Performance of a 3 cc Yb^+ trap as a microwave clock after 10 years

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***Summary*—We describe the performance of several miniature buffer-gas-cooled Yb ion radio frequency Paul traps that were sealed in 2012 and 2018. The ground state hyperfine splitting of each trapped ion ensemble is interrogated and used to correct a local oscillator forming two clocks. We also describe progress towards demonstrating a novel 369 nm edge emitting diode laser.**

Keywords*—atomic clock; microwave reference; ion trap;

Buffer-gas-cooled microwave ion clocks (MICs) have demonstrated superior time deviation after one day for a given clock volume when compared to commercially available microwave clocks (see Ref. [1]). Their reduced time loss compared to commercially available vapor cell devices is attributed to the lower buffer gas pressure they require. Additionally, the interaction of trapped ions with their container (revolving electromagnetic fields) is smaller than the interaction of neutral atoms with their container (vapor cell walls).

Despite these advantages, MICs have not been miniaturized to the same extent as vapor cell-based clocks. This is in part due to the UV-blue photons required to optically pump MICs and the high purity miniature vacuum package required to house the ion trap. Vapor cell clocks utilize near infrared photons for optical pumping. Low size, weight, and power laser architectures have been demonstrated at near infrared wavelengths but the extension of these architectures to UV-blue wavelengths has proven challenging. Below we discuss our progress towards developing a UV edge emitting diode laser as well as our characterization of several miniature ion traps that have been sealed for as many as 10 years.

Miniature Ion Traps: We have operated two 3 cc ion traps as microwave clocks using a commercial laser system along with tabletop electronics and optics. In this work, we compare the frequency offset between two local oscillators each disciplined by the measured ground state hyperfine splitting of an ensemble of Yb ions confined in separate 3 cc radio frequency Paul traps. Both ion ensembles are interrogated using a shared laser system. The ground state hyperfine splitting of each ion ensemble is interrogated using a Rabi scheme with a microwave interrogation time of 1.6 s. The ADEV and MDEV under ideal conditions are shown in Fig. 1. The MDEV exhibits $5 \times 10^{-13}\,\tau^{-1/2}$, consistent with the photon shot noise limit, integrating down to 1×10^{-14} after 2 ks of integration. An identical ion trap previously demonstrated $1.6 \times 10^{-12}\,\tau^{-1/2}$, consistent with the local oscillator instability, integrating down to 4×10^{-13} after 40 s of integration [2]. We attribute the 3× improved short term performance compared to Ref. [2] to the increased microwave interrogation time enabled by using a more stable local oscillator. Long-term instability $< 1 \times 10^{-14}$ has been demonstrated in larger vacuum packages [3,4]. We are actively investigating the sources of systematic uncertainty that currently limit the stability at long integration times.

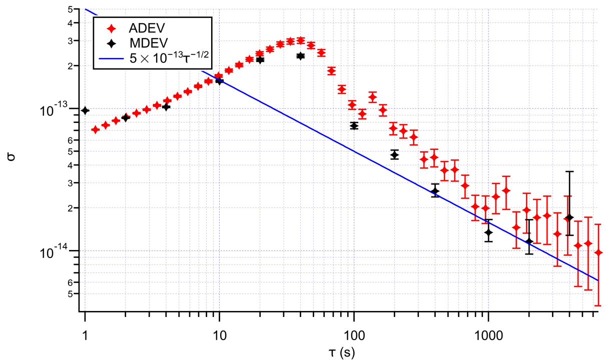

Fig. 1. Measured fractional frequency stability of the frequency offset between two local oscillators each disciplined by the measured ground state hyperfine splitting of an ensemble of Yb ions confined in separate 3 cc radio frequency Paul traps. The ADEV (red) and MDEV (black) are calculated from the same data. The blue trend line depicts $5 \times 10^{-13}\,\tau^{-1/2}$.

The two traps used to demonstrate Fig. 2 were sealed (*i.e.*, only passively pumped with a getter) in 2012 and 2018. The trap that was sealed >10 years ago has maintained a trapped ion lifetime of several weeks suggesting that the vacuum package has maintained its integrity over time. Demonstrating such a long shelf life is an important milestone towards the commercialization of miniature MICs.

369 nm Laser Development: Sandia has been developing III-N based lasers with emission wavelength at 369 nm to support $^{171}Yb^+$ clocks. Over the past few years, we have encountered numerous challenges spanning from laser design/simulation -to- epitaxial growth -to- device fabrication. Many of these challenges have been overcome leading to demonstrations of pulsed laser operation near the wavelength of interest. Here, we will highlight several of the development challenges and our solutions.

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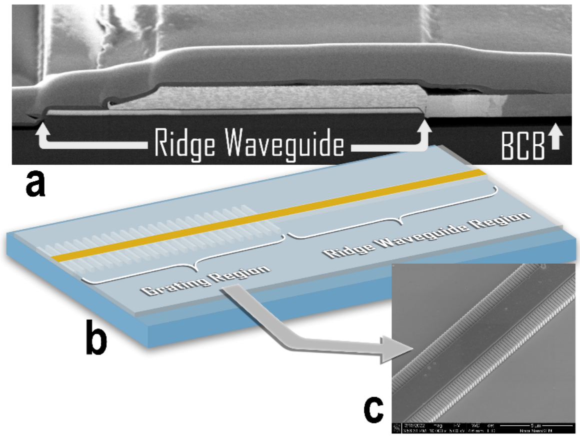

Fig. 2. a) Electron micrograph of a cross-section of a ridge waveguide device showing the thick BCB dielectric layer. b) Isometric drawing of the grating-stabilized laser design. c) Electron micrograph of the fabricated sidewall grating.

One of our first efforts was to reduce the epitaxial cracking due to strain accumulation. We are using GaN substrates and as such we need to ensure that the optical mode does not penetrate the absorbing substrate. Increasing the lower cladding thickness, in our original design, lead to wide-spread strain induced epitaxial cracking. Our solution was to decrease the thickness of the lower cladding and at the same time increase the thickness of the waveguide core, adopting a large-optical-cavity design. These changes eliminated strain induced epitaxial cracking greatly improving the diode yield across the wafer.

Fabrication of laser devices involves formation of a ridge-waveguide structure and the use of a large-area pad metallization for direct probing. We found that using a thin dielectric, such as SiN, of a few thousand Angstroms thick, resulted in electrical shorting under high current injection due to dielectric thickness variations near surface features. We solved this problem by using benzocyclobutene (BCB) as a planarization layer that both increased the separation between the pad metallization and the underlying semiconductor and offered improved processing tolerance when revealing the p-type metallization on the ridge-waveguide (see Fig. 2).

Finally, we are using a sidewall grating structure to stabilize the operating wavelength of the laser and, after exploring numerous grating formation techniques, have found that we achieve the best grating fidelity using an electron-beam defined dielectric mask to etch both the ridge waveguide region and the grating region simultaneously. This way we can have the ohmic p-metal defined and annealed prior to ridge waveguide formation. We continue to make advancements in the epitaxial layer design and anticipate continuous-wave operation in the next design cycle.

References

[1] B. L. S. Marlow and D. R. Scherer, "A Review of Commercial and Emerging Atomic Frequency Standards." IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 68, no. 6, pp. 2007-2022 (2021).

[2] Scherer, David R., *et al.*, "Analysis of Short-Term Stability of Miniature 171Yb+ Buffer Gas Cooled Trapped Ion Clock". Proceedings of the 49th Annual Precise Time and Time Interval Systems and Applications Meeting, pp. 95-99 (2018).

[3] H. Park et al., "171Yb+ Microwave Clock for Military and Commercial Applications," 2020 Joint Conference of the IEEE International Frequency Control Symposium and International Symposium on Applications of Ferroelectrics (IFCS-ISAF), 2020, pp. 1-4

[4] P. T. H. Fisk, M. J. Sellars, M. A. Lawn and G. Coles, "Accurate measurement of the 12.6 GHz "clock" transition in trapped /sup 171/Yb/sup +/ ions," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 44, no. 2, pp. 344-354, March 1997