Implementation of coherent detuning to suppress microwave leakage in cesium fountains at NIST

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***Abstract*—A potential source of frequency bias in atomic fountains is due to atomic interactions with microwave fields outside of the resonant cavity used for Ramsey interrogation. The effects of microwave leakage can be suppressed by detuning the microwaves from the atomic resonance. To apply this technique for microwave leakage while the atoms are above the Ramsey cavity, the additional detuning must introduce zero net phase accumulation between Ramsey interrogation intervals. It has been shown that this can be achieved by manipulating a direct digital synthesizer (DDS) coherently with the DDS system clock. We have developed an implementation of the coherent detuning scheme in which a commercial, off-the-shelf microcontroller is used to control the DDS. We present measurements of the phase evolution achieved with our approach and show that it can be used to suppress a large frequency bias due to microwave leakage while the atoms are above the Ramsey cavity.**

***Index Terms*—cesium fountains, microwave leakage, direct digital synthesis**

I. Introduction

In an ideal cesium fountain, atoms interact with the microwave field used for Ramsey interrogation only inside of the Ramsey cavity. In reality, the field is not perfectly confined, and it is possible for stray fields that leak out of the Ramsey cavity or the microwave synthesizer to perturb the atoms and cause a frequency bias in the fountain. Microwave leakage has been extensively investigated in cesium fountains and several techniques have been demonstrated to suppress it [1]–[4]. These techniques work by either reducing the amplitude of any leakage fields or by changing the frequency of the microwaves so that the leakage field is detuned from the atomic resonance.

In the coherent detuning approach, a frequency bias due to microwave leakage is suppressed by introducing an additional detuning into a direct digital synthesizer (DDS) that is part of the microwave synthesizer used for Ramsey interrogation [4]. By choosing the magnitude and duration of the detuning or by manipulating the phase offset registers of the DDS, one can arrange for the additional detuning to increment the phase by an integer multiple of 2π. To implement the coherent detuning scheme, it is necessary to synchronize changes in the frequency of the DDS with the DDS system clock and the fountain cycle. Kazda and Gerginov [4] achieved this by combining a complex programmable logic device (CPLD) and a delay generator phase-locked to the microwave synthesis chain to ensure that the DDS could be detuned for exactly the required number of DDS system clock cycles.

We have developed an implementation of the coherent detuning scheme based on a microcontroller unit (MCU). With this approach, we are able to implement the coherent detuning scheme using commercial off-the-shelf components and without phase locking the MCU or the fountain control system to the microwave chain. In section II, we describe our implementation and present measurements to characterize its performance. In section III, we show that the coherent detuning can be used to suppress a bias due to microwave leakage above the Ramsey cavity by introducing a large microwave leakage in NIST-F3 [5].

II. Implementation of Coherent Detuning

Our implementation of the coherent detuning scheme is diagrammed in Figure 1. A timer-counter module in the MCU observes the "SYNC-OUT" signal, which is an output from the DDS chip derived by dividing the DDS system clock, "SYSCLK". The frequency of the DDS can be changed synchronously with the rising edges of the sync-clock by manipulating a three-bit profile register [6]. The timer-counter module in the MCU includes several logical outputs that can switch state when the count passes a programmed value without the use of software or interrupt driven timing [7]. These timer-counter output pins drive the DDS profile register, which allows the MCU to make changes in the DDS frequency that are synchronized with the DDS reference clock.

In our system, we make use of the AD9956 as the DDS and the Arduino Due as the MCU[1]. The DDS reference clock frequency is 50 MHz, obtained by dividing a 100 MHz signal from the hydrogen maser driving the microwave synthesis chain. The sync-clock frequency is 12.5 MHz. The clock frequency for the MCU is 84 MHz, which makes it possible to count the sync-clock directly. At the beginning of each

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[1]Any mention of commercial products is for technical clarity only. It does not imply endorsement or recommendation by NIST.

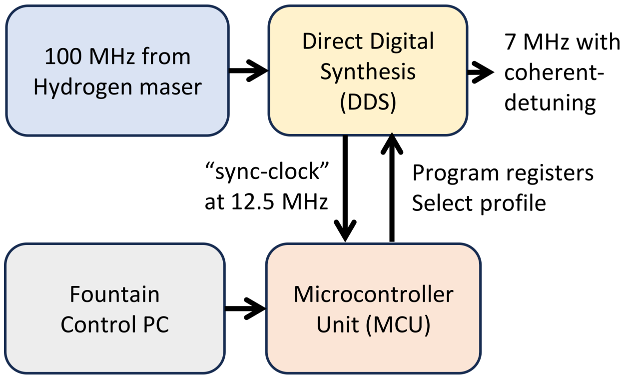

Fig. 1. Schematic diagram of our implementation of a DDS with coherent detuning while the atoms are above the Ramsey cavity.

fountain cycle, the MCU programs the frequency tuning words associated with each of several DDS profile registers. Shortly after the atoms are launched, the MCU receives a trigger from the fountain control system which initializes the timer-counter module. Since this trigger is not synchronized with the DDS reference clock, there will be timing jitter between the fountain sequence and frequency changes in the DDS up to one "sync-clock" period or 80 ns, which is negligible. For fountain operation, the DDS output frequency near 7 MHz is mixed with the output of a dieletric resonator oscillator (DRO) at 9.2 GHz. A more detailed description of the microwave synthesis chain can be found in [8].

A coherent detuning during the time the atoms are above the Ramsey cavity can be implemented with two settings of the DDS profile register. Other entries in the DDS profile register can be used to detune the microwaves before the first Ramsey interaction or after the second Ramsey interaction, when the atoms are located below the Ramsey cavity. To observe the behavior of the DDS and search for possible phase errors or transients caused by the MCU driving the DDS profile register, we use a triggerable, digital lock-in amplifier (MFLI from Zurich instruments[1]) to measure the phase of the signal output by the DDS. Several examples of the phase evolution that can be obtained are shown in Fig. 2a-c. In Fig. 2a,b, the DDS frequency is "on-resonance" only for two short windows corresponding to the two Ramsey interactions in a fountain sequence. In Fig. 2a, the detuning and duration of the DDS state between the two Ramsey interactions have been chosen so that the DDS phase increments by an integer multiple of 2π and the two resonant windows are in phase. In Fig 2b, the duration of the detuned DDS state between the two resonant pulses has been increased by one sync-clock cycle compared to Fig. 2a, which produces a phase shift. In Fig. 2c, the microwaves are only detuned after the second Ramsey interaction. For the microwave leakage experiment described below, we interleave fountain measurements with the DDS configured in "coherent detuning" mode as in Fig. 2a and "detuned below the cavity" as in Fig. 2c.

To verify that we are able to control the DDS behavior at

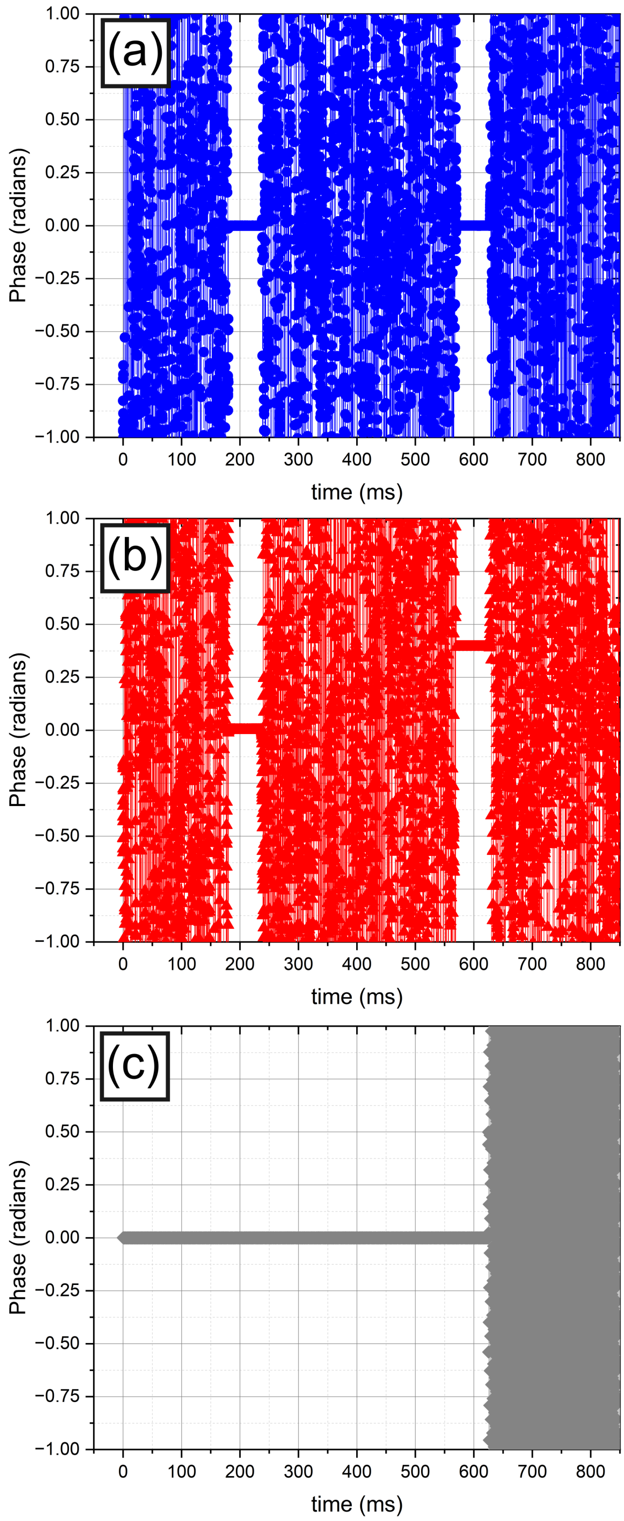

Fig. 2. Phase evolution of the DDS in three configurations. (a) coherent detuning with two "resonant pulses" in-phase. (b) coherent detuning with the duration of the state between the two resonant pulses increased by one sync-clock cycle. (c) Detuning only after the second Ramsey interaction. For these traces, the DDS nominal output frequency was 4 MHz and the additional detuning was approximately 1 MHz. When the DDS is detuned, the phase cycles continuously from $-\pi$ to $+\pi$.

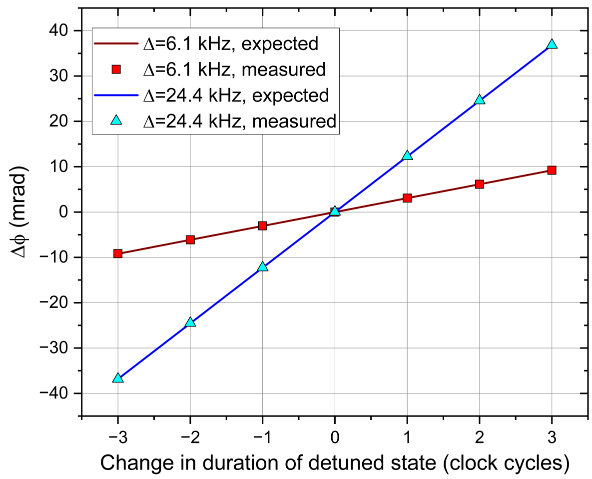

Fig. 3. Measured phase shift after the coherent detuning state as a function of the detuning and the duration. The duration of the coherent detuning state is controlled by the threshold count value programmed into the MCU. We vary the threshold count by ± 3 from the value calculated to produce a phase shift that is an integer multiple of 2π. Each point was obtained by averaging about ten runs of the DDS. For each point, the scatter in the measurements is of order 50 μrad. Error bars are not shown on the plot.

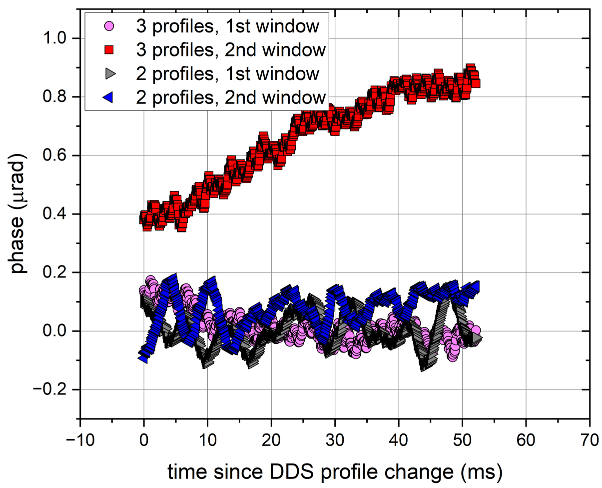

Fig. 4. Average pulse traces obtained in the two resonant windows of a coherent detuning sequence like that shown in Fig. 2 for two strategies of manipulating the DDS profile register. The detuning chosen was 12.2 kHz. Each trace is the average of about 4×10^4 runs of the DDS.

the level of one sync-clock period, we systematically vary the threshold count which controls the duration of the coherent-detuning state and measure the phase shift between the two resonant windows of the coherent detuning sequence as in Fig. 2a,b. The results of this study are shown in Fig. 3 for two different detunings. The measurements agree with the expected phase shift of $\Delta\phi = 2\pi\delta f\delta t$, where δf is the chosen detuning and $\delta t = 80$ ns is the duration of one sync-clock period.

By coherently detuning the DDS while the atoms are above the Ramsey cavity, microwave leakage effects can be reduced. However, one also has to be concerned that perturbing the microwaves could lead to synchronous transients in the microwave phase which also cause frequency biases in the fountain [3], [4]. For a Ramsey free-evolution interval of 0.5 s, a phase step of 5 microradians between the two Ramsey interactions causes a fractional frequency error of approximately 2×10^{-16}.

To check for phase transients, we measured the output phase of the DDS in coherent detuning mode with the triggerable lock-in amplifier and averaged the results. For each trace, the average phase of the first resonant window was set to zero. The averaged traces for the two resonant windows for an overnight run are shown in Fig. 4 with two different strategies for implementing the coherent detuning. In the "2 profiles" case, the same DDS profile is used for both resonant windows of the sequence. In the "3 profiles" case, a different DDS profile is used for each resonant window. This makes it possible to use the phase offset register to correct residual phase differences when the second resonant window begins, which makes the timing of the sequence more flexible.

In both cases, we observe residual transients and phase offsets that are smaller than 1 microradian, but the transients are larger in the 3 profile case. The source and stability of these transients and phase offsets are still under investigation, but they seem to be correlated with switching the DDS profile register. We have observed similar transients when the DDS profile is switched even if the frequency tuning word does not change [4]. Phase shifts of less than 1 microradian between the two resonant windows are not expected to compromise the accuracy of a fountain at the level of 1×10^{-16} in fractional frequency, but it is desireable to suppress phase errors as much as possible. Therefore, it seems preferrable to use the same DDS profile for both resonant windows of the coherent detuning sequence for regular fountain operation.

III. Suppressing Microwave Leakage with Coherent Detuning

To explore the suppression of microwave leakage above the Ramsey cavity, we introduced a large microwave leakage near NIST-F3 by splitting the output of the Ramsey synthesizer into two paths. One splitter output delivers microwaves to the Ramsey cavity of NIST-F3. In the other path, the microwaves pass through a PIN diode switch, and then they are phase-shifted, amplified by 50 dB and sent through a microwave horn as shown in Fig. 5. The PIN diode allows the leakage path to be attenuated by approximately 80 dB which makes it possible to introduce microwave leakage primarily when the atoms are above the Ramsey cavity. The phase shifter was used to maximize the measured frequency shift when the PIN diode switch was enabled so that microwave leakage was present.

With this set-up, NIST-F3 was run for several days interleaving three different modes of operation. In mode 1, the microwaves in the leakage path were always attenuated and the microwaves were detuned only after the second Ramsey interaction (Fig. 2c). In mode 2, the microwaves were also detuned only after the second Ramsey interaction, but the PIN diode switch was enabled approximately when the atoms

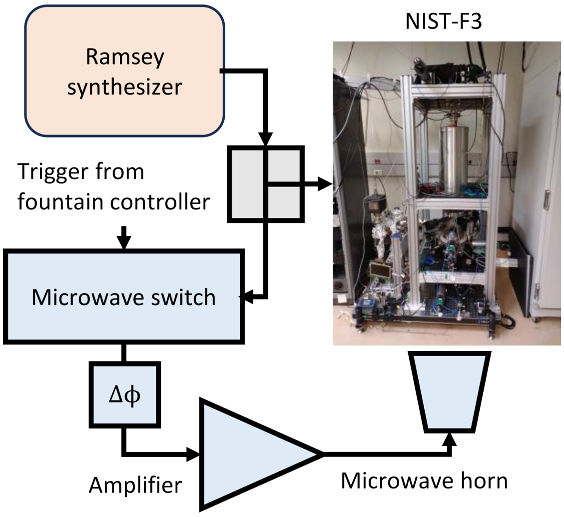

Fig. 5. Diagram of the set-up used to observe a frequency shift due to microwave leakage.

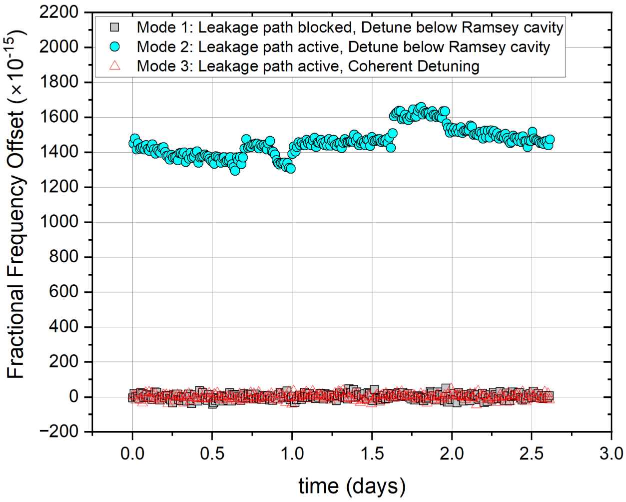

Fig. 6. Fractional frequency shifts observed in NIST-F3 with the set-up shown in Fig. 5 for the three modes of operation described in the text. The y-axis was chosen so that the average fractional frequency offset was zero for mode 1. For this experiment, the additional detuning during the coherent detuning state was set to 24.4 kHz. Each data point is the average of 200 fountain cycles. Based on the measured short-term frequency stability, the statistical uncertainty for each data point is approximately 15×10^{-15} in fractional frequency units, which is smaller than the plot symbols. No error bars are shown.

reached the apogee of their parabolic trajectory. The leakage path was attenuated 150 ms later shortly before the atoms re-entered the Ramsey cavity so that there was a microwave leakage field present in the laboratory which was also asymmetric in time around the apex of the atoms' trajectory. This configuration is expected to produce a frequency shift [1]. In mode 3, the leakage path was handled the same way as in mode 2, but the DDS was operated in coherent detuning mode. The timing of the coherent detuning sequence was chosen so that the leakage path was strongly attenuated before the second resonant microwave pulse began.

The measured fractional frequency offsets for these three modes of operation are shown in Fig. 6. For mode 2, we observe a fractional frequency shift of approximately 1460×10^{-15}. Although the microwave leakage responsible for this large shift is presumably present while the fountain is operating in mode 3, we obtain good agreement with mode 1 where the leakage is suppressed by the PIN switch. Averaged over the run, the frequency difference between mode 1 and mode 3 was $(1.2 \pm 1.3) \times 10^{-15}$. This indicates that the coherent detuning scheme can be a powerful tool to suppress frequency errors due to microwave leakage while the atoms are above the Ramsey cavity.

IV. Conclusion

We have developed an implementation of the coherent detuning scheme based on an MCU and a DDS and characterized its performance. Although the MCU is not phase locked to the microwave chain, we are able to change the DDS phase and frequency coherently with the DDS reference clock. The performance of our implementation appears to be suitable for use in the fountain microwave synthesis chain, and we showed that it can be used to suppress an artificially large microwave leakage shift. As next steps, it would be interesting to investigate the residual phase transients and phase offsets, study the suppression of the microwave leakage shift as a function of the coherent detuning parameters and implement the coherent detuning scheme in the regular operation of the cesium fountains at NIST.

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