STUDY OF NEW MICROWAVE CAVITIES FOR THE HORACE PROJECT

P.-E. Pottie, Th. Zanon, S. Guérandel, S. Bila †, M. Aubourg †, and N. Dimarcq
BNM-SYRTE / UMR 8630 CNRS - Observatoire de Paris
61, avenue de l'Observatoire, F-75014 PARIS

† IRCOM - UMR 6615 CNRS
123, rue A.Thomas, F-87060 LIMOGES CEDEX
e-mail: paul-eric.pottie@obspm.fr

Abstract

We report on the study of three potential cavities for a project of miniature atomic cesium clock called HORACE. The goal is to achieve in a resonator smaller than 1 dm^3 a frequency stability at the level of a few $10^{-13}\tau^{-1/2}$, with an accuracy below 1.10^{-14} thanks to the possibilities given by the low velocities of cold atoms. The three potential shapes for the microwave cavity are a cylinder, a sphere and a capsule. The resonant frequency and the factor of quality have been measured as a function of the temperature and of its dimensions. For spherical and capsule-shape cavities, the phase gradients have been calculated at less than 60 μrad. This is more than 2 times better than for the cylinder.

1 Introduction

The BNM-SYRTE aims at designing a miniature high performance atomic clock by the use of cold cesium atoms (HORACE project [1]). The goal is to achieve in a cavity of a few centimeters a frequency stability in the $10^{-13}\tau^{-1/2}$ range, with an accuracy below 1.10^{-14} [1]. In this project cesium atoms are cooled, prepared, interrogated and detected inside the atomic resonator itself. There is no launching of cold atoms, and the functions applied to the cold atoms follow a temporal sequence. This means that the HORACE cavity must also comply with specific optical and chemical constraints.

As an illustration of this specificity we can consider that usual techniques of cooling with 6 laser beams along the three direction of space are here irrelevant: in order to keep a large number of cold atoms for the clock transition, we have to capture a large number of atoms. As the volume of the cold atomic cloud is bounded by the cross section of the 6 beams, 6 wide laser beams shall be implemented. Actually the wide holes needed to let the light enter into the cavity would induce a huge phase gradient [1] and so a big non-systematic frequency shift out of the specifications of the project. A smart solution is then to use isotropic cooling. Its principle is quite simple. The laser light is driven into a microwave cavity of high optical quality factor thanks to optical fibers. The diameter of the fiber holes is then 1 mm, and the perturbation of the microwave field is shown to be negligible. As the inner walls of the cavity are made highly reflective or highly diffusive, the life-time of photons in the cavity is increased, and the mean laser field experienced by the atoms in the cavity is expected to be isotropic. First proved by M. W. Ketterle et al. in two dimensions for transverse cooling of an atomic beam of Na [2], this technique has been successfully implemented for Cesium in 3 dimensions in spherical and cylindrical optical cells in the past at BNM-SYRTE [4, 5]. Moreover isotropic cooling exhibits attractive features for cold atoms clocks. There is a self-angular adaptation of the resonance condition [2], so that the capture velocity increases, whereas the loading time decreases. We measure temperatures between 3.5 and 50 μK, and a number of cold atoms between 10^7 and 10^9. The temperatures and the number of cold atoms reached depend on the shape of the cell, the number and the location of the fibers, the power and the detuning of the cooling beams [3].

Numerical simulations demonstrated that the shape of the cavity and the set-up of the fibers (regarding to their number and their location) strongly affect the isotropy of both energy and wave-vector of the laser field built in the cavities. It appears from these numerical calculations that configurations working with 6 fibers set up along the directions of a regular trihedron are always the best. Three shapes of cavity have been designed to produce cold cesium atoms from a vapor in a resonant cavity at 9.192 GHz. At present time, cold atoms have already been observed in a resonant square cylinder working with 6 multi-mode fibers.

In this paper, we report the results of the measured microwave properties for three potential cavities for

[1]HORACE: French acronym for *Horloge à Refroidissement d'Atomes en Cellule (Clock with cold atoms in cell)*

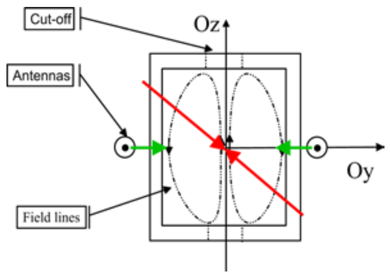

Figure 1: *TE_{011} cylindrical cavity and its magnetic field lines.*

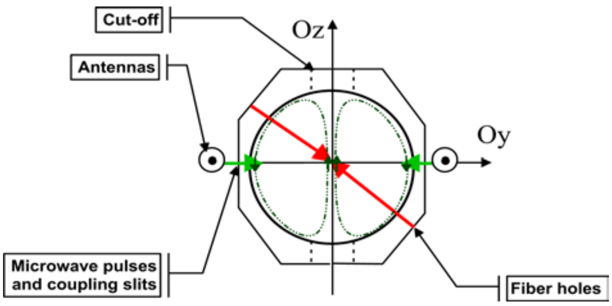

Figure 2: *Spherical cavity with a resonant TE_{011} mode. The figure shows the input direction of the laser light, and the symmetric coupling. The coupling cavities are not represented.*

HORACE, which are a square cylinder, a sphere, and a capsule. The capsule is two truncated hemi-spheres with a cylinder between the two spherical parts. The second section gives the features of the cylindrical cavity. The third and the fourth sections report the dependencies of the resonant frequency as a function of the temperature and of the inner dimensions of the microwave cavity (radius and/or height) for the sphere and for the capsule respectively. The calculus of the phase gradient reported here were done at IRCOM by a finite element method.

2 Cylindrical cavity

The cylindrical cavity is a usual TE_{011} cavity in OFHC copper [2]. Its dimensions are roughly 43 mm height and 43 mm diameter (Figure 1). There are two cut-off of 10 mm diameter. The oscillating H-field is coupled to the microwave cavity by one circular iris of 9 mm diameter. We tuned coarsely the cavity by adjusting the height of the cylinder. We measured a variation of the resonant frequency with temperature of -150 kHz/K. We tuned this cavity at clock cesium resonance. The loaded quality factor is $Q_L = 3500$. The total calculated phase gradient seen by the atoms falling from the center of the cylinder is less than 150 μrad. The residual first-order Doppler shift was then calculated to be lower than 9×10^{-15}.

A new cylindrical cavity was designed, with two symmetric coupling slits of 1×9 mm^2, the largest dimension being along the symmetry axis of the cavity. We expect to improve both the microwave quality factor and the optical quality factor since the area of the holes are smaller in case of a coupling slit. In addition, the laser field is expected to be more isotropic with the coupling slits since the losses will be symmetric.

[2]Oxygen Free High Conductivity

3 Spherical cavity

3.1 Resonant frequency

The sphere is made of two hemispheres of radius 23.33 mm in OFHC copper. The degeneracy of TE and TM modes is split by the two cut-off (diameter 10.5 mm), located at the top and bottom of the sphere (Figure 2), that break the spherical symmetry. The resonant mode is a TE_{011} mode, similar to the one of the cylindrical cavity. The oscillating H-field is coupled into the cavity by two coupling slits of 1×8 mm^2 and two symmetric antennas. Thanks to the slits, the microwave field is polarized, i.e. the TE modes are excited preferentially. We measured a loaded quality factor in the spherical cavity $Q_L \simeq 14000$.

The resonant frequency of a spherical cavity can be calculated by solving the Maxwell equations. The resonant frequency is then expressed as a function of the radius as (Eq. 1):

$$f_{res} = \frac{\alpha \cdot c}{2\pi \cdot r} \tag{1}$$

where c is the celerity of light in vacuum, α is a constant, and r is the radius of the sphere. For a TE_{011} mode, $\alpha = 4.4934$ [6]. This formula does not take into account the finite conductivity of the material used, nor the losses by the holes of the cavity (fiber holes, detection holes, coupling slit and cut-off). By derivation of this formula, one easily finds the local slope of the frequency as a function of the inner radius. We find $s = -396$ MHz/mm. We calculate the resonant frequency of our spherical cavity for several values of the radius by a finite element method, that takes into account all the losses. We then find a slope $s = -255$ MHz/mm (Figure 3).

The inner surface of the spherical cavity is optically polished in order to achieve an isotropic laser field. We measured the resonant frequency before and after polishing. The radius of the sphere has

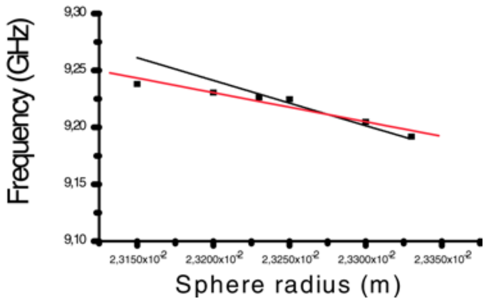

Figure 3: *Tuning of the spherical cavity. The square points are for the resonant frequency calculated by a finite element method. The plain line is for the linear fit of these data. The dotted line is the slope calculated analytically.*

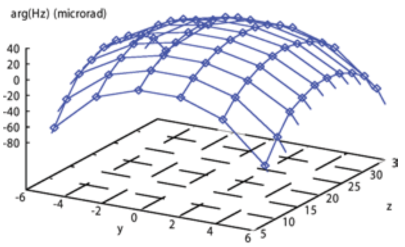

Figure 4: *Phase gradient of the resonant H-field in spherical cavity calculated by a finite element method. The atoms are falling freely in the cavity along the z axis.*

been measured by profilometry and laser interferometry methods. We then find slope of −280 MHz/mm (see figure 3), that is consistent with the result given by the finite element method at 11% level.

As the inner radius of the sphere cannot be machined in the laboratory the fine tuning to the clock frequency can be done by warping the two hemispheres, i.e. by machining the contact surface of the two hemispheres. A few 10 to 100 micrometers can be machined without disturbing significantly the geometry of the resonant mode. We measured the resonant frequency of the spherical cavity after a machining of 50 micrometers till a total machining of 200 micrometers. The resonant frequency increases linearly with a slope of +122 kHz/μm. Finally, the dependency with temperature was measured. The resonant frequency decreases linearly with a slope of −163 (±3) kHz/K.

3.2 Phase gradient

The module and the phase of the oscillating H-field were calculated at IRCOM. The plot of the phase is represented in Figure 4. It appears from Figure 4 that the total phase gradient of the resonant oscillating H-field seen by the cesium atoms distributed in a sphere of 10 millimeters diameter is lower than 60 μrad.

4 The capsule-shape cavity

4.1 Resonant frequency

In addition to the spherical cavity, we designed a capsule shape cavity. The 'capsule' is composed of two truncated hemi-spheres with a cylinder between the two spherical parts in such a way that the two hemispheres are with the same center of curvature (This is a concentric capsule, Figure 5). The main advantage is that this cavity is fully tunable in the laboratory by machining the height of the cylinder (similar to a regular cylinder cavity). The second advantage is that the volume of the cavity is bigger than the volume of the sphere. So the volume of capture is bigger too, and one can expect to get more cold atoms in this configuration.

The capsule is made in OFHC copper. The radius of the truncated hemisphere is 23.40 mm, and the cylinder height between the two hemispheres is 8.3 mm (Figure 5). The rough dimensions of the capsule were calculated to keep the volume of the TE mode equal to the TE_{011} mode volume in the cylindrical cavity [7]. The fine dimensions were adjusted first experimentally on a prototype, and second by finite element model developed at IRCOM. The resonant mode is a TE_{011}-like mode, similar to the one of the cylindrical cavity. We did not observe experimentally any degeneracy between TE and TM modes. The oscillating H-field is coupled into the cavity by two coupling slits of 1×6 mm^2 and two symmetric antennas. We measured a loaded quality factor in the capsule cavity $Q_L \simeq 16000$.

The resonant frequency of the capsule shape was only calculated by a finite element method, in the same way than for the sphere, taking as well into account all the losses. The resonant frequency was calculated by varying the radius of the spherical parts, and adjusting both the radius and the height of the cylindrical part to the dimensions of the hemispheres. We then found a slope $s = -380$ MHz/mm. This is 35% greater than the slope calculated for the sphere. This is not surprising since the height and the radius of the cylinder changed with the radius of the hemispheres. The capsule shape cavity was tuned to the clock transition of cesium by adjusting the height of the cylinder part. The resonant frequency increases linearly with the height of the cylinder. We measured

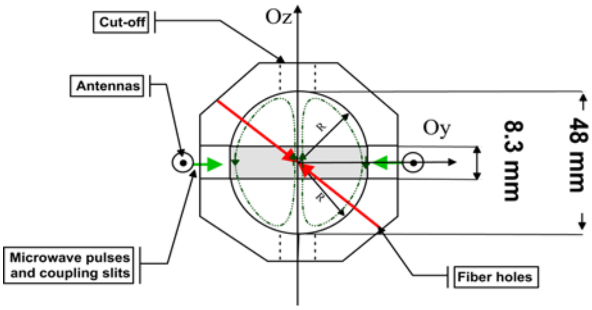

Figure 5: *Capsule-shape cavity with a resonant TE_{011}-like mode. The Figure shows the input direction of the laser light, and the symmetric coupling. The coupling cavities are not represented.*

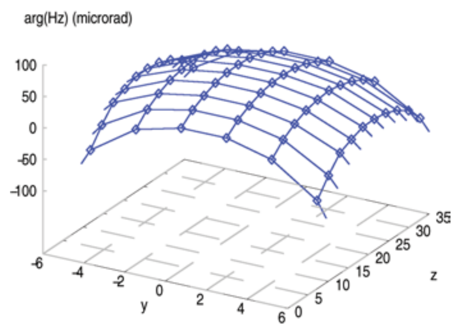

Figure 6: *Phase gradient of the resonant H-field in capsule-shape cavity calculated by a finite element method. The atoms are falling freely in the cavity along the z axis.*

a slope of +65 MHz/mm.

4.2 Phase gradient

The module and the phase of the oscillating H-field were calculated at IRCOM. The plot of the phase is represented in Figure 6. As for the spherical cavity, the total phase gradient of the resonant oscillating H-field seen by the cesium atoms distributed in a sphere of 10 millimeters diameter is lower than 60 μrad.

5 Conclusion

Three cavities have been designed and realized for the HORACE project. These three cavities exhibit very good properties for a clock transition. They are finely tunable to 9.192631770 GHz, with a potentially high Q_L, that is an advantage in case of a microwave detection of the clock signal. The phase gradient have been calculated to be lower than 60 μrad for the sphere and the capsule. Cold atoms have been obtained in the cylindrical cavity. The sphere and the capsule are currently under test for cooling.

Two detection methods of the clock signal shall be tested and compared. The first one is an optical detection of Ramsey fringes with the cycling transition $|F = 4\rangle \rightarrow |F' = 5\rangle$ on the D_2 line. A vertical standing-wave can go through the microwave cavity by the cut-off holes. The other method is a microwave detection. The atoms are first magnetized by a single $\pi/2$ pulse. If enough photons at 9.192 GHz are emitted when the relaxation of the atomic media occurs, the signal at 9.2 GHz can be collected by the coupling antennas and used to lock directly the local oscillator.

Aknowledgements

The authors gratefully acknowledge DGA and CNES that support this work. The authors deeply thank Pierre Petit for his help in the design of the capsule-shape cavity.

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