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Title: Miniature Cs vapor cells and atomic clocks in FEMTO-ST.

Abstract:

Over the last decade, the progress of micro-electro-mechanical systems (MEMS) technologies and semiconductor diode lasers, combined with coherent-population trapping (CPT) physics [1], has allowed the development of miniature atomic clocks (MACs) of great interest for many applications. These frequency references, using a buffer-gas filled micro-fabricated alkali vapor cell, a vertical-cavity surface-emitting laser (VCSEL) and electronics, deliver a fractional frequency stability in the order of 10^{-11} at 1 day integration time, for an extremely modest power consumption and volume (150mW-15cm^3). The first MAC prototype was demonstrated in NIST [2] and has led later to the first commercially-available MAC product proposed now by Microsemi [3]. While numerous projects are still actively pursued worldwide, the Microsemi product remains to date the unique commercially-available MAC using a microfabricated cell. The present talk aims to give an overview on MEMS Cs cell technology and CPT-based clocks activities performed in FEMTO-ST.

In the first section of this presentation, our MEMS Cs vapor cell technology, using post-sealing laser activation of a Cs pill dispenser, will be briefly presented [4-5]. Different buffer gas or buffer gas mixtures, using generally Ne buffer gas, have been proposed to cancel the temperature dependence of the Cs clock frequency around a desired inversion temperature [6]. More recently, the use of a cesium dispensing paste has been proposed and studied in detail [7]. The latter avoids the delicate manipulation of numerous individual pills during the cell wafer development and is expected to be more suitable with the mass production of such MEMS cells. The cell technology developed in FEMTO-ST has been recently transferred to a MEMS foundry and manufacturer industrial partner, whose facilities allows the production of about 500 microcells on 6-inch wafers. Some first statistics on this production will be given.

In a second section, two automated dedicated setups, developed in FEMTO-ST for tests of MEMS Cs cells, will be presented. The first one is used to perform Cs activation and linear spectroscopy of multiple buffer-gas filled MEMS cells at the wafer-level. The second setup is a specific CPT clock setup dedicated to measure the contribution onto the clock long-term fractional frequency stability of the buffer gas permeation process through the cell windows [8-9]. Such tests, under progress with various MEMS Cs cells using borofloat glass or alumina-silicate glass (ASG) [9], including industrial cells, will be reported.

In a third section, laboratory-prototype microcell-based Cs cell atomic clocks will be presented. These clocks use VCSELs tuned on the Cs D_1 line [10]. Novel fully-miniaturized physics packages, designed in FEMTO-ST and fabricated by our industrial partner, using the industrial version of our cell technology, have been successfully tested. The typical clock fractional frequency stability is measured to be $2.5 \times 10^{-11} \tau^{-1/2}$ up to 500 s averaging time and better than 2×10^{-11} at 10^5 s (without drift removal) [11]. A detailed short-term and mid-term stability budget, at 1 s and 1 day averaging time respectively, will be reported. The implementation of advanced electronics stabilization loops has been tested to improve the clock long-term stability.

In a fourth section, several in-progress exploration paths in the domain of miniature Cs cells and clocks in FEMTO-ST will be discussed. This includes the use of HBAR-based sources as local oscillator of the MEMS Cs clock [12], the first demonstration of Ramsey-CPT spectroscopy in MEMS cells [13] and the in-progress test of a totally-novel Cs cell filling method that would benefit from the dispenser solution advantages while tackling its residual drawbacks [14].

In the end, we'll discuss about possible exciting perspectives targeting in the future the development of next-generation miniature quantum microwave or optical clocks with stability performances about 100 times better than current CSACs at 1 day averaging time, for a modest size-power increase.

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