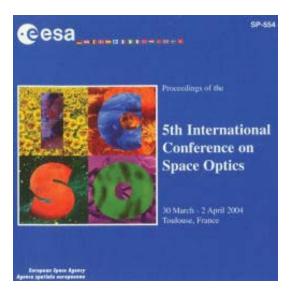# International Conference on Space Optics—ICSO 2004

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NEW OPTICAL TECHNOLOGY FOR COLD ATOM EXPERIMENTS

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ABSTRACT

In this proceeding we present a set of studies which are in progress in different labs and industrials. The aim of this project is to study the possibilities to design a very compact and reliable laser cooling bench for space and inboard applications.

INTRODUCTION

The Second is nowadays the best known unit among all the physical units. The definition of the Second is now realized with an uncertainty of about 10^{-15} in relative value. This improvement has been made possible thanks to the development of high performance atomic clocks using laser cooled atoms.

In an atomic clock, the frequency of a quartz oscillator is locked on an atomic transition frequency. The quartz oscillator has a very good short term frequency stability, but it presents some important drifts over timescale of a few minutes. In order to suppress this drift, the quartz frequency is compared to an atomic resonance frequency and locked on it with a servo loop. The quality of the clock directly depends on the duration of the interaction between atoms and the quartz signal. Longer the duration, smaller the uncertainty and higher the clock performance.

In an atomic clock using a thermal beam, the atoms come from an oven heated at about 100°C. The atoms propagate in the setup with a velocity of 300 m/s and the typical interaction duration is less than one to a ten milliseconds. In this case the quartz frequency can be ultimately locked with a relative uncertainty better than 10^{-14} .

Atoms with velocities from a few millimeter to a few meter per second can be obtained thanks to laser cooling technique. Influence of gravity is predominant for these velocities. Atoms are launched up on a ballistic trajectory in order to keep them in a limited volume during a time as long as possible. This configuration is called an atomic fountain. The interaction duration can be up to one second and the frequency stability and accuracy are better than 10^{-15}.

In a cold atom clock operating in microgravity, the interaction duration could be increased to ten seconds and the clock frequency performance could reach the level of 10^{-16}. The ACES project [1], supported by ESA, proposes to install such a cold atom clock (PHARAO developed by CNES) on board the International Space Station. USA has two similar projects : PARCS and RACE.

One of the main difficulties of these projects is to realize a compact and reliable set up, especially for the optical bench needed to cool the atoms. Several laser beams with well controlled intensity, polarization and frequency are needed to laser cool the atom.

It is clear that current optical benches are not optimized and new technologies have a very important role to play for the simplification and compactness of these optical benches.
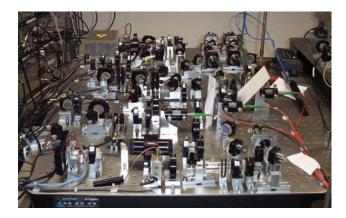

Fig. 1. Photography of a laser cooling bench used at the BNM-SYRTE (Paris Observatory) for an experiment

of cold atom gyroscope. More than a hundred components are necessary on this bench.

Several projects, impulsed by CNES, have started. The aim of these projects is to determine what are the best technologies to realized optical functions : high spectral purity laser source, frequency control, intensity control, beam splitting, … For example, reduced bandwidth DFB diodes are developed by Thalès TRT and some studies with MOEMs technology are in progress at LPMO in Besançon. In BNM-SYRTE laboratory, at Paris Observatory, we study some solutions for compact beamsplitters with different technologies (fibered optics, guided optics, miniature optical components).

The development of these reliable components is all the more important as they could be used for other setups than atomic clocks. For example, new high accuracy inertial sensors relying on atomic interferometry techniques require similar cooling optical benches. As atomic clocks, atomic inertial sensors take benefit from laser cooled atoms and operation in microgravity environment. These cold atom instruments may be used not only to test fundamental physics laws but also to improve the precision of inertial navigation and positioning systems (GALILEO, …).

PRINCIPE OF LASER COOLING BENCH

In order to cool the atoms, six well-known wavelength laser beams are necessary to trap the atoms in the three space directions. These laser beams are produced on the cooling bench, and they are transferred to the vacuum chamber where the atoms are. Frequency and intensity of these beams have to be modified during the different cooling phases (Doppler cooling, Sisyphus cooling, launching phase, …)[2].
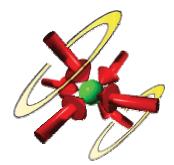
Fig. 2. Scheme of a magneto-optical trap : a cloud of about 10^9 atoms (in green) is cold and trapped. The laser beams (in red) exert a viscous force on the atoms whose velocity decrease from 100 m.s^{-1} to a few mm.s^{-1}. The width of the atomic velocity distribution is decrease in the same way. The magnetic gradient

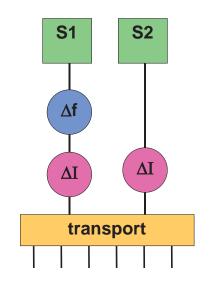induced by two coils (in yellow) exert an attractive force toward the center of the trap.

When the cooling is over the laser beams are switched off in a very good controlled way (t ~10 µs) and with a high extinction ratio (typically > 120dB).

According to the experimental setup (clock, gravimeter, gyroscope, …), atoms are then put in interaction with the physical effect to be measured (microwave field, gravity field, rotation, …). The information about the physical value is written in the atomic state then it is read in the detection phase by an interaction with a laser beam.

STRATEGY OF THE STUDY

The chosen method for this study is to separate the laser cooling bench in different functions to determine for each of them what is the well-adapted technology. Four main functions have been identified :
- Monomode laser sources with reduced spectral bandwidth (< 1 MHz for cooling and < 200 kHz for detection) and with sufficient power (typically 200 mW for cooling).
- Frequency shift of the laser beams for the different cooling and detection phases (Doppler cooling $\delta \sim -2\Gamma$ [1], Sisyphus cooling $\delta \sim -10\Gamma$, detection $\delta \sim 0$).
- Intensity control for the Sisyphus cooling ($I \sim I_{max}/10$) and for switch off the laser beams.
- Separation into six parts of the laser beams and transfer to the vacuum chamber.

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[1] δ is the frequency difference compared to the atomic transition, and Γ is the bandwidth of the transition (typically $\Gamma = 5,3$ MHz for cesium atoms)

Fig. 3. Scheme of a typical laser cooling bench. S1 is the laser cooling beam whose frequencey and intensity are controled very precisely. S2 is a second laser, called "repumping beam"which is necessary for the cooling process but which is not described in this proceeding.

Different studies with different technologies have begun, initiated by CNES, DGA and BNM-SYRTE.

LASER SOURCES

In conventional cooling bench the laser sources are Fabry-Perot laser diodes placed in external cavity (ECL) of about 3 to 5 centimeters in order to reduce its spectral bandwidth (from 30 MHz for a free laser diode to 200 kHz for a ECL) [3, 4]. The spectral selective component can be a reflective grating or a Fabry-Perot plate used in transmission. This technique has several disadvantages :

- Large number of components (from 4 for a Littrow ECL to more than 7 for an auto-aligned ECL) → unreliable with mechanical vibrations or thermal fluctuations.
- Output power is limited to about 30 mW → necessity to inject high power slave laser diode.

Three very different new projects are in progress to develop a compact and reliable laser source usable for cooling bench.

The first project, developed by Thalès-TRT and supported by CNES and DGA, is to design a distributed feedback Bragg laser diode (DFB) emitting at 852 nm (for D2 line transition of cesium). The objective is to realize a DFB diode with a sub MHz spectral bandwidth and an output power more than 100 mW.
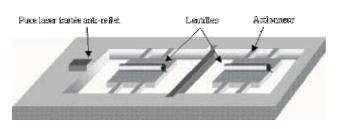

Fig. 4. Scheme of the ECL developed at the LPMO. The cavity is made by two selfoc lenses fixed on MEMs thermal actuators to control and stabilize the emitted wavelength.

A second project, developed by the LPMO in Besançon, take benefit of recent development in MEMs and MOEMs technology [5]. A laser diode chip is placed in an external cavity made by two selfoc lenses. The output facet of the first selfoc lens and the input facet of the second one act as the two faces of a Fabry-Perot interferometer which is spectral selective. The selfoc lens is fixed on MEMs thermal actuators, which permit to change the free spectral range of the Fabry-Perot.

A stabilization of the emitted wavelength on the D2 cesium line has been obtain by a technique of saturated absorption in a cesium cell. The spectral bandwidth has not been characterized yet.

SEPARATION OF THE LASER BEAM

The separation and transfer of the laser beam from the optical bench to the vacuum chamber have to verify two important conditions :

- The polarization of the beam has to be maintain during all the transfer.
- The equality of the output powers have to be insure to avoid dissymmetry and displacement of the atomic cloud.

In traditional cooling bench, laser beams are separated directly on the bench with half waveplate and polarizing beam splitter. Then six polarization maintain optical fibers are injected. A problem is that fiber injection fluctuates and induces power fluctuations at the output. The equality of power can not be guaranteed.

BNM-SYRTE and GEPI from the Paris Observatory have started a study to develop compact optical fiber splitter using miniature optical components. This splitter has two inputs and six outputs and its size is the same as this of a cigarettes packet. Design has been optimize to minimize the effects of temperature. A first prototype should be made in a few months.
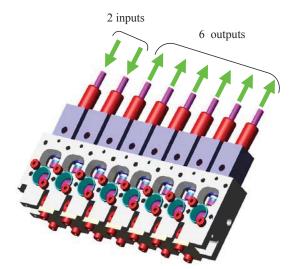
Fig. 5. Design of a splitter with 2 inputs and 6 outputs using miniature optical components (half waveplates and polarizing beam splitters).

Such splitter based on optical guide technology already commercially exist with working wavelength around 1 μm. A study for the possibility to translate this product at 852 nm is in progress. This component could be much compact as any component based on other technologies.

CONCLUSION

The cooling bench developed for PHARAO project still uses conventional optical components.
In a near future the realization of a compact and reliable cooling bench will be an important point to envisage new developments of atomic clocks and interferometers in microgravity and space environment. New technologies as optical waveguides, fibered optic, MOEMs, semiconductors developments, photonic crystals, … could offer new advantageous solutions for cooling benches.
CNES and some labs have started some studies but there is still lot of work to explore the possibilities of all these new technologies.

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