Exploring dual-frequency sub-Doppler spectroscopy for a Cs microcell-based optical frequency reference

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Abstract—**Dual-frequency sub-Doppler spectroscopy (DF SDS) in vapor cells allows the detection of enhanced-absorption natural-line-width resonances. We investigate here the application of this spectroscopy technique into a Cs micro-fabricated cell. The dependence of the sub-Doppler resonance on the laser intensity is described. The influence of the cell temperature and the retroreflection mirror position was also studied. A preliminary laser beat-note between two 894 nm lasers, each stabilized using DF SDS, demonstrates an Allan deviation lower than 2 $\times$ 10^{-12} at 1 s and at the level of 10^{-12} at 10^2 s. Main contributions to the short-term and mid-term stability budget are under study. Latest results will be reported at the conference.**

I. INTRODUCTION

Inspired by significant progress demonstrated in the domain of state-of-the-art optical clocks [1], [2] and MEMS cell-based atomic frequency references [3], [4], [5], an exciting research investigation path is to propose the development of next-generation ultra-miniaturized cell-based optical frequency references. In this field, original studies and results have already been reported. This includes the study of Doppler-free resonances in microfabricated cells [6], the stabilization of VCSELs onto Doppler-broadened resonances [7], the stabilization of a Brillouin scattering laser onto a Rb microcell [8], sub-Doppler spectroscopy technique using an integrated photonic waveguide [9] or the recent photonic integration of a miniaturized optical clock based on detection of the Rb 778 nm two-photon transition in a microfabricated cell [10]. The latter frequency reference exhibits a remarkable frequency instability level of $4.4 \times 10^{-12}\tau^{-1/2}$ until 1000 s [10] whereas previous works [7], [8], [9] were often limited at the level of about 10^{-11} between 1 s and 10^4 s. Note also excellent frequency noise performances reported by ultralow noise miniaturized external cavity semiconductor laser using whispering-gallery mode optical micro-resonators [11].

In a recent study [12], the detection of high-contrast sign-reversed natural-linewidth Doppler-free dips in a Cs vapor cell has been reported using dual-frequency sub-Doppler spectroscopy (DF SDS). Properties of these enhanced-absorption spikes, explained by the contribution of Zeeman dark states, hyperfine dark states and optical pumping effects, has been investigated in [13]. This technique has been employed to improve the frequency stability of Cs vapor cell atomic clocks [14], [15]. More recently, an extended theoretical model of DF SDS has been developed [16], highlighting the interest to apply this spectroscopy technique to short-length cells since optimized contrast of the sub-Doppler resonance can be obtained with proper adjustment of the retroreflection mirror. In the present work, we propose to investigate the potential of DF SDS in a Cs microfabricated vapor cell for laser frequency stabilization application. We describe the experimental setup. We report preliminary Allan deviation results of a laser beat-note between two lasers (one ECDL and one DFB), each frequency-stabilized using the DF SDS technique.

II. EXPERIMENTAL SETUP

The experimental setup is analog to a standard saturated absorption scheme setup [17], [18]. The main difference is that, instead of being illuminated by two counter-propagating single-frequency optical fields, atoms in the cell interact with two counter-propagating dual-frequency optical fields [12]. Both counter-propagating beams have orthogonal linear polarizations [12], [13]. The frequency difference between both optical lines of the bi-chromatic field is close to the hyperfine splitting frequency (9.192 GHz for Cs atom).

The laser source is an extended cavity diode laser, tuned on the Cs D_1 line at 895 nm. An optical isolator is placed at the output of the laser to prevent optical feedback. The laser beam, with a diameter of 1 mm, is directed into a Cs vapor micro-fabricated cell. The cell technology is analog to the one described in [19], without buffer gas. The science cavity of the cell is 2 mm-diameter and 1.4-mm long. The cell is temperature stabilized and surrounded by a mu-metal magnetic shield. At the output of the cell, the dual-frequency laser beam is reflected by a mirror. The laser beam crosses the cell a second time and is detected by a photodiode at the output of the cell.

III. EXPERIMENTAL RESULTS

We measured the line-width and height of the sub-Doppler resonance for a cell temperature of 60°C. We found that the linewidth gets close to the natural-linewidth for small laser power values and is increased with increased laser power, yielding 50 MHz for a laser power of 1 mW. The height of the resonance is increased with the laser power up to about 200 μW, before reaching a saturation plateau.

We stabilized the frequency of the ECDL onto the sub-Doppler resonance detected in the Cs vapor microcell. For this purpose, the laser current is slightly modulated (to modulate the laser frequency). The voltage signal at the output of the photodiode is synchronously demodulated with a dedicated digital lock-in amplifier. The zero-crossing error signal is then processed into a PI controller and used to correct the laser frequency. The ECDL output beam is superimposed with another laser beam, coming from a distributed-feedback (DFB) laser, stabilized using DF SDS onto a 2-cm and 2-cm diameter long Cs vapor cell. Using a fast photodiode, a laser beat-note between both lasers at about 4.6 GHz is generated. This signal is mixed with the microwave signal coming from a microwave frequency synthesizer, driven by a hydrogen maser. A final beat-note at about 22 MHz is then counted with a frequency counter.

The Allan deviation of the laser beat-note is measured, in a preliminary way, at the level of 2×10^{-12} at 1 s and 10^{-12} at 100 s integration time. This preliminary short-term stability result at 1 s is encouraging and is about 50-100 times better at 1 s than commercial chip-scale atomic clocks [20]. This demonstrates that DF SDS is an interesting approach for the development of a cell-based optical frequency reference, with potential for miniaturization. Studies are in progress to estimate main contributions to the optical frequency reference fractional frequency stability at 1 s and 100 s. Latest results will be presented at the conference.

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REFERENCES

[1] M. Schioppo et al, “Ultrastable optical clock with two cold-atom ensemble” *Nature Photonics* **11**, 48-52 (2017)

[2] [2] N. Huntemann et al. “Single-ion atomic clock with 3 10^{-18} systematic uncertainty”, *Phys. Rev. Lett.* **116**, 063001 (2016).

[3] S. Knappe et al. “A microfabricated atomic clock”, *Appl. Phys. Lett.* **85**, 9, 1460 (2004).

[4] R. Lutwak, et al., “The Chip-Scale atomic clock - recent developments”, *in Proc. 2009 Joint Meeting IEEE Int. Freqency Control Symp. and EFTF Conf.*, Besancon, France, 573-577 (2009).

[5] J. E. Kitching “Chip-scale atomic devices”, *App. Phys. Rev.* **5** 031302 (2018).

[6] S. Knappe, H. G. Robinson and L. Hollberg, “Microfabricated saturated absorption laser spectrometer” *Opt. Express* **15**, 10, 6293-6298 (2007).

[7] F. Gruet et al., *Opt. Lasers Eng* **51**, 8, 1023-1027 (2013).

[8] [8] W. Loh, M. T. Hummon, H. F. Leopardi, T. M. Fortier, F. Quinlan, J. Kitching, S. B. Papp and S. A. Diddams, “Microresonator Brillouin laser stabilization using a microfabricated rubidium cell”, *Opt. Express* **24**, 13, 14516-14524 (2016).

[9] M. T. Hummon, S. Kang, D. G. Bopp, Q. Li, D. A. Westly, S. Kim, C. Fredrick, S. A. Diddams, K. Srinivasan, V. Aksyuk and J. Kitching, “Photonic chip for laser stabilization to an atomic vapor with 10^{-11} instability”, *Optica* **5**, 4, 443-449 (2018).

[10] Z. L. Newmann et al, “Photonic integration of an optical atomic clock”, *ArxiV* **1811.00616** (2018).

[11] W. Liang et al., “Ultralow noise miniature external cavity semiconductor laser”, *Nature Comm.* **8371**, 1-6 (2015).

[12] M. Abdel Hafiz, G. Coget, E. de Clercq, and R. Boudot, “Doppler-free spectroscopy on Cs D1 line with a dual-frequency laser”, *Opt. Lett.* **41**, 2982 (2016).

[13] M. Abdel Hafiz, D. Brazhnikov, A. Taichenachev, V. Yudin, E. de Clercq and R. Boudot, “High-contrat sub-Doppler absorption spikes in a hot atomic vapor cell exposed to a dual-frequency laser field”, *New J. Phys.* **19**, 073028 (2017).

[14] M. Abdel Hafiz, G. Coget, P. Yun, S. Guerandel, E. de Clercq and R. Boudot, “A high-performance Raman-Ramsey Cs vapor cell atomic clock”, *J. Appl. Phys.* **121**, 104903 (2017).

[15] P. Yun, F. Tricot, C. E. Calosso, S. Micalizio, B. Francois, R. Boudot, S. Guerandel and E. de Clercq, “High-performance coherent-population trapping clock with polarization modulation”, *Phys. Rev. Applied* **7**, 014018 (2017).

[16] D. Brazhnikov, M. Petersen, G. Coget, V. Maurice, N. Passilly, C. Gorecki and R. Boudot, “Dual-frequency sub-Doppler spectroscopy: Extended theoreticql model and microcell-based experiments”, ArxiV 1812.09641 (2018).

[17] V. S. Letokhov and V. P. Chebotaev, “Nonlinear laser spectroscopy”, Springer, Berlin (1977).

[18] W. Demtroder, “Laser spectroscopy. Basic concepts and insrumentation”, Third edition, Springer-Verlag, Berlin (2003).

[19] R. Vicarini, V. Maurice, M. Abdel Hafiz, J. Rutkowski, C. Gorecki, N. Passilly, L. Ribetto, V. Gaff, V. Volant, S. Galliou, and R. Boudot,“Demonstration of the mass-producible feature of a Cs vapor microcell technology for miniature atomic clocks” *Sens. Actuators A: Phys.* **280**, 99-106 (2018).

[20] https://www.microsemi.com/product-directory/clocks-frequency-references/3824-chip-scale-atomic-clock-csac