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Quadratic dependence on temperature of Cs 0−0 hyperfine resonance frequency in single Ne buffer gas microfabricated vapour cell

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Presented is the observation of a quadratic temperature dependence of the Cs 0−0 ground state hyperfine resonance frequency in a single Neon (Ne) buffer gas vapour microcell. The inversion temperature, expected to be theoretically independent of the buffer gas pressure, is measured to be about 80°C for two different samples. A proposal to develop chip scale atomic clocks with improved long-term frequency stability, simpler configuration (a single buffer gas instead of a buffer gas mixture) and then relaxed constraints on pressure accuracy during the cell filling procedure is presented.

Introduction: In the last decade, the significant advances in micromachining technologies and semiconductor lasers combined with the coherent population trapping phenomenon [1] has allowed the development of chip scale atomic clocks (CSAC) [2, 3]. These miniature time references, exhibiting typical frequency stability of the order of 10^{-10} at 1 s and 10^{-11} at 1000 s to 1 day for a volume of a few tens of cm^3 and a power consumption of 150 mW, are of great interest in various portable battery-operated applications, such as navigation receivers and telecommunication systems.

The heart of these miniature frequency standards usually consists of a microfabricated alkali vapour cell, formed in a wafer of silicon with glasses bonded to both sides. The cell is filled with buffer gases in order to prevent wall relaxation, increase the atom−light interaction time, and reduce the Doppler broadening [4]. Nevertheless, slight interactions taking place between alkali atoms and buffer gases cause a frequency shift of the hyperfine transition of the atom. This shift $\Delta\nu$, of the order of several hundreds of Hz per Torr, is expected to be dependent on the nature of the gas, pressure and operating temperature T, and can be expressed as in [5]:

$$\Delta\nu = \nu - \nu_0 = P_0[\beta + \delta(T - T_0) + \gamma(T - T_0)^2] \qquad (1)$$

where ν_0 is the unperturbed Cs atom frequency and P_0 is the pressure at the reference temperature $T_0 = 273$ K. Dedicated measurements of β, δ, γ values, known as pressure and temperature shift coefficients, are mainly limited by the uncertainty of the filling pressure and temperature at the time of cell fabrication [6−8].

Quadratic dependence on temperature of hyperfine resonance frequencies, as expressed in (1), has already been observed in various atomic vapours using a single buffer gas [9]. However, in that case, inversion curvatures often occur at unpractical temperatures for such devices. Thus, in most cases, a strong quadratic dependence of the frequency on temperature is obtained by using a mixture of buffer gases [5]. This technique is well-known for the implementation of rubidium frequency standards. Nevertheless, this method presents numerous challenges. First, the precise determination of the required total pressure as well as the buffer gas pressure ratio to (hopefully) obtain the quadratic dependence at the expected working temperature is made difficult by the fact that temperature coefficients reported in the literature suffer from a relatively wide dispersion. This difficulty is enhanced in the case of the Cs atom for which quadratic temperature coefficients γ values are unknown. Secondly, from a technological point of view, the accurate control of the filling pressure and temperature at the time of cell fabrication is a relevant challenge. This key task is particularly critical in the case of microcells usually sealed by anodic bonding techniques at high temperatures (350°C) and presenting a very small volume.

Based on simple temperature shift measurements, in this Letter the possibility of developing CSAC architectures based on Cs vapour cells filled with a single Ne buffer gas is demonstrated. This original solution would greatly release constraints and reduce the difficulties previously mentionned.

Experimental setup and measurements: We have realised pressure shift measurements through optical detection of CPT resonances in Ne buffer-gas-filled Cs vapour cells, microfabricated according to the process flow described in [10]. The experimental setup is shown in Fig. 1. Two phase coherent optical frequencies needed to perform dark line resonance spectroscopy are generated by phase modulating

at 4.596 GHz (half of the Cs hyperfine 0−0 transition frequency) a single distributed feedback (DFB) laser using an external pigtailed electro-optical modulator (EOM). The DFB laser emits a wavelength resonant with the Cs D1 line at 894 nm. At the output of the EOM, the collimated beam is attenuated with a variable neutral density filter, changed to circular polarisation and sent through a 2 mm-diameter and 1 mm-long microcell. The microcell temperature is stabilised to within 1 mK. The atomic resonator is surrounded by a solenoid applying a static magnetic field of 160 mG in order to raise the Zeeman degeneracy. The ensemble is inserted into two cylindrical mu-metal magnetic shields to prevent perturbations from external spurious magnetic fields. The laser frequency is locked near the centre of the Doppler-broadened absorption line by modulating the laser DC current at 50 kHz and demodulating the photodiode signal with a lock in amplifier (LA1). The dark line resonance is detected by scanning the frequency of the microwave synthesiser (MS) driving the EOM and measuring the transmitted power through the cell. To increase the signal-to-noise ratio, the synthesiser frequency is modulated at 556 Hz and the photo-diode signal is demodulated with a second lock-in amplifier (LA2). The experimental procedure to measure the Cs-buffer gas pressure shift is similar to the one described in [11]. For each temperature, light shift measurements are previously realised. Interpolation to null intensity is then assumed to reject the contribution of the light shift and then estimate the pressure frequency shift after the subtraction of the Zeeman shift contribution. It has been observed that the light shift can be greatly reduced by adjusting the RF power injected in the EOM. In the optimal case, the light shift is reduced to a level of a few $Hz/(mW/cm^2)$.
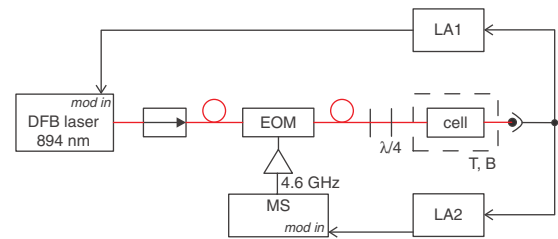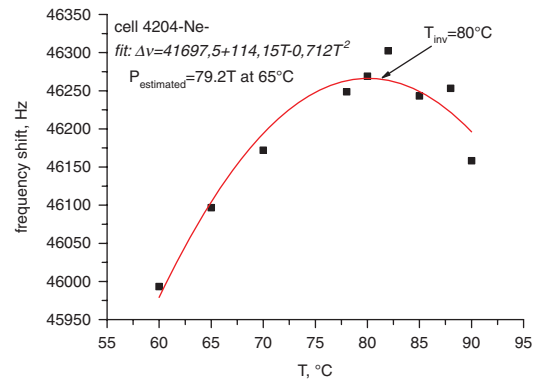

Fig. 1 *Experimental setup*

Fig. 2 *Frequency shift against cell temperature*

Fig. 2 shows the frequency shift of the Cs 0−0 hyperfine resonance against the operating temperature of a Cs microcell filled with Ne buffer gas. The squares are the experimental data while the solid line is a computer fit of (1) to the data. It is clearly shown that the frequency−temperature dependence is nulled at the first order for an inversion temperature $T_{inv} = 80$°C. This measurement is in agreement with the buffer gas pressure shift measurements recently made in SYRTE, Observatoire de Paris [12] using a high-performance pulsed CPT clock. From the fitted curve, we deduce through temperature coefficients given by Beverini [8] that the actual Ne pressure in the microcell is 79.2 Torrs. In this relatively high-pressure condition, the CPT resonance linewidth is measured to be about 8 kHz using a total laser power $I = 100\,\mu$W. The curvature C around T_{inv} of the frequency−temperature characteristic defined as $C = 1/\nu\delta^2\nu/\delta T^2 = 2P_0\gamma/\nu$ is $1.5 \times 10^{-10}\,K^{-2}$. Assuming that the temperature control system allows to set the cell temperature T_c at $T_{inv} \pm 100$ mK with rms temperature fluctuations $dT = 10$ mK around T_c, the clock frequency stability would be

limited to 1.5×10^{-13}. A similar result has been obtained with a second Ne-filled Cs microcell, presenting about the same inversion temperature. To our knowledge, such an observation for Cs−Ne interactions has never been reported in the literature. Note that we also tested microcells filled with Argon (Ar) in the same temperature range, but no quadratic dependence has been observed. In that case, pressure shift data are very well fitted by a pure linear function in the 40−90°C temperature range.

Conclusions: We report on Cs−Ne buffer gas pressure shift measurements through the optical detection of CPT resonances in a vapour microcell. An inversion temperature for which the sensitivity of the Cs 0−0 transition frequency−temperature fluctuations is nulled at the first order, is observed around 80°C. This result highlights exciting opportunities to develop CSAC using a single buffer gas cell with improved long-term stability.

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