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NEW CONCEPT OF MINIATURE OPTICALLY PUMPED CESIUM BEAM FREQUENCY STANDARDS WITH A MULTIWAVELENGTH CYLINDRICAL CAVITY

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Abstract **-We developed an optically pumped cesium beam resonator based on a cylindrical cavity meeting the requirements of frequency stability in the range $10^{-11}\ \tau^{-1/2}$, compactness, lifetime and low cost, for telecom applications. It is named PHACS which means Probatoire d'Horloge Atomique Compacte Simplifiée. We demonstrated that the TE_{012} cylindrical cavity is the best choice. The interaction length is equal to 90mm. The configuration of the microwave field in the cavity requires a longitudinal static magnetic field, created by a solenoid which surrounds the cavity and the optical regions dedicated to the state preparation and to the detection of the atoms. Constitutive elements of the resonator are designed with a cylindrical symmetry. The resonator is operated with only one optical frequency tuned to a transition in the D1 line of the cesium atom. The main drawback of the cavity is the distributed phase along the atomic path. To control this problem, we implemented an original magnetic coupling which enables us to control any asymmetry between the two cavity lobes. The main features of the resonator PHACS are : a volume of 1.8 dm^3, a line-width of 2.2kHz and a signal to noise ratio of 10,000 in a 1Hz bandwidth. The short term frequency stability is 1.2 $10^{-11}\ \tau^{-1/2}$ from 1s to 10,000s. The relative frequency offset is 2.5 10^{-12} from TAI.**
Keywords – Atomic clocks, resonant cavity, frequency stability

I. INTRODUCTION

The purpose of this paper is to describe the design of an optically pumped cesium clock studied for telecommunication applications and to report the obtained results. The volume must be about 1dm^3, the target performance specifications are a frequency stability of about $10^{-11}\ \tau^{-1/2}$, a floor frequency stability better than 10^{-13} and a frequency accuracy better than 5. 10^{-12}. Consequently a cesium clock is needed.

Low cost is the main requirement in the domain of atomic clocks dedicated to telecom applications, and this is why rubidium clocks are generally used in this field. In the case of a cesium clock, in order to achieve a low cost design, it is necessary to significantly reduce the complexity of the device. We present the original design and realization of a compact resonator using a cylindrical cavity [1]. Indeed, the classical Ramsey cavity is a complex device that is used in the current commercial cesium clocks, but which is not compatible with a low cost design. Due to its cylindrical symmetry that leads to a very simple structure of the whole resonator, without the need of any mechanical adjustment during assembly, a cylindrical cavity should more easily meet the stated requirement.

II. CHOICE OF THE CAVITY

The choice of the cylindrical resonant cavity consists in determining the mode TE_{01n} which will provide the best frequency stability for a given volume. Consequently, we have investigated the modes for which i) the cavity Q factor remains high enough, ii) the resonant frequency is not too much dependent on the dimensions and iii) the signal to noise ratio of the atomic response remains high. Calculations were made assuming a cavity length of 90 mm. The three considered modes are shown in fig 1a, 1b and 1c.

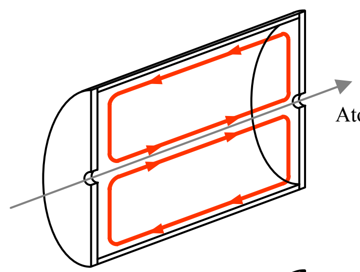


Fig.1a : TE_{011} mode
Atomic line-width = 3.7 kHz

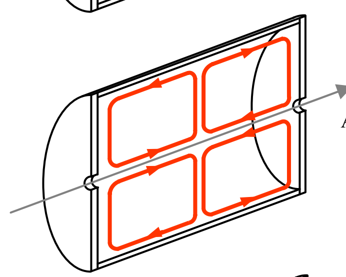


Fig.1b : TE_{012} mode
Atomic line-width = 2 kHz

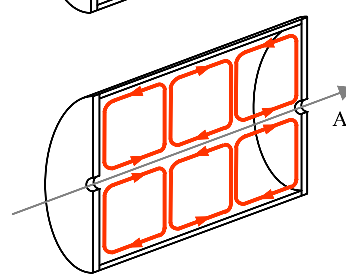


Fig.1c : TE_{013} mode
Atomic line-width = 3.6 kHz

The calculated atomic line-width is about 3.6 kHz for the TE_{011} and TE_{013} modes, and it is 2kHz for the TE_{012} mode, which provides an inverted fringe and other additional advantages [2]. As the expected signal to noise ratios are very similar in these three cases, the TE_{012} configuration is the most appropriate.

III. MICROWAVE FEEDING

The microwave signal can be injected either into one lobe or into both lobes of the TE_{012} mode, as respectively shown in figs. 2a and 2b. In order to determine the distributed phase along the atomic path, which can eventually induce a large frequency offset and likely associated frequency fluctuations, it is necessary to evaluate phase offset ϕ between the two lobes. The ideal phase offset is π, the calculated phase shift is $\pi+\phi(z)$, where $\phi(z)$ is the distributed spurious phase shift along the atom path. Without any calculation, it is obvious that :

- in the simpler case (fig.2a) the energy flux from the microwave feed, set in the middle of the first lobe, towards the distributed losses in the cavity walls will provide a very asymmetrical behavior and consequently $\phi(z) \neq 0$
- in the case of the double injection (fig.2b), the energy losses are symmetrical and should strictly provide $\phi(z) = 0$.

The phase shift calculation was made by the academic institute IRCOM (Institut de Recherche en Communications Optiques et Micro-ondes) located at Limoges, France, using a finite elements method.

The derivation of the relative frequency shift induced by the phase shift $\phi(z)$ requires the precise calculation of the atomic response with respect to the input frequency, then the simulation of the operation of the frequency servo that locks the ultra-stable oscillator frequency to the atomic reference line [3]

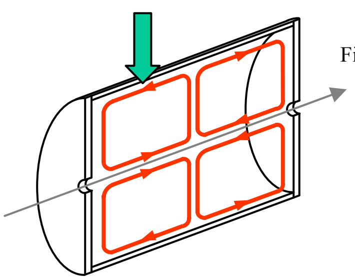


Fig.2a : Injection into one lobe
$\phi \approx$ 250 µrad
$\Delta f \approx$ - 80mHz
$\delta f/f \approx - 9.\ 10^{-12}$

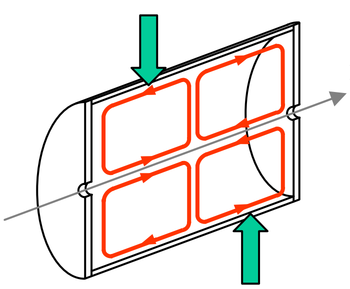


Fig.2b : Double injection (symmetrical)
$\phi \approx$ 5 µrad
$\Delta f \approx$ - 1.4mHz
$\delta f/f \approx - 1.5.\ 10^{-13}$

The results are shown aside the corresponding figures. The single injection scheme (fig.2a) does not fulfil the performance specification and cannot be retained.

With respect to the performance specification, the double injection set-up (fig.2b) is quite satisfactory though it does not provide a theoretical frequency offset strictly equal to zero. This might be due to the finite size of the calculation step of the micro-wave field. This set-up requires means to properly balance the power and the phase of the two injected signals. This is the only exception to the simplicity of our design.

IV. RESONATOR ASSEMBLY

As previously mentioned, the leading idea of this resonator conception is simplicity. The cylindrical symmetry of the general structure makes possible the automatic alignment of all its coaxial parts.

Assembling this resonator is a very simple operation : the various components are progressively added around the resonant cavity shown in fig.3, where we see the two coupling devices. The microwave feeding is provided by two semi-rigid cables of appropriate lengths entering two flat non resonant boxes coupled to the cavity by an iris.

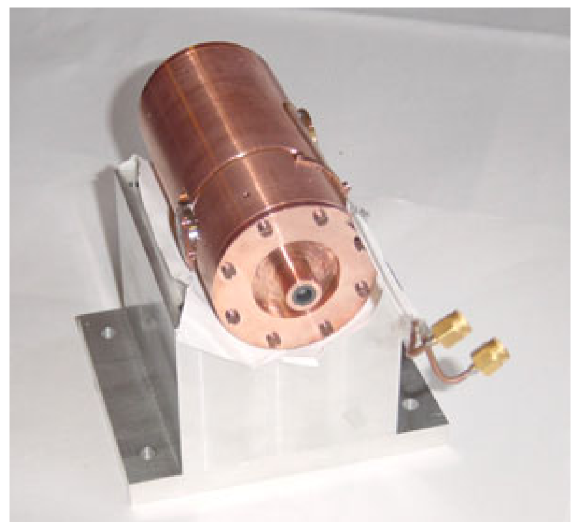


Fig.3 : The cylindrical cavity and its double microwave feeding

The optical blocks for the optical preparation and the optical detection of the cesium atoms are fixed at the ends of the cavity. In fig.4, the right optical set-up is dedicated to the atomic preparation by means of optical pumping.

Fig.4 : The resonant cavity and the optical blocks

The laser light is injected in the horizontal plane, and the fluorescence light detected through the upper hole is used to lock the laser.

The left optical set-up is dedicated to the detection of the atoms after their interaction with the microwave field. The fluorescence light is detected through the upper hole and it provides the so-called "clock signal".

The ensemble is surrounded by a cylinder holding the solenoid which generates the static magnetic field (fig.5).

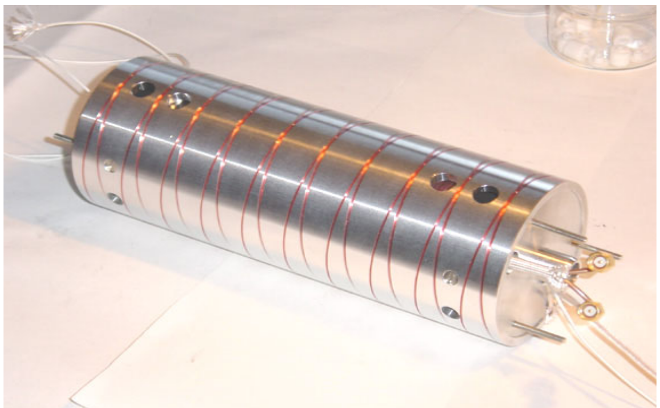


Fig.5 : The solenoid and its support

The next steps consist in placing the magnetic shields around the solenoid and the ensemble in the vacuum tank. The vacuum envelope holds the cesium oven, and the mono-channel ejector is mechnically centered on the axis of the resonator, which coincides with the atomic beam path.

It is worth mentioning that assembling this resonator does not require any adjustment. The volume of the vacuum enclosure is roughly $2.5dm^3$, but the basic volume of the resonator including the magnetic shields and the cesium oven is only $1.8dm^3$ and can be reduced.

V. Optical configuration

The optical source is a DBR laser at 894nm from SDL. Its line-width is typically 5MHz, and the available power is about 10mW. The light is π polarized. A single optical frequency is used, and it is tuned to the $F = 3 \rightarrow F' = 4$ hyperfine transition of the cesium atom D1 line, by means of a frequency-lock using the detected fluorescence signal in the preparation region. The choice of this transition provides several advantages [4]: i) since this transition is insensitive to the Hanle effect, it is not necessary to have several separated magnetic field zones in the resonator, which allows the use of a single solenoid as previously mentioned and of a simple magnetic shielding structure, ii) since the transitions are well separated, by more than 1GHz, it is not necessary to have a very narrow laser line, and the frequency servo of the laser is easy to implement using the fluorescence light in the first optical interaction zone, iii) this transition provides a very efficient preparation providing a population difference equal to 14,4% and delivers a satisfactory average number of 2.4 photons per atom in the detection zone.

The scheme of the optical set-up is presented in fig.6 and it shows the very simple design of the optical part.
The optimum light powers are 2.5mW and 0.1mW in the pumping and the detection zones respectively.

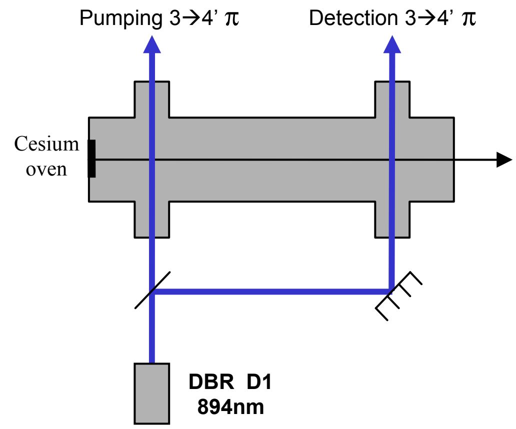


Fig. 6: Scheme of the optical set-up

VI. Experimental results

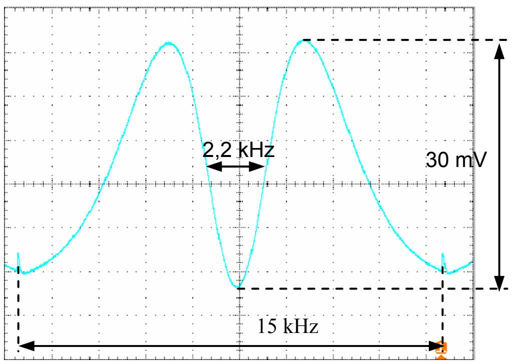
The seven resonance patterns are in agreement with the predictions concerning the TE_{012} cavity [3], in particular the fact that the resonance line is inverted.

The mean static magnetic field, derived from the splitting between the reference line and the neighboring lines, is 8.785µT. The possible microwave π transitions [5] [6] which should be located between the seven microwave σ transitions are not seen. This is due to the very small diameter of the atomic beam compared to that of the microwave cavity and consequently to the very small value of the microwave field components perpendicular to the static field. Furthermore, this shows that the static magnetic field is closely parallel to the cavity axis.

The reference fringe is depicted in fig.7. Its line-width is 2.2kHz, which is in good agreement with the theoretical prediction. The signal to noise ratio is 10,000 in a 1Hz bandwidth.

In the very first stability measurements, made with the simpler, but asymmetrical microwave feed, coupled to one of the two lobes of the cavity field, the stability curve showed several bumps. It did not reach the 10^{-13} level but remained in the vicinity of 10^{-12} for sampling times of a few hours. In this initial experimental configuration, the second microwave input, coupled to the other field lobe, was loaded by 50Ω. We observed that the frequency was very dependent on the microwave power, of the order of several 10^{-11} /dB in the vicinity of the optimum level. The corresponding relative frequency offset was -3.10^{-11} and we probably observed frequency fluctuations induced by small microwave power fluctuations.

S/N = 10000



Detuning / reference frequency

Fig.7 : Central reference line

Then, the 50Ω load on the second microwave feeding was suppressed, and we observed the reduction of the spurious effects. The sensitivity of the frequency to power fluctuations was then a few 10^{-12}/dB, the optimum stability was in the range of several 10^{-13} and the frequency offset was -1.10^{-11}, in good agreement with the theoretical prediction of -9. 10^{-12} corresponding to the single injection configuration.

Then we implemented the double microwave feeding set-up which appears to be necessary to fulfil the specifications. Taking into account our previous experimental remarks, we adjusted the phase and power balances to minimize the sensitivity of the frequency to power fluctuations. After a quick adjustment of the balance, we obtained the curve indicated as "second measurement" in fig.8.

The frequency stability is in very good agreement with the signal to noise ratio of 10,000. The Allan standard deviation is $\sigma_y(\tau) = 1.2\ 10^{-11}\ \tau^{-1/2}$. The medium term stability shows a significant bump at half a day, which probably means that the balance between the two microwave inputs was not perfect, or that this balance was not stable enough in this preliminary test.

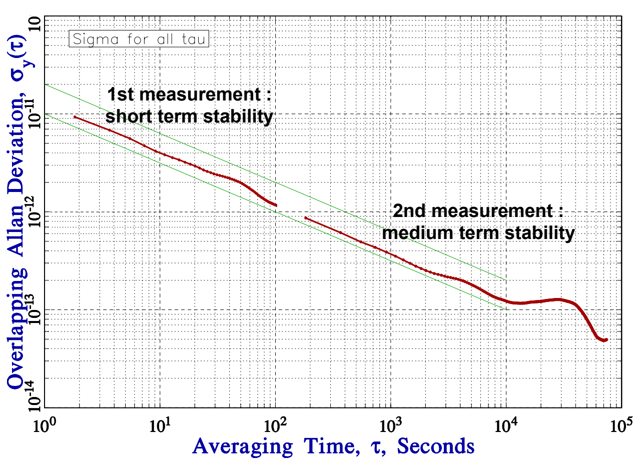


Fig.8 : Frequency stability of PHACS

The relative frequency offset obtained with this double feeding configuration is 2.5 10^{-12}, which is a satisfactory value for a compact clock dedicated to telecommunication applications.

Conclusion

This new concept for a compact frequency standard gives very satisfactory results and the target specifications are fulfilled. The accuracy budget is not yet known, but the measured frequency offset is quite promising. The external balance adjustment provides the means for externally compensating the internal phase shift : today, this easy and interesting feature does not exist in any other cesium beam clock.

Acknowledgment

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