diameter of about 25 mm have been produced with performance in the 1–100°/h category.

5.1.9 Integrated optical gyroscope

There have been developments in this highly desirable sensor, as it is a 'gyroscope on a chip'. The sensing element is an optical waveguide on a substrate with the light travelling in opposite directions. The relative position of the resonance within the ring is a measure of the applied optical rotation rate about an axis that is perpendicular to the ring. The fundamental operation of this device is described more fully in Section 5.1.7.

These integrated optical gyroscopes are created on wafers and combine micromachined electromechanical system processes and integrated optical fabrication processes. Speciality glasses are formed by highly specialised techniques such as flame hydrolysed deposition, radio frequency and reactive sputtering. The flame hydrolysed deposition allows the refractive index of the medium to be controlled so that the glass can be doped with rare earth laser ions, such as neodymium, ytterbium or erbium, creating lasers and laser amplifiers within the chip.

The definition of the waveguide is still quite a challenge, as vertical sidewalls with very low roughness are required to minimise losses. Clearly, the etching process is potentially the limiting process in the fabrication as there are likely to be various compositions of glass with varying dopant concentrations.

Currently, the performance goal is to meet applications requiring performance in the 0.1–1°/h regime. This class of sensor offers significant size and mass reduction, of the order of a factor of 20 compared with conventional fibre gyroscopes. Additionally, the power consumption is likely to be reduced by a factor of 5 or 6 along with a significantly lower cost owing to the reduced number of optical components.

5.2 Cold atom sensors

5.2.1 Introduction

This is an approach or technique for measuring inertial properties; such devices are also known as atom interferometer devices and owe much to the excellent work of Professor Chu of Stanford University. The technique is in the early stages of practical development and offers the prospect of a route to the most accurate accelerometers, gyroscopes, precision clocks and gravity gradiometers therefore performance enhancements of several orders of magnitude are predicted. If successful devices can be devised then, given precise knowledge of the gravity field, there is the prospect of a sub 10 m/h navigation capability without using global positioning system (GPS) or other external aiding techniques.

The sensor relies on the super cooling of an atom or molecule by techniques such as laser cooling and uses the de Broglie wavelength of an atom, which is about 3×10^4 smaller than the wavelength of visible light. The physical principle relies on the fact that atoms in any medium have mass and internal structure and that atomic interferometers are extremely sensitive. This method has some similarities with the NMR gyroscope described in Section 4.5.1, or use could be made of the Sagnac effect to detect the angular rotations experienced by the sensor through variation in atomic motion round a closed path.

In research studies to date, devices have used incoherent atoms propagating in free space. However, in the future it may be feasible to use coherent Bose–Einstein condensates propagating in a guiding medium, achieved by using laser-cooling techniques.

Laser cooling of atoms and atom-trapping techniques are being used in a number of applications in many scientific areas. An example is atom interferometry, where an atom is placed into a superposition of two or more spatially separated atomic states, which will interfere with each other if they are subsequently brought back together.

This technique has enabled atom interferometers to be created and have now been established as very sensitive techniques for the detection and measurement of inertial forces. These sensors have been used to make measurements of gravity gradients, local gravity and rotations [27–29]. These devices are still being developed in the laboratory and use laser beams to cool, manipulate and control the associated atomic wave packets.

One possible application for this technology is the observation of very small changes in the gravity vector to detect changes in the density of the Earth's surface. This could be used in prospecting for oil deposits or for monitoring the development of underground facilities.

5.2.2 Rotation sensing

Very accurate and stable measurement of rotation has been achieved [28] using an atom interferometer based on the principle of having two counter-propagating atomic beams, as used in the Sagnac effect with ring laser gyroscopes. This device uses stimulated Raman transitions, to manipulate atomic wave packets of caesium atoms. The device uses counter-propagating high-flux atomic beams of caesium to form two interferometers with opposite Sagnac phase shifts that share key components, such as the Raman atomic state manipulation laser beams. Subtraction of the interferometric signals from the two separate atomic beams allows the common-mode rejection of spurious noise sources and various systematic effects.

In this sensor the interferometer is arranged in a Mach–Zehnder configuration [30], in which caesium atoms from a thermal atomic beam are arranged to be the interfering particles. The laser light pulses act as beam splitters and mirrors for the atoms to form a closed cavity, allowing the two counter-propagating beams to travel round their defined closed paths. The light pulses are used to put the atoms in a superposition of two states, corresponding to different spatial trajectories that separate and recombine enclosing a given area of the Sagnac device, as shown in Figure 5.15.

The two counter-propagating caesium atomic beams are transversally laser-cooled and optically pumped before entering a 2 m long magnetically shielded interaction region of the vacuum chamber. Three sets of light pulses, from two photon-stimulated Raman transitions, serve to divide, deflect and recombine the atomic wave packets.

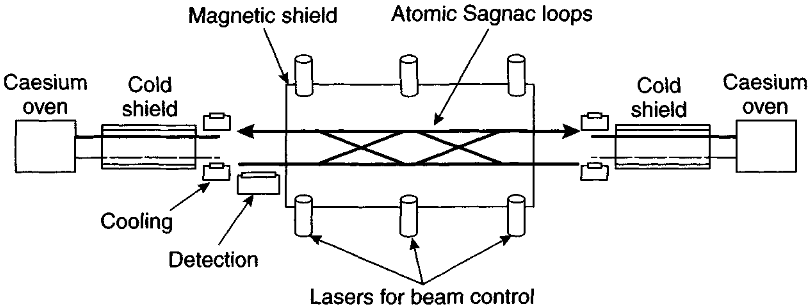

Figure 5.15 Cold atom sensor – Sagnac loop

The Interference signal is observed by detecting the number of atoms in the $F = 4$ ground state by resonant fluorescence.

Results from the device indicate a short-term stability in the region of 3×10^{-9} rad/s/$\sqrt{\text{Hz}}$.

5.2.3 Measurement of acceleration

An atom interferometer, based on an atomic fountain of laser-cooled caesium atoms and using laser light to 'form' the atom optical components, has been used to make a very accurate measurement of 'g'. This atom interferometer uses optical pulses of light to stimulate transitions between two internal states of the atoms that initially drift apart and then recombine after a second pulse of light encourages a second transition in the internal states of the atoms, which complements the initial transitions. A further illumination pulse with the appropriate phase relative to the atomic phase encourages a further complementary transition.

The phase difference between the two parts of the interferometer is a function of the phases of the laser at various positions and times in the cavity at the start of the optical pulse, the frequency of the light and the optical paths in the interferometer. In this interferometer the frequency of the light is changed in a phase-continuous way, so that it remains resonant with the transitions as the atoms accelerate under the influence of gravity. As a consequence the phase difference between the two paths in the interferometer is proportional to the gravitational attraction.

In the atomic fountain, shown in Figure 5.16, caesium atoms are extracted from a low-pressure background vapour and loaded into a magneto-optical trap during a 600 ms period. The magnetic fields are turned off and the captured atoms are launched into the atomic fountain of this sensor using a specialised technique, known as moving polarisation gradient optical molasses. During this period further cooling of the 'launched' atoms occurs, using resonant techniques and in the final stage of the launch the laser intensities are reduced to zero in 400 μs, so that the atoms are adiabatically cooled.

The launched atoms are subjected to a series of pulses that place the atoms in a specific internal state with an effective vertical temperature of 10 nK. This low

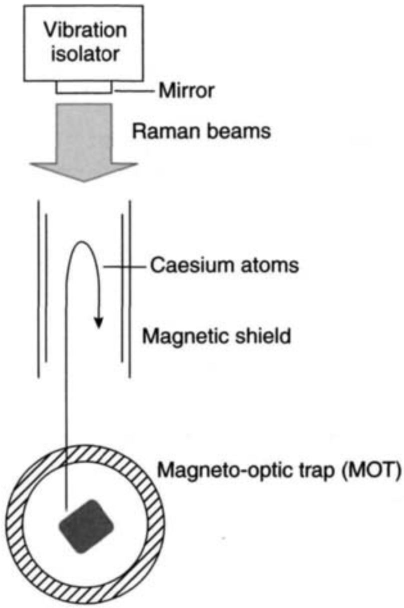

Figure 5.16 Atom interferometer – overview of experimental set-up

velocity spread leads to a high fringe contrast over a period of about 150 ms. The interferometer measurement occurs in a magnetically shielded region.

This type of device is capable of measuring 'g' to better than a part per billion accuracy.

5.2.4 Gravity gradiometer

Gravity gradiometers are particularly useful sensors for detecting changes in the gravity vector close to the surface of the Earth. The changes may indicate a number of features that may be present in the Earth's shell owing to local changes in the density. The local changes to the gravity vector may be caused by many reasons; it may indicate a number of features, such as the position of oil reserves, mineral deposits, voids or other phenomena.

An atom interferometry technique has been used to create a gravity gradiometer (Figure 5.17), using two laser-cooled and trapped sources of caesium atoms, as described above and a pair of vertically propagating laser beams. The device is arranged so that two independent measurements of acceleration can be made using the two vertically separated ensembles of caesium atoms in freefall, under the influence of gravity.

The caesium atoms are launched into a vertical trajectory from the magneto-optical trap and conditioned to be in a particular internal state using optical and microwave techniques. These atoms are then suitable for interacting with the gravity vector and

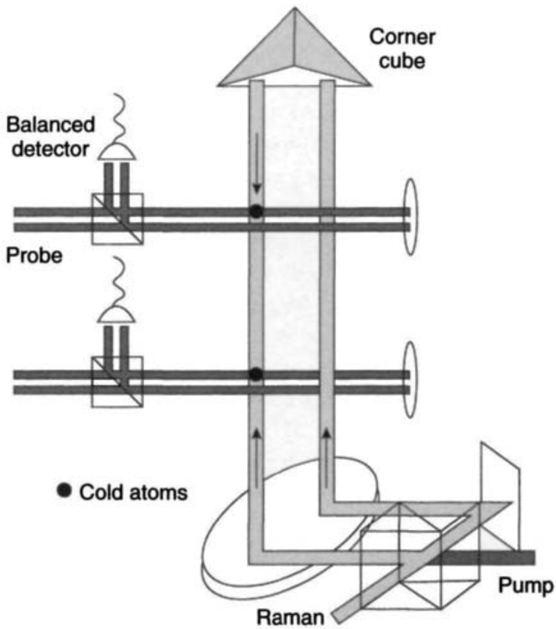

Figure 5.17 Cold atom gradiometer

then changes in the atomic states due to gravitational acceleration can be detected in the interferometer due to gravitational acceleration.

This cold atom device is particularly sensitive as it uses atoms as proof masses, rather than macroscopic objects. This eliminates variability from device to device and provides insensitivity to many environmental perturbations, such as temperature gradients and magnetic fields. Moreover, the two absolute accelerometers used in this device are operated in a differential mode to give enhanced performance.

A light-pulse atom interference method is used to measure the acceleration of each atomic ensemble with respect to a reference frame defined by the wave fronts of the interrogating optical fields. The two simultaneous measurements of the effects of gravity on the pair of vertically separated sensors are made with respect to the same set of Raman laser fields. This is achieved by a simultaneous measurement of the fraction of atoms excited by the laser pulse sequence at the two positions where the gravity vector is measured. The differential acceleration is given by the differential phase shift between the upper and lower atomic ensembles, and this difference in phase shift is proportional to the difference in the mean value of 'g' measured at the two parts of the sensor.

The difference between the measured acceleration experienced by each atom ensemble, divided by their separation, is a measure of the in-line component of the gravity-gradient tensor. Accelerations of the common reference frame, defined by the optical field wave fronts, are rejected as a common mode in the differencing process.

The gradiometer references its calibration to the wavelength of the measurement laser, which is locked to an atomic spectral line, thus providing absolute accuracy and long-term stability. The propagation axes of these laser beams are aligned to pass through both ensembles of atoms. Moreover, the sensitive axis is defined by the Raman propagation vector, and the measurement of acceleration is referenced to only one retro reflector, consequently, the two accelerometers may be separated by some distance without destroying the common mode vibration-rejection features. Increasing the separation between the two accelerometers linearly increases the sensitivity to gravity gradients and gives insensitivity to near-field perturbations.

High signal-to-noise ratio is vital to give high interferometer sensitivity. The device uses a balanced modulation transfer technique to reduce laser-induced detection noise and differentiate cold atoms from thermal background atoms [31]. Additionally, each interference fringe is recorded a number of times in consecutive cycles of the observation, typically 15. The number of points per scan is kept small to reduce sensitivity to long-term drifts in signal amplitude and fringe contrast. The predominant noise source in the observations is atom shot noise; this is the Poissonian fluctuation that occurs from detecting atoms in coherent superposition states.

The differential performance is of the order of $4 \times 10^{-9} g/\sqrt{\text{Hz}}$.

Other 'atomic techniques' are being investigated for this sensor, such as:

- Interferometric devices using diffraction in the Raman–Nath regime [32], using short intense pulses of light applied to the atomic ensemble.
- Large area interferometers using adiabatic transfer of momentum [33] have been used in proof-of-principle experiments, in this case the atoms are put into coherent superpositions of two states using a microwave pulse.
- Use of the a.c. Josephson effect in arrays of Bose–Einstein condensed atoms [34], where condensate atoms tunnel from an array of vertically spaced lattice sites and atoms tunnelling from different sites subsequently interfere. The resulting interference pattern is a periodic train of atomic pulses whose frequency is a function of the strength of the gravitational potential.

Direct gradient measurements can be made using multiple-loop Raman-pulse based interferometers such as a double loop or a figure-of-eight loop [29], by modifying the sequence of phase pulses applied to the ensemble.

5.3 Summary of gyroscope technology

There are many types or classes of sensor that can be used to sense or detect angular motion. Many of these devices have been considered in the foregoing text, particularly those that are used currently, or could be applied in the future, in strapdown applications. These instruments range from the conventional mechanical gyroscopes, using a rotating mass, to the unconventional, using atomic spin.

A great deal of effort has, and still is, being expended to develop the so-called novel technology, the aim being to produce a 'gyroscope' on a chip. New technology used in industry, such as robotics, is helping to sustain this effort. However, this is also being applied to the conventional technology and is helping to keep the mechanical gyroscope competitive.

The range of accuracy that can be achieved from the spectrum of rotation sensing devices spans many orders of magnitude. Some sensors have a bias of less than 0.0001°/h, whilst others are in the 1°/s class or worse. Most sensors show some unwanted sensitivity to the environment in which they operate. The goal of much research is to reduce these sensitivities or improve the ruggedness of the instruments as many, particularly some high-precision devices, are quite sensitive to vibratory motion.

A summary of typical performance characteristics for a range of sensors suitable for strapdown application is given in the following table.[1]

Characteristic	RIG	DTG	Flex gyroscope	DART/ MHD	Vibratory gyro	RLG	FOG
g-Independent bias (°/h)	0.05–10	0.05–10	1–50	360–1800	360–1800	0.001–10	0.5–50
g-Dependent bias (°/h/g)	1–10	0.01–10	1–10	180	36–180	0	<1
Anisoelastic bias (°/h/g^2)	1–2	0.1–0.5	0.05–0.25	18–40	18	0	<0.1
Scale-factor non-linearity (%)	0.01–0.1	0.01–0.1	0.01–0.1	0.5–0.1	0.2–0.3	5–100	0.05–0.5
Bandwidth (Hz)	60	100	100	100/80	500	>200	>100
Maximum input rate (°/s)	>400	1000	>500	800/400	>1000	>1000	>1000
Shock resistance	Moderate	Moderate	Moderate	Moderate	>25 000g	Good	Good

In general, a significant amount of precision engineering and high technology is required to produce a device that is functional. As the accuracy required from the sensor increases, so does the precision and the size needed to fulfil the requirement, although this is not universally true. In some of the recent research programmes, an effort has been made to alleviate the need for ultra high precision for the high accuracy instruments. Usually, however, this has led to the need to apply very high technology, such as superconductivity, which imposes its own demands such as cooling to cryogenic temperatures.

The performance of developed inertial sensors for near-term applications requiring angular motion data is shown in Figure 5.18. The figure shows the

[1] These are typical values applicable over the range of parameters stated. In many cases, the values given could be improved. However, it is not normally possible to have all the best case values in a single unit, particularly for the conventional sensors. These values are only for general indicative purposes.

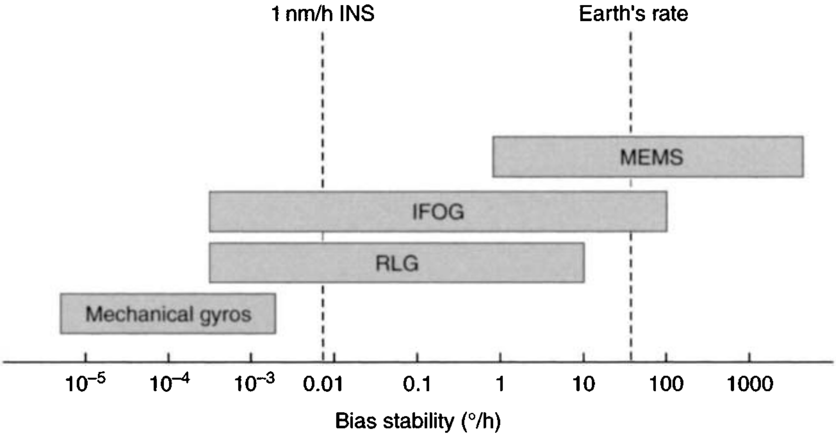

Figure 5.18 Near-term gyroscope performance summary

anticipated division between the micro-machined electromechanical system (MEMS, see Chapter 7), optical (ring laser gyroscope (RLG) and IFOG) and mechanical gyroscopes covering the low, medium and high accuracy system applications respectively. Despite advances in optical sensors, the high performance applications (10^{-4}–10^{-5} °/h) remain the regime of the mechanical gyroscope. For the mid-range applications requiring very high scale-factor stability, the ring laser gyroscope is the sensor of choice. In the longer term, it is expected that MEMS gyroscope performance will continue to improve and find increasing application in higher performance systems.

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