Chapter 1

Introduction

Over the past several years, the manipulation of atomic matter waves has become a dominant theme for atomic physics experiments. The creation of the first Bose-Einstein Condensate (BEC) in 1995 by E. Cornell and C. Wieman at JILA [1] and W. Ketterle at MIT [2] has opened up a whole new field of research, namely the study of coherent matter waves. In the same way as coherent light sources in the form of lasers have revolutionized modern optics, the manipulation of coherent matter waves is creating a deep impact on atomic physics. In fact, the analogy between light waves and matter waves is very fundamental and leads to the idea of atom interferometry, i.e., using atomic matter waves for measurement of rotation in a similar way as lasers are used in laser gyroscopes.

The measurement of rotation rates using a laser gyroscope is based on the Sagnac effect, in which a phase difference between two interferometer arms arises due to a rotation, whose rotating axis is perpendicular to the interferometer plane. Macek and Davis firstly recognized in 1963 [3] that photons propagating in different arms see different path lengths when the rotation happens, thus carry a phase difference, which is given by

$$\Delta\phi = \vec{A} \cdot \vec{\Omega}_{rot} \frac{E_r}{\hbar c^2}, \tag{1.1}$$

where $\vec{A}$ is the enclosed area of the interferometer, $\vec{\Omega}_{rot}$ is the rotation rate, $E_r = \hbar\omega$ is the energy of the photons, and c is the speed of the light. By detecting this phase difference, the rotating motion can thus be measured. Today, optical gyroscopes, such as ring laser gyros or fiber gyros, are widely used as precise inertial sensors for the navigation.

Atom interferometry offers an exquisite precision measurement capability with far greater sensitivity than its photon-based counterpart. For example, the fundamental limit on the signal-to-noise ratio of an atom Sagnac gyroscope is a factor of 10^{11} greater than the optical one, given comparable enclosed areas and particle flux. This amazing improvement is due to the high relativistic energy of an atom, mc^2, as compared to the photon energy, $E_r = \hbar\omega$. Besides, atoms can be sensitive to electric and magnetic fields. Because of this, atom interferometry may be suited to a substantially larger number of sensor applications despite being sensitive to more detrimental noise sources. Atom interferometry experiments have revealed promising and sometimes stunning measurement capabilities [4, 5, 6, 7, 8].

Experimental research in the field of BEC has been dealing with two different aspects. First, experiments have investigated and are continuing to explore the fundamental properties of BECs. Second, new technological developments allow us to create and manipulate BECs in a more and more flexible way. One key element here is the development of “atom chips”.

Atom chips seek to implement atom-based devices on a small scale [9, 10, 11, 12, 13]. For example, one can incorporate conductors, magnetic elements, and optical components on a single substrate to produce fields that confine, control, and manipulate atoms. One can also incorporate atom detection and signal conversion on that same substrate. Moreover, because the source of the magnetic fields on a chip are close to the atoms, one can typically apply much larger forces (or use much less power to apply those forces). Most importantly, the atom chip approach offers substantial control over the geometry of an atom interferometer.

Most attempts to implement a coherent beamsplitter/recombiner, which is essential for an interferometer, on a chip have used current-induced magnetic fields to split a condensate cloud. The magnetic field typically forms a double potential well that merges and then splits apart either in space, in time, or in both. However, atom-atom interactions due to high density in the waveguide can cause instabilities during the splitting or recombining process in such a double-well potential [14] and also reduce the phase coherence [15]. Various detrimental atom-surface and atom-wire interactions [16, 17, 18, 19, 20] have been reported. Because of those interactions, the coherence of the condensate is destroyed during the splitting process and attempts to demonstrate on-chip interference have been stymied. However, optical beamsplitters using standing light waves have offered promising potential for coherent manipulation of atoms [6, 7, 8]. The combined optical and magnetic forces have enabled a study of coherence properties of matter waves confined in a microstructure.

This thesis work brings together the two aspects of modern BEC research by exploring coherent processes of light-matter interaction and implementing them on an atom chip to demonstrate the first working on-chip atom interferometer. This work is done in collaboration with Prof. M. Prentiss at Harvard University.

In this thesis, I will show the first on-chip atom interferometer using a standing-light wave. The details of the atom chip and the apparatus are described in Chapter 2. In Chapter 3, we also introduce an alternative way of making a condensate by surface-induced evaporative cooling . The surface-induced cooling provides a promising technique, which can potentially be used to produce a continuous-wave (cw) Bose-Einstein Condensate (BEC) on a chip. Coherent splitting and reflecting of the condensates by diffraction from a standing light wave are discussed in Chapter 4. An innovative double-pulse beamsplitter, which offers a simple solution for coherently splitting condensates, is described in Chapter 5. In Chapter 6, we develop an on-chip Michelson interferometer to split, reflect, and recombine the condensate and read out interference signals. To prove that the interferometer is working successfully, a differential phase shift is created by a magnetic gradient and alternatively by an initial velocity in a trap with a longitudinal frequency of 5 Hz. This robust interferometer technique could potentially be used for an atom gyroscope.

In summary, this thesis demonstrates the first realization of a guided atom interferometer on an atom chip, which has been a long-standing goal of research in this field. The experiments described in this thesis are successful “proof-of-principle” experiments, providing a way for future applications of BEC in the field of ultra-high precision measurement.