FREQUENCY STABILITY OF CELL-BASED PASSIVE FREQUENCY STANDARDS: REDUCING THE EFFECTS OF LOCAL-OSCILLATOR PM NOISE

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Abstract

Experimental measurements in our present diode-laser-pumped Rb buffer-gas-cell frequency standard show that the sensitivity to microwave PM noise is approximately a factor of 10 lower when square-wave modulation is used in place of the more traditional sine-wave modulation. This result virtually eliminates what had been a serious limitation to the frequency stability attainable in cell-type standards. It also has ramifications for low-cost, commercial standards.

1. Introduction

Several studies indicate that laser-pumped, passive Rb cell standards have the potential of achieving very high short-term frequency stability. See for example [1,2]. However, as was first pointed out by Kramer [3], phase modulation (PM) noise on the microwave interrogation signal at even harmonics of the modulation adds excess white frequency-modulation (FM) noise to the detected demodulation signal. This effect can be much larger than the intrinsic white FM noise of high-performance passive standards and can severely limit the achievable short-term frequency stability of the standard [4-7].

For the special case of cell-type standards, De Marchi, et al [8], have pointed out that square-wave modulation leads to insensitivity to this otherwise fundamental problem. They have developed a model that allows one to calculate the effect of PM noise on the microwave-interrogating signal with either sine-wave or square-wave modulation. In this paper, we report experimental results confirming the model and demonstrating that the stability degradation resulting from PM noise is reduced by more than an order of magnitude when using square-wave modulation in place of sine-wave modulation.

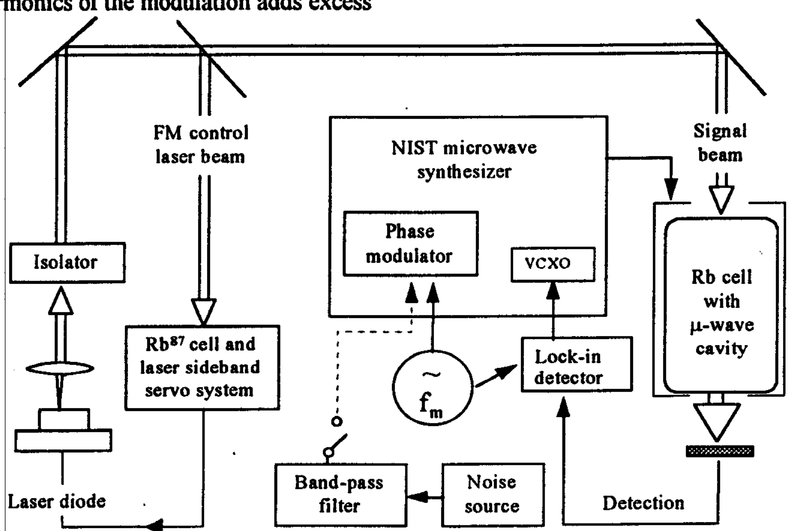

Figure 1. Block diagram of the Rb clock.

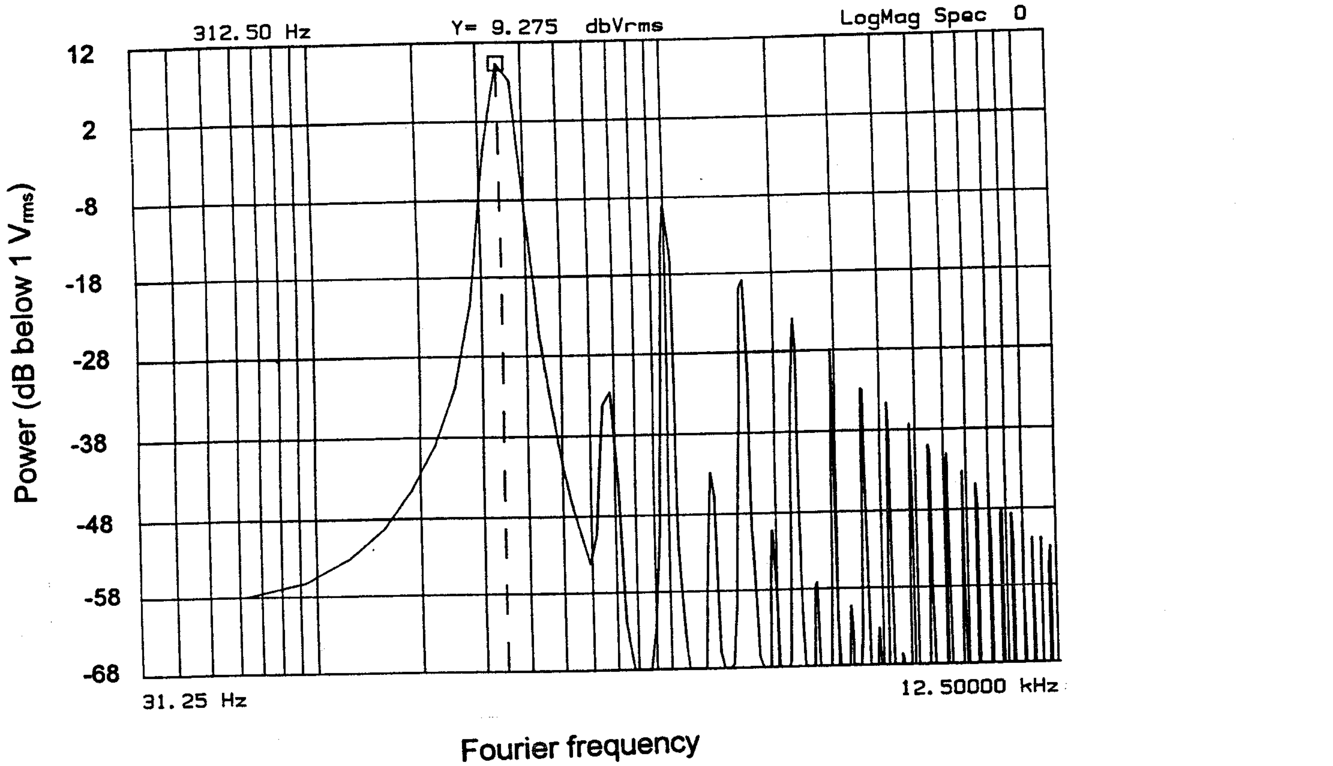

Figure 2. Spectrum of the triangular wave modulation.

2. Experimental results

Figure 1 shows the block diagram of the setup used to evaluate the effect of the microwave PM noise on the fractional frequency stability of our Rb gas cell. By driving the phase modulator with either a sine-wave or a triangular-wave we could generate sine-wave or square-wave FM on the interrogating signal. This made it possible to evaluate the two different modulation waveforms using the same apparatus without any changes to the synthesis. Our results for sine-wave modulation have been reported previously [9,10]. In this paper we report only the results for square-wave modulation.

Figure 2 shows a spectral analysis of the waveform resulting from our triangular-wave PM. The distortions in the waveform, although not zero as evidenced by the small even-harmonic contributions, are small enough to determine if the sensitivity to source PM noise is less when square-wave FM is used instead of sine-wave PM. We use square-wave demodulation but the band-limiting pre-filter has the effect to make the demodulation waveform equivalent to sine-wave.

Using square-wave FM at a frequency of 287 Hz, we first measured the fractional frequency stability as a function of narrow-band PM noise centered on the 2nd, 4th, 6th, and 8th harmonics of the modulation. Next we measured the fractional frequency stability as a function of PM noise that included about 43 harmonics centered at harmonic 44, 132, 225, and 304. Since the sensitivity to PM noise varies slowly with harmonic number, we could estimate the average of 43 coefficients from a single measurement. The limit to the fractional frequency stability is given by

$$\sigma_y^2(\tau) = \sum_{i=1}^{\infty} C_{2i}^2 S_\phi(2if_m) \cdot \tau^{-1},$$

where f_m is the modulation frequency and the C_{2i} are the coefficients for the degradation of fractional frequency due to PM noise on the interrogation signal.

The results are given in Fig. 3. For comparison we show our previous results which were obtained with the same apparatus using sine-wave modulation and square-wave demodulation [9-11]. The coefficients we have obtained with square-wave modulation are about one order of magnitude lower than those we obtained with sine-wave modulation. Furthermore, these measurements confirm the prediction that sensitivity to PM noise at the fundamental and other low odd harmonics of the modulation is negligible compared to noise at the even harmonics [8-11]. See also the earlier work in [4, 5]. As in the case of sine-wave modulation, the coefficient C_2 of the 2nd harmonic is the largest, about one order of magnitude higher than C_4, C_6, or any of the other coefficients.

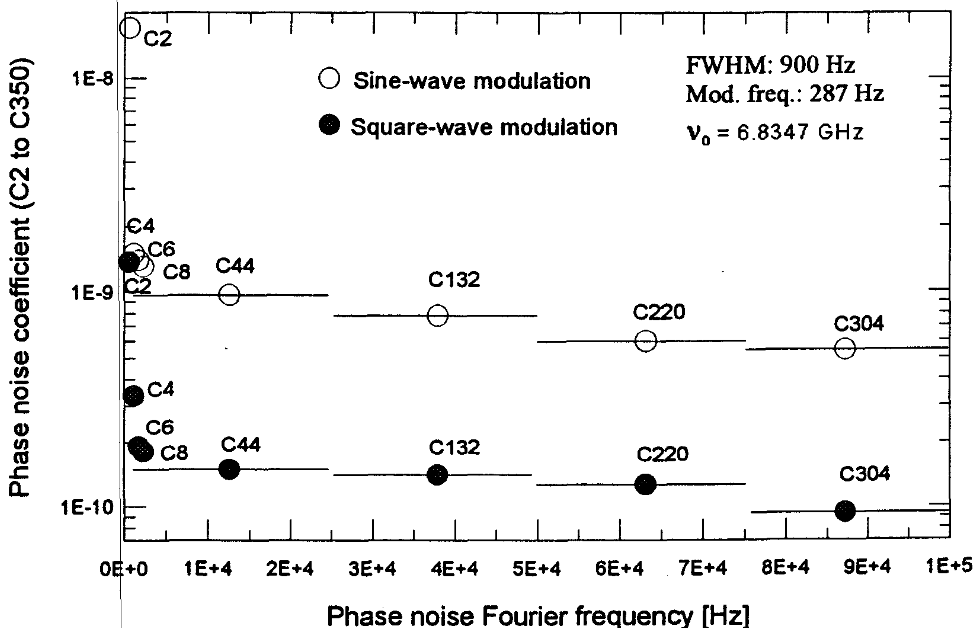

Figure 3. Comparison of the coefficients for the degradation of fractional frequency due to PM noise on the interrogation signal at harmonics of the modulation frequency.

Using the PM noise data of our improved microwave synthesizer [9] and the coefficient measured above, we have calculated the resulting limit for the short-term frequency stability of our Rb cell clock for a square-wave modulation of 287 Hz. The results are summarized in Table 1. The limit to the short-term frequency stability is below 1x 10^{-14} $\tau^{-1/2}$, which is one order of magnitude lower than that for sine-wave modulation. If we use a notch filter at the second harmonic, the limit is reduced to 1.4 x10^{-15} $\tau^{-1/2}$ [9, 10].

Table 1. Limit to the Rb clock stability (σ_y(1 s)) with the improved synthesizer.

Harmonic contribution	*2nd 574 Hz*	*4th 1148 Hz*	*6th 1722 Hz*	*8th 2296 Hz*	*10th to 350th 2.87 to 100 kHz*	*4th to 350th 1.148 to 100 kHz*	*Total Limit*
Square wave FM	$7.5 \cdot 10^{-15}$	$8.1 \cdot 10^{-16}$	$4.6 \cdot 10^{-16}$	$4.6 \cdot 10^{-16}$	$1.0 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$7.6 \cdot 10^{-15}$
Sine wave PM	$9.3 \cdot 10^{-14}$	$3.6 \cdot 10^{-15}$	$3.4 \cdot 10^{-15}$	$3.2 \cdot 10^{-15}$	$6.8 \cdot 10^{-15}$	$9.0 \cdot 10^{-15}$	$9.3 \cdot 10^{-14}$

3. Conclusion

We have experimentally demonstrated that the use of square wave FM in cell-type frequency standards can reduce the sensitivity to PM noise on the interrogating microwave radiation by more than an order of magnitude compared to that obtained with the case of sine-wave modulation. This result will allow state-of-the-art, cell-type standards to reach much closer to their intrinsic atom-limited performance. It also may allow lower performance, commercial standards to be designed with much less exacting local oscillators and microwave synthesis chains

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