooling techniques, combining dipole traps with dissipative laser cooling, has resulted in a further increase of the phase-space density. In particular low-dimensional geometries are interesting, since these provide a large solid angle for secondary photons to escape, so that the problem of re-absorption is reduced. The highest phase-space densities obtained are for Cs for which a phase-space density of 1/30 has been realized using Raman sideband cooling [5], and for Sr, where a sample of $4 \times 10^4$ atoms has been cooled to a phase-space density of 1/10 using Doppler cooling on a narrow, spin-forbidden optical transition, while the atoms were trapped in a far off-resonance dipole trap [6].

1.2 Manipulating atoms using evanescent waves

An EW that is far detuned from an atomic transition such that it becomes a repulsive potential acts as a mirror for atoms. Such a mirror was proposed by Cook and Hill [7]. It was first demonstrated with an atomic beam at grazing incidence by Balykin et al. [8] and later with cold atoms at normal incidence by Kasevich et al. [9].

An atom can undergo a Raman transition to another internal state when it reflects from an EW mirror. This dissipative process leads to a loss of energy of the atom. Atoms that have made such a transition will bounce inelastically, i.e. to a lower height. This process will also lead to cooling of the sample of atoms, which was first demonstrated by Laryushin et al. [10]. This feature is used in the gravito-optical surface trap (GOST) by Ovchinikov et al. [11] where multiple inelastic bounces led
to a significant increase of the phase-space density.

The combination of an attractive and a repulsive EW potential can lead to a trapping configuration. This is called a double EW trap (DEWT) and was proposed by Ovchinikov et al. [12]. Hammes et al. [13] have successfully demonstrated loading a DEWT trap from a GOST trap combined with a “dimple potential”, trapping 20 000 Cs atoms at a temperature of 100 nK.

EWs also provide a tool to selectively detect atoms in close proximity to a dielectric surface. This is useful to detect atoms that are trapped close to such a surface. Aspect et al [14] have proposed a technique to detect atoms close to a surface in a non-destructive manner by detecting the phase change of a far detuned EW. In chapter 6 we present a novel technique to probe atoms at distances on the order of an optical wavelength from a dielectric surface, by measuring the absorption of a resonant EW. The approach is tested using cold atoms that are dropped onto the surface [15]. The possibility to detect atoms at these distances from a dielectric surface gives access to measuring cavity QED effects. An experiment that measures the effect of a nearby surface on the linewidth of the atoms was recently published [16].

1.3 Loading scheme for evanescent-wave traps

The phase-space densities obtained by laser cooling fuelled the hope that Bose-Einstein condensation could be realized using these techniques. The theory of Bose-Einstein statistics [17, 18, 19] predicts that for non-interacting atoms with sufficiently low temperature a large fraction of the atoms accumulate in the lowest energy quantum state. This happens when the de Broglie wavelength $\lambda_{dB}$ becomes larger than the mean interparticle separation $n^{-1/3}$, or better $n\lambda_{dB}^3 > 2.61$. All these atoms are in the same quantum state and thus form a macroscopically sized quantum system. Such a system is called a Bose-Einstein condensate (BEC). However, this has not been achieved using laser cooling until today.

EWs are common in schemes for further increasing the phase-space density in a fully dissipative optical way. During the reflection of a sample of atoms from an EW mirror the density in the turning point is significantly increased. This density increase can be employed by making use of the highly localized scattering properties of EWs. A Raman transfer, induced by scattering an evanescent photon, to an internal state that no longer interacts with the repelling evanescent field, but does interact with a tightly confining trapping potential will lead to an increase of the phase-space density [20]. The low dimensionality automatically deals with the problem of the re-absorption of the secondary photon.

Gauck et al. [21] have demonstrated the proof of principle of this loading scheme using metastable Ar* atoms. Their attempts were restricted by the metastable character of the Ar* atoms, which enables Penning ionization and therefore excludes high densities. For sufficiently high phase-space densities the transfer into a single state of the trap will be enhanced due to the bosonic nature of the atoms [22], which corresponds to the stimulated emission process of a laser. Inouye et al. [23] demonstrated this effect in free space using condensed samples.
Chapters 6 and 7 discuss our efforts to implement this method for $^{87}\text{Rb}$ atoms. These atoms are advantageous because they are trapped in the ground state and therefore do not suffer from Penning ionization. On the other hand the energy separation between the bouncing and trapped state is too small to decouple the trapped atoms from the repelling evanescent field. Spreeuw et al. [20] discuss a dark-state trap that should by-pass this problem.

In chapter 6 the atoms are trapped in a standing-wave dipole trap after their transfer. Due to the highly localized scattering of an EW all atoms are concentrated in just a few potential minima of this trap. The evanescent probing technique was used to detect the trapped atoms. Chapter 7 discusses the EW dark state trap proposed in [20] in more detail. Several geometries are discussed. Within the range of experimentally realistic parameters, optimum values for these parameters are derived from a numerical analysis of the experiment. The actual implementation of the experiment was prevented by technical problems, which are also discussed.

1.4 Bose-Einstein condensation

In 1995 Bose-Einstein condensation was realized using evaporative cooling of magnetically trapped atoms in Boulder [24], MIT [25], and at Rice university [26, 27]. Laser cooling was only used as the initial step to prepare a sample of atoms that was loaded in a magnetic trap. A subsequent phase of forced evaporation led to an increase of the phase-space density until the quantum degeneracy limit was reached. By outcoupling atoms from a BEC, atom lasers have been realized [28, 29, 30, 31, 32]. However, because the condensate is depleted their output is pulsed. In 2001 E. Cornell, W. Ketterle, and C. Wieman were awarded the Nobel prize for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates [33, 34]. Since the first realization of a BEC, it has been realized for many atomic species, and diatomic molecules [35, 36, 37]. Furthermore several trapping geometries are commonly used nowadays and BEC is for instance achieved for atoms trapped in micro-structured atom chips [38, 39].

Bose-Einstein condensation of atoms trapped in far off-resonance dipole traps has also been realized [40, 41]. The phase-space density density is, however, still increased by means of forced evaporation while the atoms remain trapped in a conservative potential. So far these experiments were only successful for dipole traps created by CO$_2$ lasers with a wavelength of 10.6 $\mu$m. Chapter 3 discusses a possible extension for obtaining BEC in a far off-resonance dipole trap. It investigates the possibility to use an alternative, experimentally more practical wavelength in order to accomplish the same goal.

There are other experiments that aim at or have realised high phase-space densities using EWs. However they all make use of an evaporative cooling stage. Colombe et al. [42] are working towards loading a DEWT surface trap from a 3D $^{87}\text{Rb}$ BEC. Rychtarik et al. [43] have created a two-dimensional BEC of Cs atoms, by trapping thermal atoms in a GOST, increasing the density using a dimple potential [44], and
a subsequent evaporative cooling stage.

Even though BEC has been realized, it is still interesting to investigate the possibility of realizing a quantum degenerate system in a fully dissipative, optical way. One reason is that this could open routes to reaching quantum degeneracy for atomic species with unfavorable s-wave scattering lengths, for which evaporative cooling can not be applied. Another reason is that it is possible to create quantum degenerate samples in excited vibrational states of the trap. With a thermal process like evaporative cooling, only condensation to the ground state is possible. Finally these systems may lead to cw atom lasers. Even before BEC was realized several schemes to realize this have been proposed, e.g. [22, 45].

### 1.5 Interferometry

Chapter 8 describes a novel type of interferometer and addresses the question whether spontaneous emission can perform the role of the beam splitter. Atoms that bounce inelastically from an EW mirror have made a transition to another internal state during their reflection, see e.g. [46]. This transition can occur on the ingoing or the outgoing part of the trajectory, and the two possible paths follow a different trajectory through phase space. Since this transition is a spontaneous Raman transition, which is generally considered to be an incoherent process, the question arises whether these paths could give rise to interference. This thesis ends with an unambiguous and surprising answer to this fairly general question by numerically solving the Schrödinger equation.