ATOM INTERFEROMETER GYRO

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Abstract

A potentially promising technology, which is in its early development stages, is inertial sensing based upon atom interferometry (sometimes known as cold atom sensors). Laser/atomic physics interactions determine the relative motion between the inertial frame (defined by the atom de Broglie waves) and the sensor case (defined by the laser beams) Atom is in a near perfect inertial frame of reference (no spurious forces). An interferometer is a physical device that splits single particles or their complimentary waves into two different paths, which are then recombined, not before each path accumulates a phase related to the effective length of the trajectory and an optical phase added during the splitting and recombination. A phase difference of an integer product of 2 π *means constructive interference, where the intensity of the resultant interferometer output beam is higher than the sum of intensities in the two paths. A typical atom de Broglie wavelength is* 30,000 times smaller than an optical wavelength, and because atoms have mass and internal structure, atom interferometers are extremely sensitive. In theory, this means that atom interferometers could make the most accurate gyroscopes, accelerometers, gravity gradiometers, and precision clocks, by orders of magnitude. Atom interferometer inertial sensors to date have used incoherent atoms propagating in free space, and laser pulse based free space interferometers appear to offer the best potential for practical applications in the short to intermediate term. In the future, it may be possible to use coherent Bose-Einstein condensates for atom guided interferometer structure, although problems of excitation of internal degrees of freedom of the condensates, need for high vacuum, and the complex processes involved need to be overcome.

The wide variety of internal degrees of freedom of an atom opens up new possibilities for interferometry which do not exist in the more traditional types of interferometry using photons, electrons and neutrons. In addition, the large atomic mass gives rise to high sensitivity concerning measures of rotation, acceleration and gravitation.

This paper deals with adopting the concept and realizing as a practical gyro for the space application. The very high drift stability achievable with the atom interferometer gyro will be very useful for the interplanetary missions as well as for space transportation, considering the much less accumulated error over long period without any updates, Also the paper deals with the aspects of miniaturization of the gyro.

Keywords: Atom interferometer Gyro, Raman pulses.

1. Introduction

The atom interferometer technique and its application has created a major interest in the field of inertial sensors. The advancement in quantum engineering offers an opportunity for creating an inertial sensor using cold atoms. Cold atom interoferometry can be used for realizing high stability gyroscopes with very high accuracy.

Atomic cloud, when cooled to a sufficiently low temperatures and high densities, would collapse into a single quantum state in which all of the physical properties used to describe each atom, such as its position and velocity, would be the same. If we can place these atoms into well defined quantum states and manipulate these states using photons coherently, we can use it for measuring inertial parameters.

An atom interferometer Gyroscope works on the Sagnac principle. Atom is cooled using laser beams and are split and made to converge at a point after following two identical paths. This is achieved using Raman pulse sequence of $\pi/2 - \pi - \pi/2$. These are used as atomic mirrors and splitters. A relative atomic phase difference will occur due to the inertial effects (rotation etc.) on the wave function over the paths. In an atomic interferometer the phase difference between the two paths will reflect as an intensity signal on a detector, which can be detected and the rate can be measured.

2. Atom cloud generation and laser cooling.

An atom laser is analogous to an optical laser, but it emits matter waves instead of electromagnetic waves. Its output is a coherent matter wave, a beam of atoms which can be focused to a pinpoint or can be collimated to travel large distances without spreading.

A photon has no rest mass, but a momentum defined by p = (*hf*)/c where *h* is the Plank constant and *f* the frequency of the photon. Due to the particulate nature of light, it can be seen that when a photon collides with an atom, the photon would transfer its momentum to the atom causing it to change velocity. A vapour cavity containing noble alkali metal vapours are used to generate atom clouds. A pumped laser beam along the optical pumping axis is used to impart energy to the atoms and to convert it to an excited state. However, the atom can only absorb photons of certain discrete frequencies, because absorption of light by atoms causes the atom to be excited; the electrons to move to one of the higher energy levels. According to the laws of quantum mechanics and the quantization of the electron, they are only allowed to have certain

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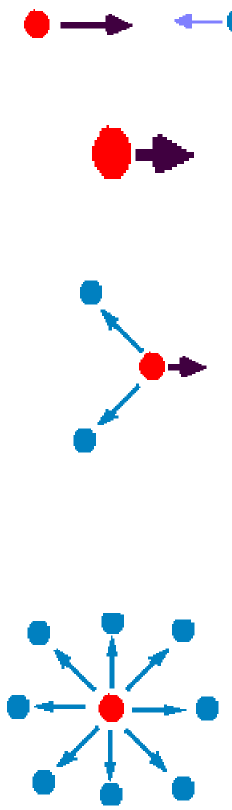
energies. The energy of a photon is related to its frequency by the equation E = *hf* where E is the energy of the photon. This transition requires an increase in energy and the energy is provided by the absorbed photon. The laser beam frequency will have to be the same as the carrier frequency of the atomic cloud. Otherwise they would just pass through the atoms. The precise control and manipulation of frequency and phase of a stable laser source is required for precision measurements. Ultra low-noise phase-locked continuous lasers can be used for the purpose. External cavity diode lasers are widely used, because their output frequencies and phases can be easily controlled by changing the injection current. The power of diode lasers are less and may require optical power amplifiers.



(a)

(b)

(c)

(d)

Figure1. (a) Dot on the left represents atom in collision course with proton (right dot) (b) The velocity of the atom reduces after absorption of photon (c) The atom spontaneously emits photons in random direction (d) The velocity of the atom is reduced to almost zero with multiple photon absorption and emission.

Cooling an atom is the process of reducing the kinetic energy of the atoms by reducing their mean velocity. The atomic velocity is around 300 m/s and will have to be brought down to a few centimeters per second using lasers. Atom absorbs light (photons) at very precise wavelengths. The absorption of photon will increase the energy of the atom and imparts momentum to it, p = E/c = h/λ. With each photon absorption an atom will recoil with an impulse mv ~k; where m is the atomic mass. After a while the atom will spontaneously emits photons in random directions. The time-averaged impulse applied to the atom by spontaneously emitted photons is zero due to the random and symmetric. Since one absorption would slow an atom by only about a few cm/s, thousands of photons are required to reduce the atom momentum to zero.

2.1 Doppler Cooling

The absorption can also add momentum along the direction of the atom and will speed up an atom if it catches it from behind, so it is necessary to have more absorption from the optical pumping axis opposing the direction of travel of the atom in order for the atom to slow down. This is accomplished in practice by tuning the laser slightly below the resonance absorption of a stationary atom. For the atom, the head on photon is seen as Doppler shifted upward toward its resonant frequency and it therefore more strongly absorbed than a photon traveling in the opposite direction which is Doppler shifted away from the resonance. Considering that an atom only absorbs photons with energies corresponding to transitions in the atom's energy spectrum, we can use the Doppler laser light such that only a certain velocity group interacts with it. In this way we can slow down atoms by impending red shifted laser light in the opposite direction of their motion. Thus the velocity of the atom can be reduced to a few mm/s. Similarly, detuned laser beams from opposite directions can be used to slow down atoms with regards to a single axis. However, if we actually want to cool atoms we will have to slow them down in all directions. Using three pairs of concurrent laser beams in three mutually perpendicular directions, the atoms are stopped at their point of encounter, and thus we can effectively cool down clouds of cold in high vacuum to very low temperatures. This technique is referred as optical molasses due to the molasses-like effect the atoms experience at the intersection point of the laser beams.

2.2 Magneto Optical Trap (MOT)

A small fraction of less than a percentage of the atoms fall back to a different state reducing the cold atom population. The cooled atoms if not confined will diffuse. Random walks cause the atoms to eventually leak out of the trapping region. This can be prevented by applying a restoring force, which will confine the atoms. This force is generated by the application of a spatially varying Quadrupole magnetic field such that there exists a field minimum in the center of the molasses .A anti Helmholtz configuration with two identical circular coils separated by their diameter, with the trap in between is used. The current through the coils are counter propagating. A cooling laser light detuned slightly below the atomic resonance is also used and are called the magneto-optical trap. Since the magnetic field drops linearly towards the

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center of the trap this would mean that the atomic transition frequency will change in the same manner due to the position dependent Zeeman shift. It is proportional to the distance from the center of the trapping region, thereby changing the effective detuning as seen by the atom. Consider red detuned light and an atom moving in a direction such that the negative Zeeman sublevels decreases in energy, and hence increases in detuning, with a velocity against $\sigma-$ light, will be preferentially absorbed and scattered by the atoms rather than scattering from $\sigma+$ light as the m = −1 level is shifted closer to resonance and the m = +1 level is shifted out of resonance. The same is true for an atom moving toward the other sign of the field gradient with velocity against $\sigma-$ light. The above trapping scheme is called a magneto-optical trap (MOT). During these cycles of absorption and subsequent spontaneous emission the atom loses kinetic energy due to the recoil momentum transfer of the oppositely propagating photons. As a results the atoms are accumulated around the trap center and stored for long times.

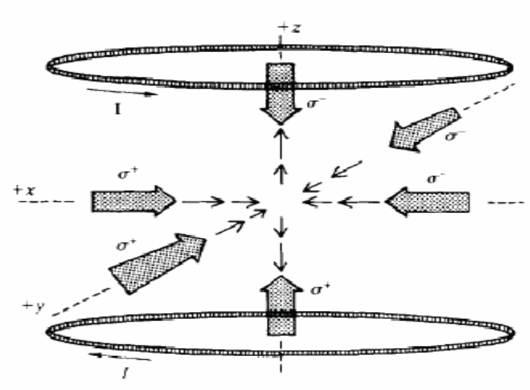

Figure2. A Magneto Optical Trap configuration.

Lasers beams are incident from all six directions and opposite currents produce a magnetic field that is zero in the middle and changes linearly along all three axes From the magnetic trap ,lowering of the walls will allow atoms with higher energy to escape. This leaves an atomic collection of lower energies and lower temperature. The phenomenon of cooling by evaporation will lower the temperature further from that can be achieved by Doppler cooling and also will increase the density of cold atoms.

Measurement of the temperature of extremely cold atoms is very difficult, since even the slightest disturbance of the system will generate heat. Fluorescence imaging technique can be used to measure the temperature in a MOT; we can measure the free (or ballistic) expansion of the atom cloud due to random thermal motion of the atoms. In this method the trap will be opened by switching off the laser for a known time and the laser is switched on to image the fluorescence signal for the determination of cloud size. Repeating this process while scanning over the amount of time we allow for free expansion we can perform of time we allow for free expansion we can perform precise (average) temperature measurements for the atom cloud in a MOT.

3. Interferometer

The cold atom molasses from the MOT is pumped back to the chamber using laser optical pumps. In the chamber the cold atoms are manipulated using Raman pulse sequence of $\pi/2 - \pi - \pi/2$.

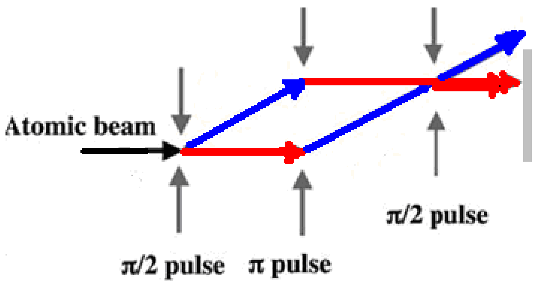

Figure 3. An atom interferometer representation.

A Mach-Zehnder topology is well suited for the measurement of inertial forces due to its symmetry. This type of atom interferometer can be implemented with three such Raman processes separated in time and/or space. The first pulse the $\pi/2$ coherently transfers the atoms initially prepared in one of the two hyperfine states to two spatially separating matter wave modes, when the two light fields are counter propagating, similar to a 50/50 beam splitter in optics. The second Raman process, a $-\pi$. pulse, flips the internal state and the relative momentum of both matter waves and thus acts like a mirror. The third Raman pulse of $-\pi/2$ recombines the two matter wave. The phase difference between the matter wave modes leads to a varying population difference between the two atomic states which is measured by fluorescence detection. This setup is sensitive to acceleration and gravity along with rotation. So a dual MOT with simultaneous counter propagating atomic beams can be used for measure rotation and can be kept at uniform gravitational potential to counter gravity.

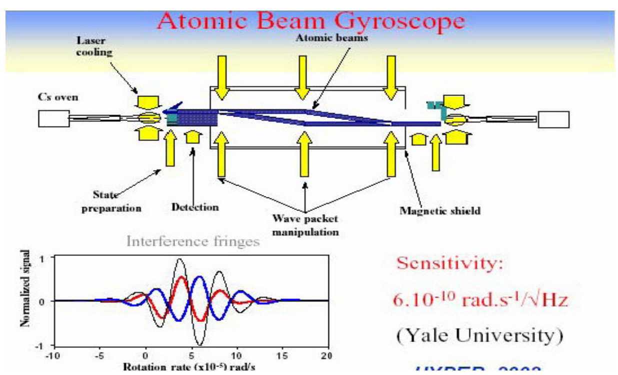

Figure 4. Stanford/Yale gyroscope configuration

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The rotation phase shift is extracted from the difference between the signals of the two interferometers. The standard deviation is plotted.
The short term sensitivity of the rotation signal will improve with integration time. A sensitivity of 10^{-8} rad s^{-1} is reported with 1000s integration by SYRTE.

4. Errors

An atom interferometric gyro is sensitive to many errors. The absorption of photon will happen only if the laser frequency matches. The laser frequency can change due to external mechanical vibration causing the photon to pass through. even under close loop control the system is likely to have residual frequency fluctuations. The trap will work with minor variations, but these fluctuations will cause increase of noise in the detector.

Quantum projection noise dominates the short term sensitivity and the use of a double-interferometer will cancel the phase shift due to parasitic vibrations. The major contributor to the drift is the fluctuations of the atomic trajectories. When coupled to the Raman wave-front distortions, these fluctuations also limit the long term stability of the rotation measurements.

5.Compact atom interferometer for future space application.

The highly sensitive and stable cold atom gyroscopes have got many potential applications in spacecrafts and human space transportation systems. The major constraint in the development of sensors for space application is the size and mass of the setup. The life of laser source in the space environment, maintaining the system vacuum for longer period is other areas to concentrate. Even though a compact system is demonstrated by LNE-SYRTE, it is still on the higher side. The major lab setup which is space consuming is the turbo molecular and sublimation pumps which are used to create vacuum of the order of 10^{-9} mbar. For space application a vacuum sealed units can be used and minimum leak rate is to be ensured. Another area to address is the laser sources. Diode lasers are preferred compact sources, but the optical output power available is less.

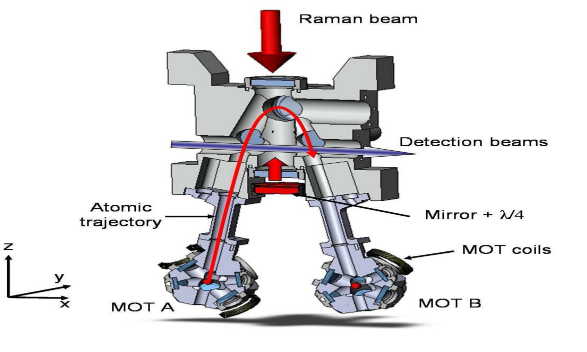

Figure 5. Scheme of the vacuum chamber by SYRTE showing the two MOTs, the interferometer.

The compact portable system developed by syrte is 30cmx 10cm x 10cm, without the vacuuming system. The only promising method for the gross reduction in size and weight is by the use of micromachining technology. The inherent imperfections in the mechanical structure significantly limit the performance, stability, and robustness of MEMS gyroscopes but are not very critical for atomic gyroscopes. The effect of structural imperfections on the sensing element becomes irrelevant and thus can be pursued for the fabrication of miniature atomic-scale gyroscopes with navigation grade performance.
In building atom physics based quantum devices on a chip calls for the integration numerous technologies on the same device, material quality and ultra high vacuum compatibility. High current is required for MOT and optical manipulation. Handling high current density inside the chip is another area to be addressed. Ultra cold atoms are extremely sensitive to variations in the magnetic potential and can be caused by non uniform current flow in the wires. Use of permanent magnetic film is another way of creating a Magnetic trap. These high current density lines will induce electrical stress on the substrate.

Multi layer chip fabrication techniques are instrumental. in an integrated atom chip, large structures (10 to 500 μm) for the initial trapping and cooling of atoms have to be combined with functional structures on the (sub) micrometer scale to achieve controlled manipulation at a length scale where tunnel coupling between sites becomes important. Further more, the versatile application of electric and magnetic potentials requires the crossing of wires on the chip without contact. In many applications the chip surface needs to be a high quality mirror, be it for cooling and accumulating the atoms in a mirror MOT or for imaging atoms close to the surface. Furthermore, reflection of light from the chip surface allows integrating optical dipole traps and optical lattices on the atom chip. By integrating micro optics and fiber optics on the atom chip one can incorporate optical micro manipulation and efficient detection of atoms. The atom chip is an ideal platform to integrate other solid state MEMS quantum devices. In future by integrating further optical sources and micro vacuum pumps into the atom chip we will be able to make compact atom gyroscopes for space applications.

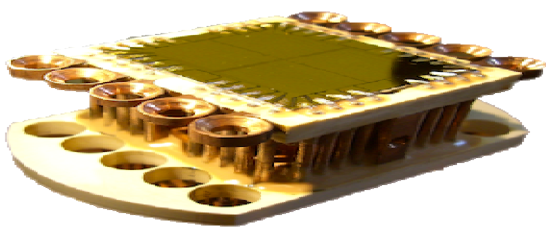

Figure 6. Multi layer atom chip realized by BEC scientists.

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6. Conclusion

Atom interferometry represents a quantum leap in the technology for the ultra-precise monitoring of inertial parameters like accelerations and rotations. A new kind of sensors using the matter wave interaction is realized by many research laboratories. The advancement in the field of matter-wave optics and interferometry techniques coupled with the quantum jump in the fabrication techniques of micro and nano structures will enable the realization of ultra compact cold atom gyroscopes with very high stability of the order of a few pico-radians for space applications.

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