Cesium Microcell Optical Reference at 459 nm With Short-Term Stability Below 2.5×10^{-13} at 1 s

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***Summary*—We report on the development and short-term stability characterization of lasers stabilized onto the $6S_{1/2}$-$7P_{1/2}$ transition of Cs atom at 459 nm using a microfabricated vapor cell. A laser beatnote, obtained between two quasi-identical systems, demonstrates an instability below 2.5×10^{-13} at 1 s, in good agreement with the noise budget, and limited by the laser frequency noise through the FM-AM conversion process and the intermodulation effect. The dependence of the laser frequency to the laser power at the cell input and the cell temperature variations are also measured. These results are promising for the demonstration of microcell-based optical references with stability performances approaching those of hydrogen masers in a simple architecture.**

Keywords—Optical references; sub-Doppler spectroscopy; microfabricated cells; alkali vapor; frequency stability;

Hot vapor MEMS-cell based optical frequency standards can constitute the basis of a new generation of miniaturized clocks. These references keep the benefit of using wafer-scalable and mass-producible vapor cells, prevent ultra-high vacuum technologies and laser cooling, and are well adapted for integration and low power features, with the use of low-noise integrated lasers, photonics, and frequency combs.

Several approaches have been explored with microfabricated cells, most of them based on sub-Doppler spectroscopy techniques. The two-photon spectroscopy of Rb atom at 778 nm has met a great success. This transition exhibits a natural linewidth of about 330 kHz and can be accessed using frequency-doubled telecom lasers. The photonic integration of a 778 nm two-photon Rb microcell clock was first demonstrated in [1]. Efforts were then produced to achieve a compact optical reference [2] while record stability results at the level of 1.8×10^{-13} at 1 s and approaching the 10^{-14} level after 100 s, were later obtained by using a low noise external cavity diode laser (ECDL) to probe the atoms [3]. Short-term stability results in the low 10^{-13} range were also obtained by using a different transition of ^{87}Rb atom in a Rb vapor microfabricated cell [4].

Short-term stability results in the low 10^{-13} range at 1 s were also achieved in a Cs microcell using dual-frequency sub-Doppler spectroscopy [5]. However, this technique requires the generation of a microwave modulated optical field, generally obtained with an EOM, complexifying the architecture of the microcell optical reference.

Saturated absorption spectroscopy (SAS), that yields the detection of sub-Doppler resonances in the bottom of Doppler-broadened absorption profiles in a simple configuration setup, is also an elegant technique for laser frequency stabilization. SAS was extensively used for laser frequency stabilization in glass-blown vapor cells [6, 7]. We'll mention here the nice integration of a very compact Rb cell optical reference in [8, 9], ensuring a stability of 1.4×10^{-12} at 1 s and below 10^{-11} at 10^5 s.

Modulation transfer spectroscopy (MTS) [10] is also a frequently-explored option for laser stabilization. MTS was used to stabilize lasers in the 10^{-14} range on the D_2 line of Rb [11] and at the level of 2.1×10^{-13} at 1 s using the $6S_{1/2}$-$7P_{1/2}$ transition of Cs atom at 459 nm [12]. However, these tests were performed in cm-scale long glass-blown vapor cells. In addition, MTS is obtained by separating the pump and probe beams, thus adding an electro-optic modulator in the pump beam path, such that the reference setup complexity is increased.

In a previous work [13], we have characterized sub-Doppler resonances detected in a microfabricated cell by probing, with SAS, the Cs atom $6S_{1/2} - 7P_{1/2}$ transition at 459 nm. This transition is attractive since it exhibits a natural linewidth lower than 1 MHz and a frequency twice higher than more usual near-infrared transitions. The impact of the laser intensity and cell temperature on the sub-Doppler resonance was experimentally investigated while detection noise measurements allowed to project a short-term stability in the low 10^{-13} range at 1 s.

In this work, performed in the continuity of [13], we describe the implementation and short-term frequency stability characterization of a laser beatnote obtained between two ECDLs, each stabilized onto the $6S_{1/2} - 7P_{1/2}$ transition of Cs atom at 459 nm, using SAS in a basic retroreflected configuration setup, within a buffer-gas free Cs microfabricated vapor cell [14]. The MEMS cell consists on two cavities etched in silicon, connected by channels, and sandwiched between two anodically-bonded glass wafers. Filling of the cell with alkali vapor is performed after its final sealing by laser-activating a pill dispenser embedded into the cell during its fabrication. The chamber in which the atom-light interaction takes place is 2-mm in diameter and 1.5-mm in length. Experiments were performed at a cell temperature of about 118°C.

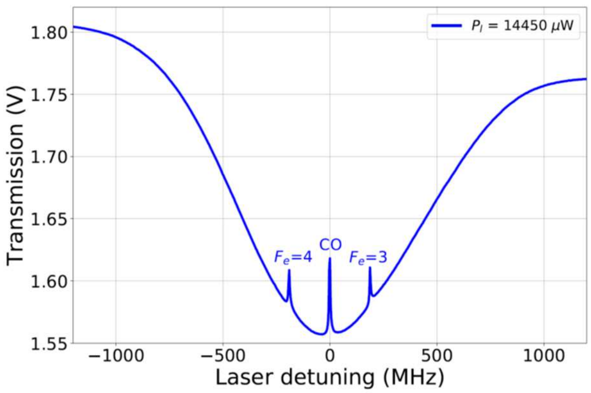

Fig. 1. Sub-Doppler spectroscopy of the $6S_{1/2}$-$7P_{1/2}$ transition in a Cs-microfabricated vapor cell. The lasers are locked onto the central cross-over resonance.

Each laser system simply combines an ECDL, an isolation stage and a retro-reflected SAS setup in a Cs microcell. The reflected probe beam, obtained by placing a mirror at the cell output, is detected through a cube placed at the cell input by a photodiode. The photodiode output signal is sent into a lock-in amplifier used to demodulate synchronously the atomic signal and generate a zero-crossing error signal, used to send back, through a PI controller, a correction to the laser current driver. No laser power stabilization stage was implemented to date.

Figure 1 shows a typical spectrum at the output of the cell when the laser is scanned over a wide range. Each laser is stabilized onto the central cross-over resonance that appears in the middle of both transitions, corresponding to F_e=3 and F_e=4 excited states of the $7P_{1/2}$ state, frequency-split by 377.6 MHz. Results reported in this work were obtained with a total laser power at the cell input of about 14 mW.

The laser beatnote between the two laser systems is obtained through the use of an AOM. This beatnote at 110 MHz is then amplified, filtered, and counted by a frequency counter, referenced to a 10 MHz signal from an active hydrogen maser.

The laser beatnote obtained between the two laser systems demonstrates an instability lower than 2.5×10^{-13} at 1 s, currently limited by the laser frequency noise through the FM-AM conversion process and the intermodulation effect [15]. Assuming that both lasers contribute equally to the total frequency fluctuations, the stability of a single laser system is then below 1.8×10^{-13} at 1 s. The Allan deviation of the laser beatnote was measured to average down in the low 10^{-14} range at 100 s, before being degraded by frequency shifts that remain to be studied in more detail, and later mitigated.

Studies are in progress to possibly improve the microcell references' short-term stability. Lasers with lower FM noise would help. To date, in the lab, the increase of the laser modulation frequency and of the probe/pump power ratio are possible options envisioned in a first step. The possibility to reduce the total laser power at the cell input, while maintaining comparable short-term stability performances, will be also explored.

Recently, we have measured the lasers' frequency reference to variations of some key experimental parameters. Measured coefficients are in the order of a few 10^{-11}/K for the cell temperature and lower than 10^{-12}/mW for the total laser power. These values are in the same order of magnitude than coefficients reported in [7] in a saturated absorption spectroscopy setup. The important thermal sensitivity suggests that careful control of the cell temperature will be required for good long-term stability.

Latest results, both for the short-term and the mid-term stability, will be reported at the conference.

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