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PROGRESS ON PROTOTYPE SYNTHESIZER ELECTRONICS FOR ^{199}HG^{+} AT 40.5 GHz ◆

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ABSTRACT

The design and specifications of a synthesizer for the ^{199}Hg^{+} ion standard will be presented. A fractional frequency stability of $5\text{x}10^{-15}$ at 100 s will be required if we are to reach the fundamental linewidth imposed by the shot noise of the atomic signal. This might be achieved by first locking a low-noise 5 MHz oscillator to an active hydrogen maser. A 100 MHz oscillator can then be locked to the 5 MHz oscillator to reduce close-in phase noise. A commercial digital synthesizer can be used to offset lock a 100.018 MHz oscillator to the 100 MHz signal. Frequency resolution and modulation capabilities will be provided by the digital synthesizer. The 100.018 MHz will be multiplied by 5, filtered, amplified, and routed through a step recovery diode (SRD). The 81st harmonic will be extracted to probe the hyperfine resonance of ^{199}Hg^{+} ions. A long-term stability of $6\text{x}10^{-17}$ is expected from the first prototype.

INTRODUCTION

Several groups have been working on developing a frequency standard based on ions contained in a linear rf ion trap [1-3]. These standards utilize a time-domain Ramsey interrogation scheme. The frequency stability for this configuration varies as

$$\sigma_y(\tau) = \frac{1}{2\pi\upsilon_0\sqrt{\tau n \tau_R}}, \quad \tau > \tau_R \qquad (1)$$

where τ is the measurement time, τ_R is the cycle time, n is the number of ions, and υ_0 is the transition frequency. From Eq. 1, projected frequency stability for approximately 50 ions and τ_R=100 s is $\sigma_y(\tau) = 5\text{x}10^{-14}\ \tau^{-1/2}$. To achieve this frequency stability, the local oscillator (LO) is required to have a frequency stability of order 5×10^{-15} at 100 s, unless one has at least two groups of ions that can be alternatively probed, as outlined by Dick et. al [2]. Currently, only active hydrogen masers have a frequency stability that satisfies the stability requirements at 100 s [4-5]. However, there is considerable effort to develop other local oscillators with frequency stabilities that are better than room temperature active masers [4,6-9]. The purpose of this paper is to describe the design and design criteria of a prototype synthesizer that is suitable for such a standard. In doing this, many problems must be solved. The most demanding are to provide the interrogation signal at the atomic line with both frequency and amplitude modulation capabilities, frequency resolution of 1×10^{-16}, and a phase stability within the electronics of approximately 0.5 ps at 100 s and 5 ps at 10^4 s. The design outlined here is a prototype aimed at solving these practical problems. It is hoped that this will lead to a vigorous discussion about the relative merits of various approaches to the many problems.

GENERAL DESIGN

Figure 1 shows the block diagram of the synthesizer. The internal reference is assumed to be phase locked to an external standard such as an active hydrogen maser or possibly a diode laser pumped rubidium standard [9]. The stability requirement on the external reference is roughly 5×10^{-15} at 100 s. The optimum bandwidth for locking the internal 5 MHz reference appears to be approximately 5 Hz. This is large enough to force the internal reference to track the

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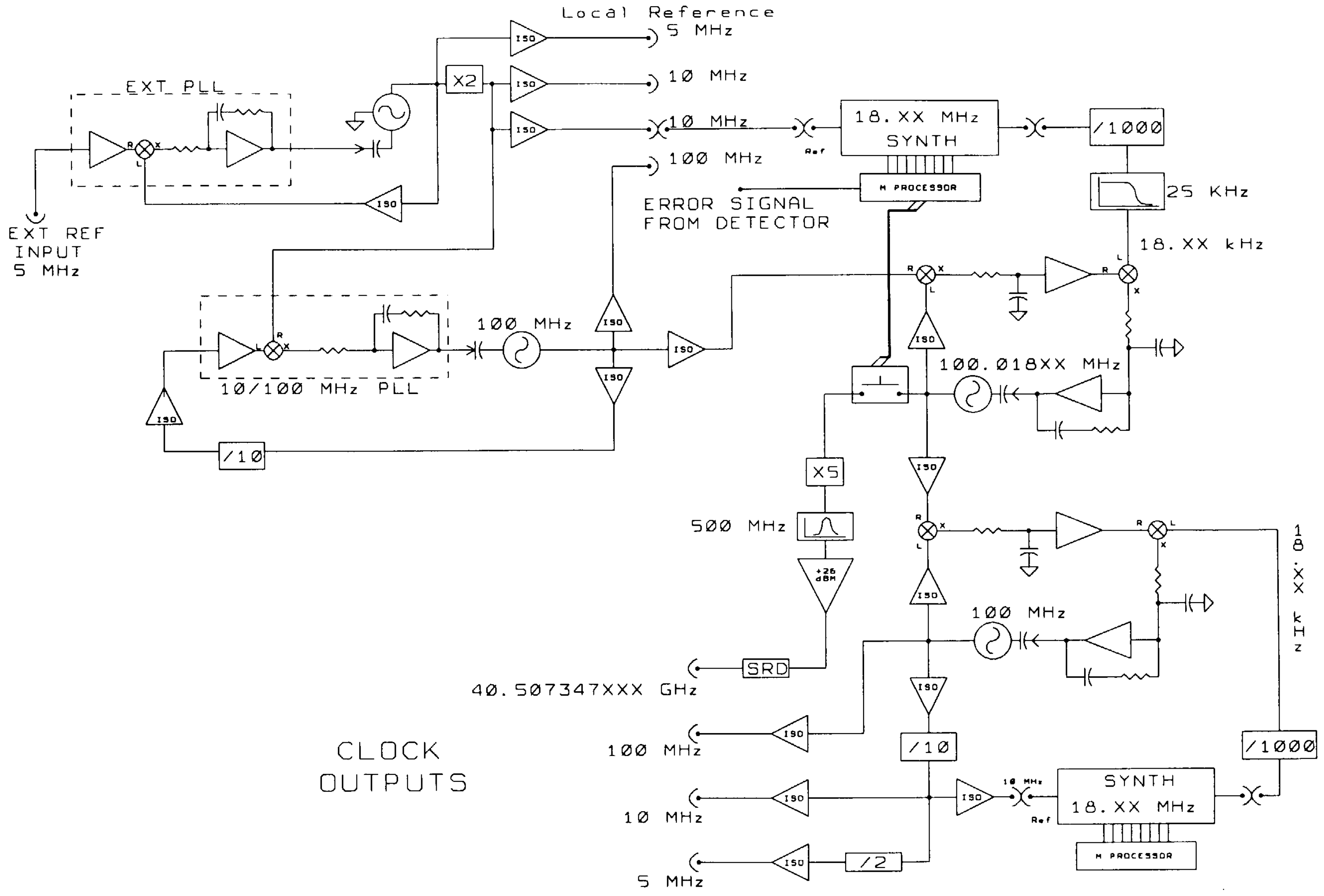

Figure 1 Overall block diagram of $^{199}Hg^{+}$ synthesizer

external reference and slow enough to avoid imposing 60 Hz and its harmonics on the internal reference. The low-noise internal 5 MHz oscillator is multiplied to 100 MHz and used to phase lock a 100 MHz oscillator with a bandwidth of 100 Hz. Noise-filtered reference frequencies at 5, 10, and 100 MHz that are phase locked to the external standard are made available for diagnostic measurements. The 5, 10, and 100 MHz isolation amplifiers follow Felton's general design [10]. The post regulators are used to eliminate the effects of noise from the voltage regulators on the phase noise of the frequency multipliers and rf amplifiers.

A 100.018 MHz oscillator is offset locked to the internal 100 MHz reference using a 18.14 kHz signal derived by dividing the signal from a digital synthesizer by 1000. If the synthesized signal at 18 kHz is added directly to the 100 MHz oscillator, it becomes extremely difficult to attenuate the unwanted side bands at 100 and 99.81 MHz sufficiently. During the multiplication to 40.5 GHz, the amplitude of these side bands increases by 52 dB and could therefore take a large percentage of the power from the desired signal. Figure 2 shows the phase noise of the digital synthesizer at 18 MHz. Dividing the frequency of the digital synthesizer by 1000 reduces the close-in phase noise and spurious lines by 60 dB and increases the frequency resolution to 1 nHz. The divided signal should have a phase noise spectrum equal to that of the input, minus 60 dB, plus the output noise of the divider [11].

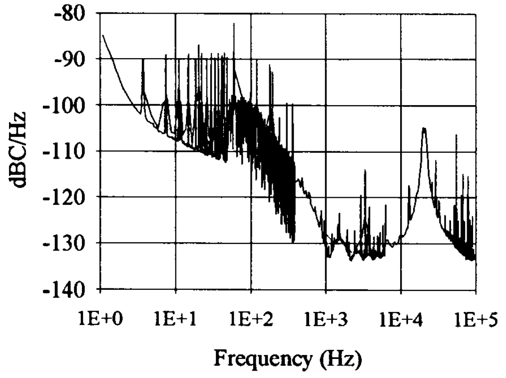

Figure 2 Phase noise of digital synthesizer at 18 MHz

A phase-lock loop with a bandwidth of approximately 100 Hz is used to control the close-in phase noise of the 100.018 MHz oscillator.

The output of the 100.018 MHz oscillator is multiplied by 5 and filtered in a 4 stage interdigital filter with a bandwidth of approximately 4 MHz. The output of the filter is amplified by 26 dB in a balanced amplifier, and routed to a SRD. The 81st harmonic at approximately 40.507 GHz corresponds to the center of the $^{199}Hg^+$ ground state hyperfine resonance.

The 40.5 GHz signal is frequency modulated with the digital synthesizer and amplitude modulated with a switch to implement the Ramsey interrogation process and to measure any perturbations that may depend on the various operating parameters of the trapped ions. The error signal from the detector could, in principle, be used to steer the output frequency of the hydrogen maser, and the output frequency of the maser reference at 100 MHz would then be the clock output. This, however, requires a maser dedicated only to the $^{199}Hg^+$ standard. An alternative is to use the error signal to steer the average frequency of the high-resolution synthesizer. This requires a separate channel to construct the clock output because all of the frequency modulation would have to be removed. This might be done using another high resolution synthesizer to offset lock the 100 MHz output oscillator to one of the isolated outputs from the 100.018 MHz oscillator. The second synthesizer could be frequency modulated inversely with respect to the first to reduce modulation on the output signal. Using the second synthesizer is advantageous because one maser could be used as the reference for several frequency standards. A potentially attractive alternative to provide improved performance would be to use a diode laser pumped rubidium standard as the reference. See the paper by J. Camparo et. al in these proceedings [9].

The frequency error signal derived from the detector [1-3] controls the average frequency of the 18.14 MHz synthesizer via a microprocessor. The 100.018 MHz oscillator is a direct sub-multiple (405) of the $^{199}Hg^+$

hyperfine transition. The microprocessor also controls the modulation of the synthesizer and the switch used to amplitude modulate the interrogation signal.

The primary output frequency of 100 MHz was chosen because of the difficulties of maintaining or even measuring frequency stability at the expected performance level of this clock at 5 or 10 MHz [13].

PRESENT STATUS

The prototype of the 5 MHz to 100 MHz synthesis is complete. Figure 3 shows the phase noise of the free running 100 MHz reference and the phase-locked 100 MHz reference. The excess phase noise from approximately 50 to 300 Hz from the carrier is due to noise in the 100 MHz to 10 MHz frequency divider [11]. This noise could be reduced by using frequency multipliers; however, they would have little effect on the frequency stability of the output [9]. Small phase variations with temperature in this portion of the synthesizer are relatively unimportant since the clock output is derived from the 100.018 MHz oscillator.

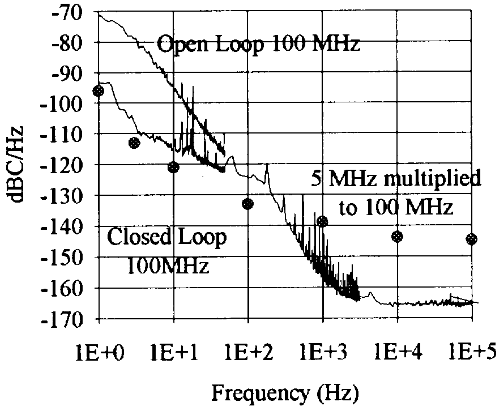

Figure 3 Phase noise of 100 MHz quartz crystal

Phase shifts in the 100.018 MHz circuit contribute directly to instability in the output signal. Figure 4 shows one of the four isolation amplifiers that distributes the 100 and 100.018 MHz signals. The isolation amplifiers are constructed as balanced FET amplifiers with low harmonic distortion. Squaring amplifiers are currently used to drive the divider chain. The phase stability versus temperature of two isolation amplifiers is shown in Figure 5. The power amplifier is a balanced-junction, bipolar amplifier and provides about 26 dB gain, an output power of 0.5 W, low harmonic distortion, low noise, and good phase stability versus temperature.

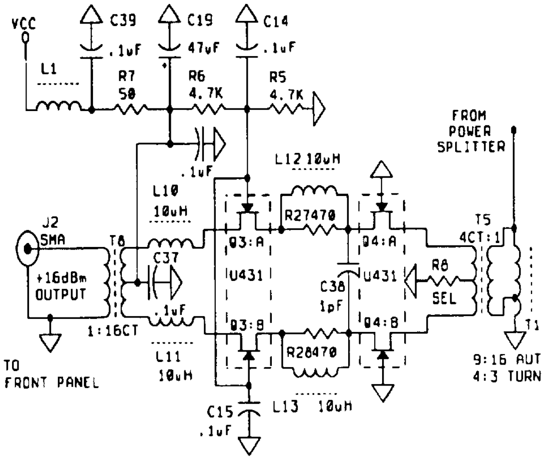

Figure 4 Schematic of 100 MHz distribution amplifiers.

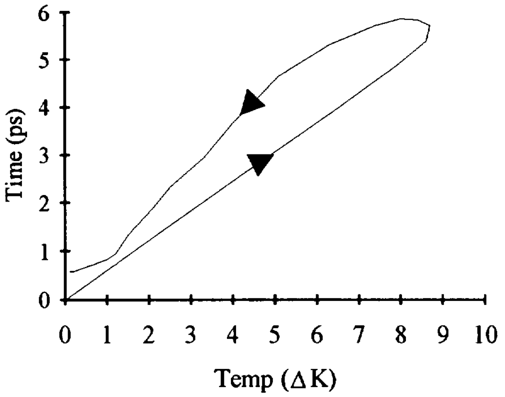

Figure 5 Temperature coefficient of 100 MHz distribution amplifier.

The multiplication chain of 100 MHz to 500 MHz through the SRD has been constructed and tested out to 10.6 GHz. Figure 6, top trace, shows the phase noise of such a signal at 10.6 GHz. The decrease in noise of the bottom trace above 3 kHz is due to locking the 10.6 GHz signal to a cavity-locked dielectric resonator oscillator (DRO) as described in [12]. The additional multiplication to 40.5 GHz would increase the phase noise by 12 dB. Figure 7 shows the phase variation between two 100 MHz to 10.6 GHz synthesizers over 12 hours. Frequency stability of the synthesis is shown in Figure 8 and is approximately $6\mathrm{x}10^{-16}$ at 100 s and $5\mathrm{x}10^{-17}$ at 10^4 s. The temperature coefficient for the 100 MHz to 10.6 GHz synthesis is shown in Figure 9. The coefficient of 3.8 ps/K is believed to be dominated by the SRD. By properly biasing and ovenizing the SRD, this coefficient could be greatly reduced.

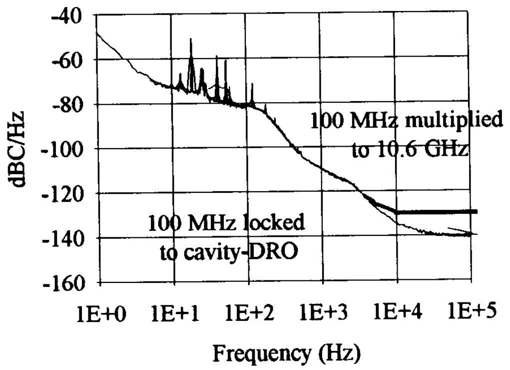

Figure 6 Phase noise of 10.6 GHz synthesis.

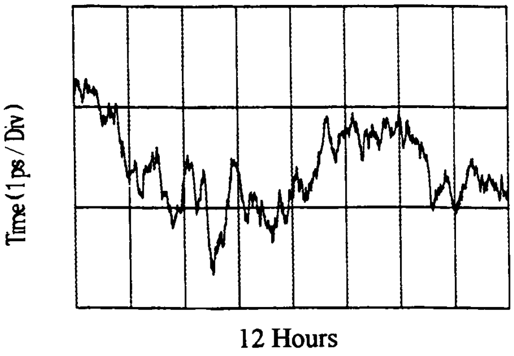

Figure 7. Phase stability of 10.6 GHz synthesis.

The offset lock using the digital synthesizer has not yet been implemented. The frequency stability of the synthesizer is shown in Figure 10. Its contribution to instability is reduced by $5.5\mathrm{x}10^3$ because it is an offset on a 100 MHz signal. This brings its contribution to $7\mathrm{x}10^{-16}$ at 100 s and $1\mathrm{x}10^{-18}$ at 10^4 s.

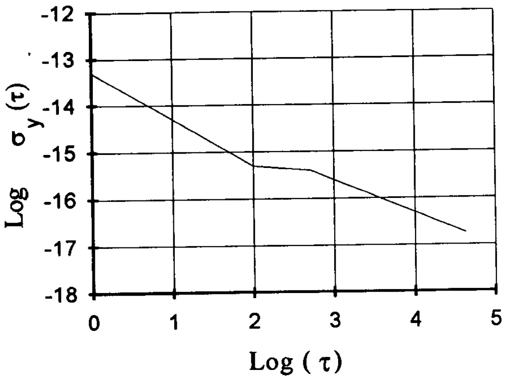

Figure 8 Frequency stability of 10.6 GHz synthesis

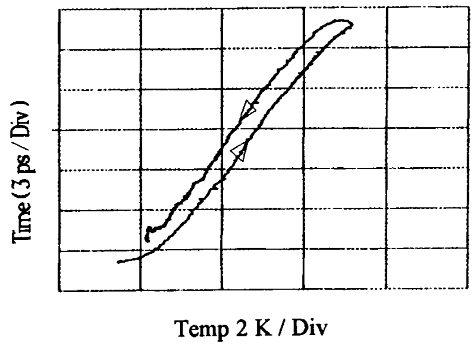

Figure 9 Temperature coefficient of 10.6 GHz synthesis

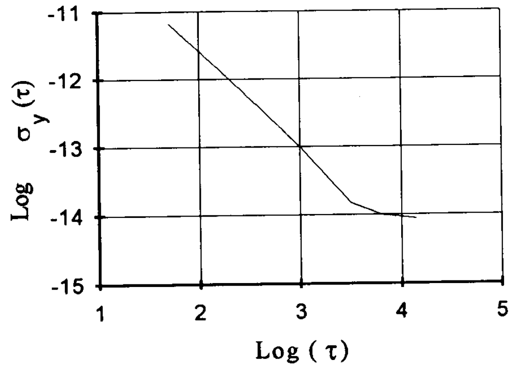

Figure 10 Frequency stability of commercial digital synthesizer

CONCLUSION

Development of a 40.5 GHz synthesizer for a highly stable and accurate $^{199}Hg^{+}$ ion standard is well under way. With existing components, we should be able to produce a synthesizer that is suitable for preliminary testing of the ion standard. By offset locking instead of adding the signal in with a mixer, we eliminate residual sidebands that could cause problems in the multiplication to 40.5 GHz. By analysis of our existing 10.6 GHz synthesis and stability measurements from the digital synthesizer, we can project stabilities for such a system to be 2×10^{-15} at 100 s and 6×10^{-17} at 10^{4} s. Redesign of the synthesizer using techniques and materials to minimize environmental effects [13] should bring the stability down to levels needed for the final version of the $^{199}Hg^{+}$ ion standard.

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