Optically-Based Low Noise Microwave Phase-Locked to a H-Maser for the SYRTE Atomic Fountains

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***Summary*— Reaching quantum projection noise in atomic fountains requires a low-noise ultra-stable microwave signal. Here we present results on our microwave generation based on the frequency division of a 1542 nm carrier by a frequency comb, while being phase-locked to an H-maser on long time scales. We discuss preliminary spectroscopy results on Cs and Rb in our four microwave fountains.**

Keywords*— *atomic fountain; microwave generation; remote clock comparison; optical frequency comb; quantum projection noise

I. Introduction

The short-term stability of state-of-the-art microwave atomic fountain clocks is limited to a few $10^{-14}/\sqrt{\tau}$ by the Quantum Projection Noise (QPN). To reach such a level, a sufficiently low phase noise microwave source must perform the probing of the metrological atomic transition.

At SYRTE, Observatoire de Paris, three Cs and one Rb microwave fountains are currently in operation and contribute to the realization of UTC(OP) and to the calibration of the scale unit of TAI (International Atomic Time). A Cryogenic Sapphire Oscillator (CSO) cooled with liquid Helium is used to filter out the short-term noise of the reference H-maser which allows us to reach the QPN of these four atomic fountains [1]. This CSO operates at 11.98 GHz, it exhibits a short-term frequency stability at the 1×10^{-15} level, and is slowly phase-locked (time constant ~1000 s) to the H-maser.

Nevertheless, the worldwide ongoing helium shortage, resulting from the international context, forced us to stop the operation of the CSO in early May 2022. In order to recover the capacity to run our fountains at the QPN level, we started the development of an operational low-noise microwave signal based on the frequency division of a 1542 nm carrier by an optical frequency comb [2,3], and phase-locked to the H-maser on longer timescales.

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II. Methods/Results

Our historical configuration is based on a 1542 nm ultrastable laser featuring a frequency floor at 5×10^{-16} at 1s, and frequency locked to the reference maser on time scales of a few 100 s. This hybrid oscillator acts as an optical reference for our two operational erbium fiber laser based frequency combs, and for the REFIMEVE research infrastructure. Nevertheless, in order to avoid inaccuracies due to phase changes, a phase-lock must be implemented. In this paper, we present our approach to replace the CSO-based 11.98 GHz low-noise microwave by a signal at the same frequency but resulting from optical division. The objectives are long-term reliability and high uptime, rather than extremely low phase-noise.

Since the 1542 nm laser features a behavior considerably less predictable than the CSO, together with a largely superior drift, preparatory steps were necessary to evaluate experimental parameters and to perform numerical simulations. We first calculated the various sets of frequency comb parameters and offsets to add in the optical and/or RF domains to reach the target frequency. We then numerically optimized the feedback algorithm taking into account a realistic behavior of the 1542 nm ultrastable laser. Notably, we discuss the possibility to add various layers of numerical integrators in order to counter residual frequency excursions of the 1542 nm laser and to best follow the maser phase. Simulations show the capacity to remain at most a few 10^{-15} away from the target frequency.

Our experimental setup takes as reference a 12 GHz maser signal distributed by a stabilized fiber link. It is compared to the 48th harmonics of the repetition rate of an optical frequency comb, pre-adjusted such that $48f_{rep} \sim 11.98$ GHz. The difference is offseted close to 275 kHz, and multiplied by 200 to produce a ~ 55 MHz signal measured by a dead-time free phasemeter. The comparison to an exact 55 MHz signal yields an error signal numerically integrated to correct the tuning word of a DDS (Direct Digital Synthesizer) used as offset on the optical frequency, with a time constant of ~ 10 s. Optical comparisons to independent ultrastable lasers (698 nm, 1062 nm) give access to the out-of-loop behavior of the 1542 nm laser. They show the slow phase-lock to the maser allows the 1542 nm frequency stability to remain at the few 10^{-15} level or below until the maser drift (~1×10^{-16}/day) kicks in.

Finally, we present the results of the comparison between this new 11.98 GHz source and our Cs or Rb atomic fountains. An independently stabilized link disseminates the signal to the fountains lab, where it feeds the existing microwave architecture in replacement of the CSO. Preliminary results show promising fountains stabilities, potentially approaching the QPN limited regime.

III. CONCLUSIONS

In this paper, we present our new scheme to generate a hybrid microwave, featuring both the excellent short-term frequency stability of an optical cavity and the long-term phase predictability of an H-maser. Preliminary stabilities against microwave fountains confirm its capacity to replace our 11.98 GHz cryogenic oscillator. In the context of fibers links-based international fountains comparisons and of the upcoming PHARAO-ACES mission, recovering this capacity is of utmost importance. Future work will aim at building a fully operational system, and at verifying that the spectrum of the new signal does not induce unwanted biases on the fountains signals.

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