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ULTRA-HIGH STABILITY SYNTHESIZER FOR DIODE LASER PUMPED RUBIDIUM

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Abstract

We describe the design of a synthesized local oscillator for a rubidium [Rb] passive frequency standard pumped by radiation from a diode laser. The design goals for this new oscillator are:

1) To operate at room temperature,
2) To have the ability to step quickly to different frequencies for measuring parameters such as magnetic fields,
3) To contribute less than $2 \times 10^{-14} \tau^{-1/2}$ to the frequency stability of the Rb standard for measurement times between 30 and 200 seconds.

Potential limits for obtaining these goals, as well as solutions to such problems, are discussed.

Introduction

A number of concepts for new atomic frequency standards have the potential for achieving a frequency stability better than $1 \times 10^{-14} \tau^{-1/2}$ and inaccuracies less than 1×10^{-16} [1-7]. One of the difficulties of realizing this performance in passive atomic standards, however, is obtaining a local oscillator with the necessary frequency stability for interrogating the atomic resonance. Several of these new frequency standards require an interrogation cycle that range from 30 s to 200 s. To achieve the full capability of the new atomic standards, the local oscillator must maintain a frequency stability that is roughly comparable to the atomic performance for a time at least as long as the interrogation cycle time. Dick, et al. have investigated in detail the frequency instability in a standard that is caused by noise in the local oscillator [8]. In situations where there are two or more atomic samples, it is possible to shape the interrogation cycle to significantly reduce the contribution of the local oscillator to the white frequency noise level [8]. However, for those systems where only one atomic sample is used (currently the majority of the systems), the noise in the local oscillator is still an overriding limitation.

Since none of the present room temperature rf oscillators possesses a frequency stability of $1 \times 10^{-14} \tau^{-1/2}$ for 30 s to 200 s, it is of interest to pursue special frequency standards which might achieve this level of stability. One such candidate is the passive, diode-laser-pumped, rubidium-gas-cell standard analyzed by Camparo, et al. [9]. They project that with an optimum choice of parameters, a rubidium frequency standard could be built that has a frequency stability of less than $1 \times 10^{-14} \tau^{-1/2}$. Although this passive standard also needs a local oscillator with stability near 1×10^{-13} at 10 to 30 ms, the loop attack time could be as short as 0.03 s since the linewidth of the resonance is expected to be on the order of 100 Hz and the modulation frequency about 37.5 Hz. A good quartz oscillator can meet this requirement.

For a passive standard using sinusoidal phase modulation, the phase noise at the second harmonic and fourth of the modulation frequency appear as additional white frequency terms which limit the ultimate short-term frequency stability [10-15]. The most thorough treatment of this problem is given by Audoin, et al. [14,15]. They have shown that this limit is approximately given by

$$\sigma_y(\tau) = (f_m/\nu_o)\,[0.723\, S_\phi(2f_m) + (C)\, S_\phi(4f_m)]^{1/2}\ \tau^{-1/2} \qquad (1)$$

where $S_\phi(2f_m)$ and $S_\phi(4f_m)$ is the power spectral density of phase noise in the oscillator at twice and four times the modulation frequency f_m, respectively, and ν_o is the carrier frequency. Modulation parameters such as modulation depth determine the value of C (typically $C \simeq .1$) [15]. A typical quartz oscillator and a modulation frequency of 37.5 Hz would produce a standard with a stability of about $1 \times 10^{-13}\,\tau^{-1/2}$. In this paper we describe a method using currently available technologies to reduce this effect to below $2 \times 10^{-14}\,\tau^{-1/2}$.

Design of a New Passive Rubidium Servo System

Since one of the limitations to the frequency stability is the noise at the second harmonic of the modulation frequency and not significantly from the noise at other Fourier frequencies [10-15], filtering the noise from the local oscillator signal only in the region about the second harmonic of the modulation is sufficient to reduce this effect. Figure 1 shows a block diagram of one approach to achieve this filtering of a signal suitable for interrogating the Rb resonance at 6.83 GHz. The output of our low noise 5 MHz oscillator [$S_\phi(75\ \text{Hz}) = 6.3 \times 10^{-17}$ (rad^2/Hz),($\mathscr{L}(75\ \text{Hz}) = -165$ dBc/Hz)] is doubled to 10 MHz, phase modulated at f_m, filtered at $\pm 2f_m$, frequency multiplied to 500 MHz, and mixed with a tunable synthesizer (1/16 μHz resolution) to produce a submultiple of the Rb resonance near 488.14 MHz. The 488.14 MHz signal is multiplied by 14 in a step recovery diode (SRD) to produce a 6.834 xx GHz signal which can be used to interrogate the Rb resonance. The error signal from the detector is used in the traditional way to steer the 5 MHz quartz oscillator.

The key element is the filter following the phase modulator. This filter (Figure 2) has notches that are spaced symmetrically about the carrier and located at twice the modulation frequency from the carrier ($\nu_0 \pm 75$ Hz). Calculations by Smythe [16] show that using crystal resonators with an unloaded Q-factor of 1×10^6 should yield notch filters with an attenuation at the center of the notch of order 20 dB and an insertion loss at the carrier frequency of less than 1 dB. Placing the notch filter after the modulator also allows the filter to attenuate the frequency error associated with second harmonic distortion within the modulator.

A notch filter has significant advantages over a passband filter for this application. Since the crystal resonators in the notch filters do not absorb significant power from the carrier, we can transmit power more efficiently through this type of notch filter than through a passband filter. Also, the phase of the carrier signal is affected much less by small variations in the frequency of the notch filter than for a passband filter. Calculations indicate [16] that an equivalent noise resistance of order 10 Ω is possible. This corresponds to an added noise of 0.4 nV/$\sqrt{\text{Hz}}$ or $S_\phi(f) = 8 \times 10^{-20}$ (rad^2/Hz), ($\mathscr{L}(f) = -194$ dBc/Hz) for a carrier level of + 13 dBm. At this noise level, the stability limit calculated from Eq.(1) is approximately 1×10^{-15}.

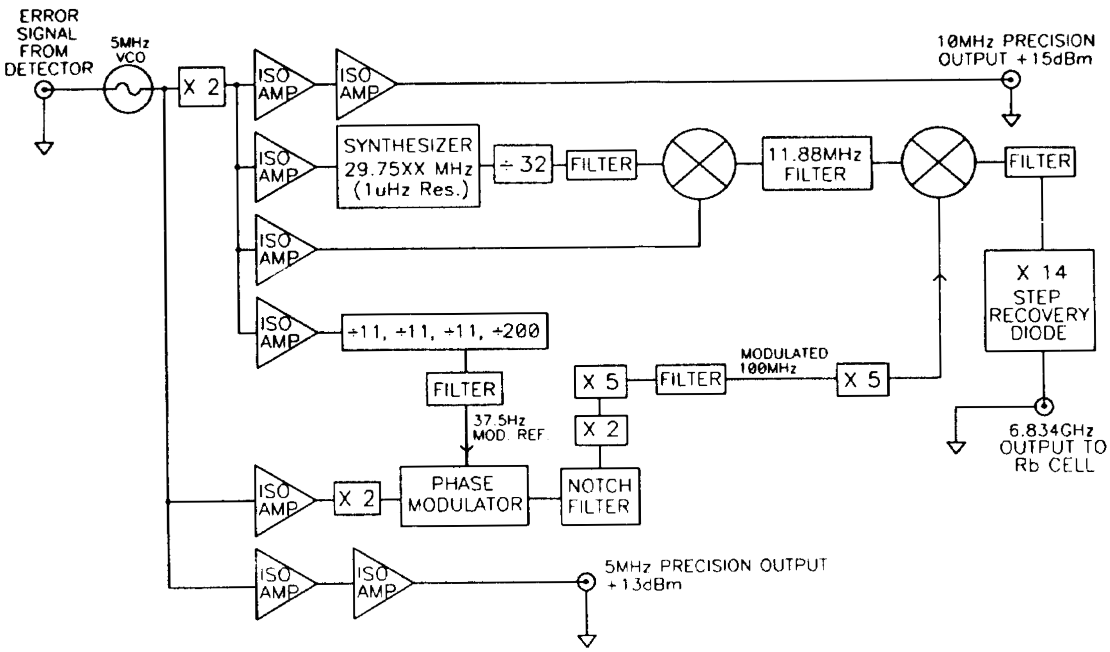

Figure 1. Block diagram of Rb synthesizer.

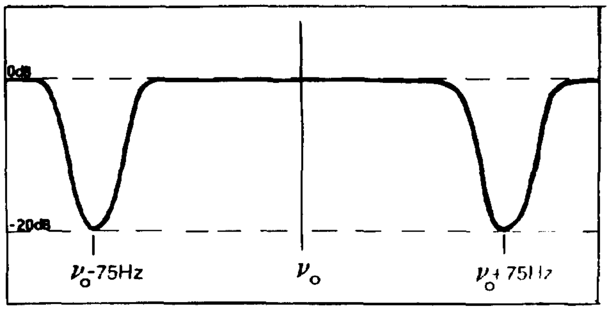

Figure 2. Notch filter at $\nu_o \pm 2f_m$.

A potential limit to the overall stability of the servo system is the noise added by the frequency multipliers. Typical doublers have added phase noise at approximately $S_\phi(75\ Hz) = 6.3 \times 10^{-17}$ (rad^2/Hz), and $S_\phi(150\ Hz) = 4.0 \times 10^{-17}$ (rad^2/Hz) which would limit the stability to $2.4 \times 10^{-14}\ \tau^{-½}$. Using the work of Felton [17], we have developed a series of ultra-low noise doublers. These multipliers feature an equivalent input phase noise of $S_\phi(75\ Hz) = 4.2 \times 10^{-18}$ (rad^2/Hz), and $S_\phi(150) = 2.6 \times 10^{-18}$ (rad^2/Hz) for doubling 10 MHz to 20 MHz (Figure 3). Based on this level of performance, the stability limitation would be 6.7×10^{-15}. Preliminary results show the phase noise of the 20 MHz to 100 MHz multipliers will contribute approximately 1 dB to the overall phase noise.

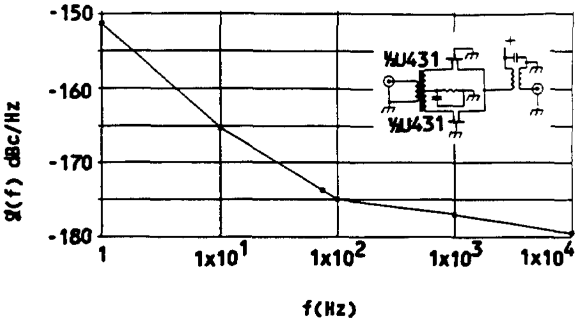

Figure 3. Residual phase noise of the 10 to 20 MHz doubler circuit.

The 100 MHz distribution amplifiers and the 100 MHz to 6.83 GHz (through 488 MHz) synthesis is completed. Results on similar 100 MHz to 10.6 GHz synthesizers show that phase variations within the synthesizers correspond to a frequency stability of 2×10^{-17} at 1000 s, which is well below the requirements [18].

The phase modulator is a linear, small-angle crystal modulator [19]. This phase modulator has very low second harmonic distortion and would enable one to find the center of the resonance to an accuracy of 0.1 ppm of the resonance linewidth. However, the added phase noise of the modulator is $S_\phi(75\ Hz) = 8 \times 10^{-16}$ (rad^2/Hz), ($\mathscr{L}(75\ Hz) = -154$ dBc/Hz) (Figure 4a). Figure 4b shows the anticipated improvement of the phase noise at 75 Hz due to the incorporation of

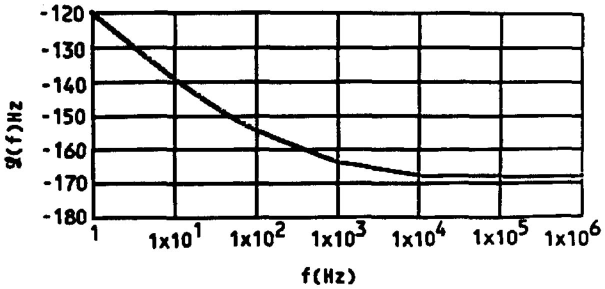

Figure 4a. The phase noise of the small-angle crystal modulator.

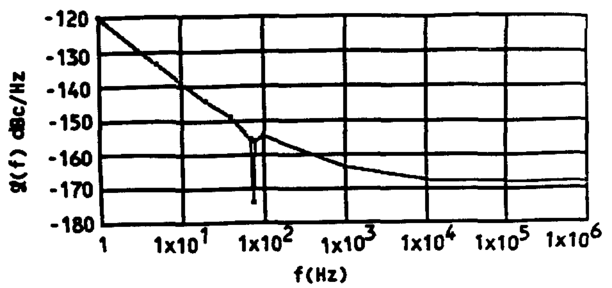

Figure 4b. The phase noise of the small-angle crystal modulator and notch filter.

the notch filter. Figure 5 shows the contribution of the electronics to $\sigma_y(\tau)$ versus τ for the complete standard, calculated with and without the noise in the present small-angle modulator and a bandwidth of 100 Hz. The phase lock loop was assumed to be second order with a unity-gain attack time of 0.03 s and an integrator attack time of 0.12 s. Clearly the noise of the modulator dominates the frequency stability. Reducing the level of random walk FM has no effect on the stability nor does increasing the measurement bandwidth.

Although the white frequency noise limit is within specifications, $\sigma_y(\tau) = 1.4 \times 10^{-14}\ \tau^{-½}$, further improvements are possible by reducing the phase noise of the small-angle phase modulator. One possibility is to use a lower noise phase modulator in place of the small-angle modulator at the expense of second harmonic distortion. The notch filter following the modulator would help reduce the effect of higher distortion. If necessary, two filters in series could be used.

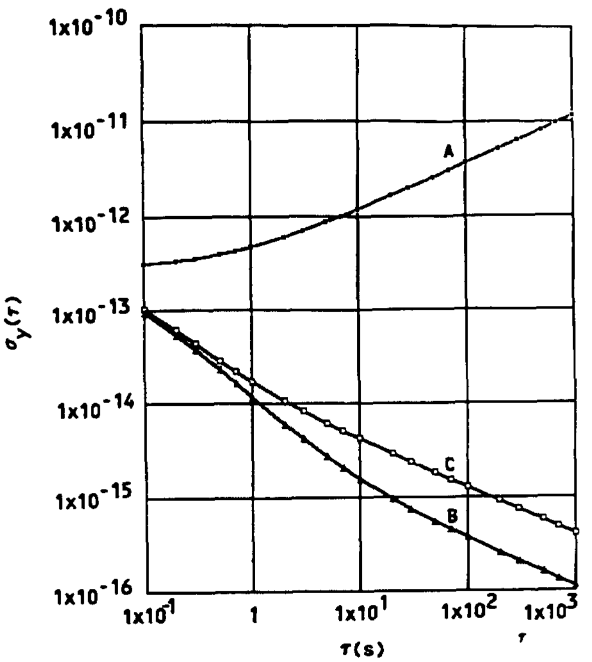

Figure 5. Stability calculations for the complete standard. Curve A shows the stability of the open loop oscillator, curve B shows the stability of the closed loop oscillator without the noise of the modulator and curve C shows the stability with the noise of the modulator added.

Conclusion

We have shown that it is possible to develop a synthesizer for a laser-pumped rubidium standard with the noise performance necessary to support a stability of 1.4 x 10^{-14} $\tau^{-1/2}$ up to approximately 200 s. This was accomplished by incorporating notch filters about the carrier at the second harmonic of the modulation frequency. Also, lower noise multipliers were incorporated to help reduce the phase noise present. The resulting rubidium standard may be used as the local oscillator for other standards which need high stability during their interrogation cycle. Other approaches are being pursued to increase the stability even more.

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