Improved rubidium frequency standards using diode lasers with AM and FM noise control

Csaba Szekely† and Robert Drullinger
Time and Frequency Division
National Institute of Standards and Technology
Boulder, Colorado 80303

ABSTRACT

Diode-laser-pumped, rubidium cell frequency standards have potential short-term stability that is vastly better than their lamp-pumped counterparts. However, AM and FM noise in monolithic laser diodes limit their performance. With extended-cavity, grating-feedback diode lasers, the AM and FM noise can be controlled. In the preliminary work reported here, we have used such a laser to make measurements in two different rubidium cell systems. Measured line Q and signal-to-noise ratios corresponding to $\sigma_y(\tau) = 4 \times 10^{-13} \tau^{-1/2}$ in a commercial, buffer gas type standard and $\sigma_y(\tau) = 2 \times 10^{-13} \tau^{-1/2}$ in an evacuated, wall-coated cell are demonstrated. We believe both of these numbers can be improved significantly in a fully engineered and optimized standard.

1. INTRODUCTION

Optically pumped, rubidium-cell, frequency standards have theoretical, atomic shot-noise limited performance that is ***several orders of magnitude*** better than what is actually achieved in lamp pumped devices.[1,2] The reason for this tremendous difference between potential and achieved performance is, in part, related to the spectral output of the lamp. The non-monochromatic nature of the lamp output has two deleterious effects on the short-term stability of the standard. The presence of light that does not directly contribute to the optical pumping adds a background signal and, hence, noise to the detected signal. Additionally, nearly resonant light actually leads to some active de-pumping, thus limiting the use of the available atoms. Our preliminary experiments with diode lasers in place of lamps support this argument. The amount of light reaching the detector is typically a factor of 30-100 less than that in the lamp-pumped standards, while at the same time, the "clock" signal in terms of absolute amount of light change at the detector is larger, in some cases by a factor of 10.

The goal of the work presented here is to investigate the limits to the short-term stability attainable in a rubidium cell type standard when pumped with a diode laser. The use of diode lasers to pump rubidium standards is not a new idea. There have been several previous investigations of short-term stability.[3-8] All of them have used commercial rubidium standards and solitary diode lasers without explicit AM or FM noise control. None of them has resulted in a measured stability that was better than the original lamp-pumped standard. It is generally thought that this failure to produce better short-term stability is related to FM noise in the lasers.[1,3,5,6] In the work reported here, we have used extended-cavity diode lasers with their inherently lower FM noise. Additionally, we have added an intensity servo system for AM noise control. With these lasers, we have been able to show that at least a large part of the theoretical, short-term stability of rubidium cell frequency standards is experimentally achievable in both buffer-gas cells and evacuated, wall-coated cells.

2. EXPERIMENTAL WORK

We have used an extended-cavity, grating feedback laser as the optical pumping source for two different physics packages. The laser operates on the D_1 line (794.9 nm). The cavity length is servo-controlled to lock the laser frequency to a saturated-absorption feature in an external, evacuated ^{87}Rb cell. This laser configuration allows control of both AM and FM noise; see discussion below.

†Csaba Szekely is on leave from the Institute of Atomic Physics-IFTAR Bucharest, Romania

The first experiments were done with the same commercial standard used in Ref. 2. The standard uses a TE_{111} cavity and the cell contains a natural mixture of ^{87}Rb and ^{85}Rb. Because of the presence of ^{85}Rb, we obtained the best optical pumping on the F = 1 to F' = 2 transition. At the normal operating temperature of the standard($\approx 70°C$), the relative absorption dip ($\Delta I/I$) was $\geq 3\%$ whereas it was $\leq 0.1\%$ when pumped with its lamp. The measured short-term stability of the standard, without AM control on the laser, was $4 \times 10^{-12} \tau^{-1/2}$; Fig. 1. This is a factor of three improvement from the performance of the same standard when lamp pumped. Limitations in the electronics package and restrictions in the physics package prevented further improvements. In changing from the lamp to the laser, the amount of light falling on the detector decreased by a factor of 80 while the absolute magnitude of the microwave-induced change in light signal increased by a factor of 3. The microwave resonance linewidth was essentially unchanged.

The second physics package consisted of a TE_{011} cavity and an evacuated, wall-coated cell with ^{87}Rb.[9] The microwave cavity was surrounded by two magnetic shields and the temperature of the cell/cavity could be controlled separately from the rubidium reservoir. The diameter of the spherical cell was about 3.5 cm. The laser beam had an elliptical crosssection of about 0.25 cm^2. This device was never operated as a frequency standard because a microwave electronics package with adequate phase noise was not yet available; see discussion section. Rather, the parametric dependence of line Q and signal-to-noise ratio (S/N) with optical power, microwave power, and spin density were investigated. At room temperature and low microwave power, the resonance is a pure Dicke narrowed, symmetric, Lorentzian line with a FWHM of 87 Hz; Fig. 2. The microwave signal, in units of percent of the optical signal is shown in Fig. 3, as a function of the laser power and the microwave power incident on the cavity. A limited search for optimum temperature and spin density was made. However, on heating of the cell/cavity, from room temperature to 340 K, the line Q decreased by a factor of about 2. This was attributed to magnetic effects of the heater but the issue is not resolved at this time. The results quoted are for the actually measured linewidth. At a cell wall temperature of 340 K and for rubidium densities ranging from 1.9×10^{10} to 2.6×10^{11} atoms/cm^3 we evaluated the short-term stability dependence on laser and microwave power; Fig.4.

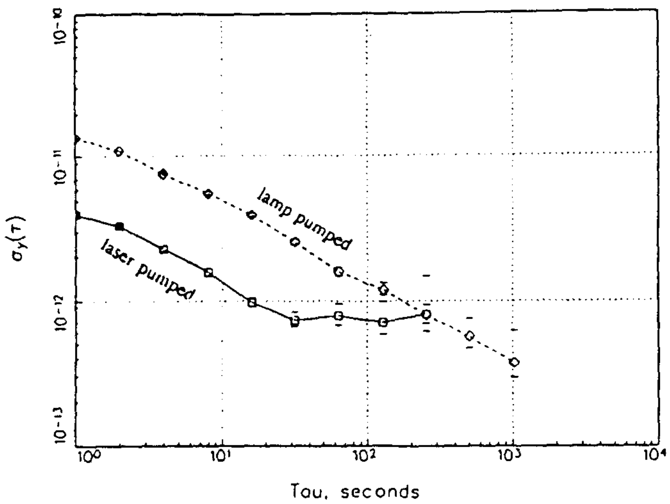

Fig. 1. Frequency stability of commercial standard with lamp pumping and laser pumping. The flicker floor seen in the laser data at times greater than about 20 s is the result of unregulated laser amplitude.

3. DISCUSSION

It now seems clear that at least a large part of the stability potential suggested by theory is actually available in a properly engineered, laser-pumped rubidium standard. However, AM and FM noise in the laser must be addressed. The use of extended cavity lasers is one way to achieve this control.

Simple, solitary laser diodes have linewidhs of the order of 50 MHz, and the output wavelength is an extremely sensitive function of temperature and current; $d\nu/dT \approx 30$ GHz/K and $d\nu/di \approx 3$ GHz/mA. For grating-feedback lasers operating in the high feedback limit, the linewidth is reduced 2-3 orders of magnitude and the tuning with current and temperature are reduced by almost as much.[10] With the wavelength set by the grating angle and cavity length (a piezo-mounted mirror), the current and temperature become almost free parameters. In our laser, comparatively crude temperature control is used to adjust the band gap and help with mode selection while the laser injection current is used to set and stabilize the laser output power.

AM noise can be rather easily controlled to the shot-noise limit. Only a very small fraction of the laser output power is needed for the microwave-optical double resonance. Half of the laser power can be used as a monitor in a power-stabilization/noise-control servo. This allows the laser output to be AM-controlled within 3 dB of the shot-noise limit.[11] If, for example, 1% of the laser power is used to probe the rubidium cell, the shot noise-limited S/N ratio on this beam will be 10 dB less than that for the full output of the laser. Hence, controlling the full laser power within 3 dB of its shot-noise limit insures that the probe beam used in the clock will be shot noise limited.

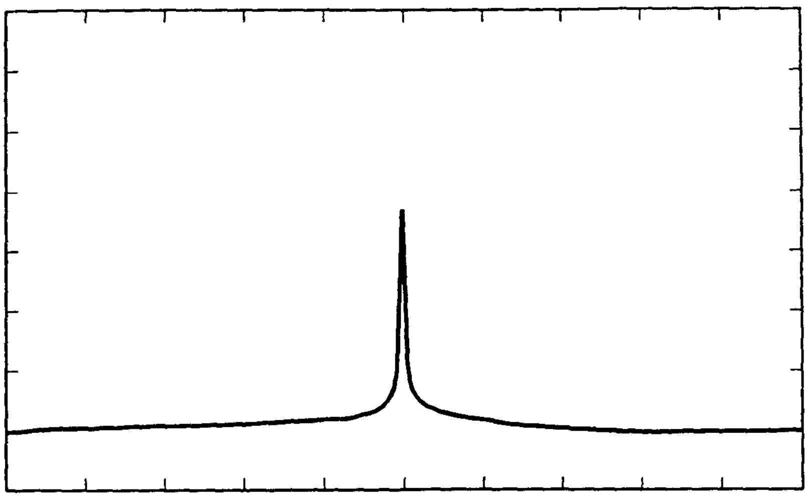

Fig. 2. Dicke narrowed lineshape observed in an evacuated, wall-coated cell in a TE_{011} cavity. The cell is at room temperature. The measured linewidth (FWHM) is 87 Hz.

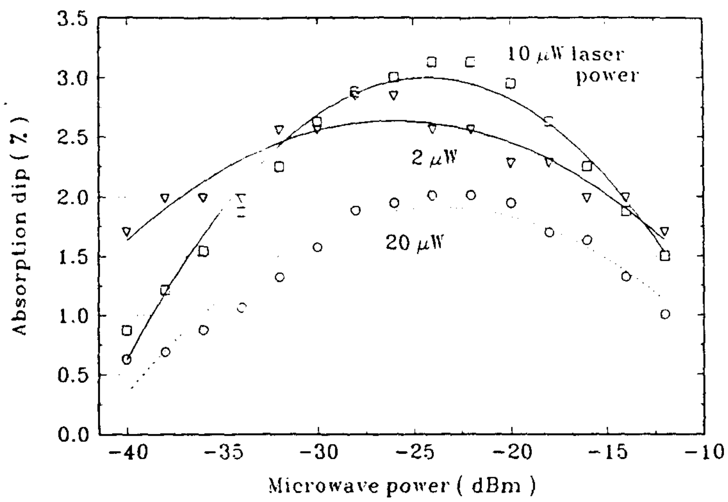

Fig. 3. Microwave resonance strength (ΔI/I) as a function of microwave power at the synthesizer. The cell is at room temperature. The maximum signal (3%) is vastly higher than any lamp pumped standard even operated at 70°C.

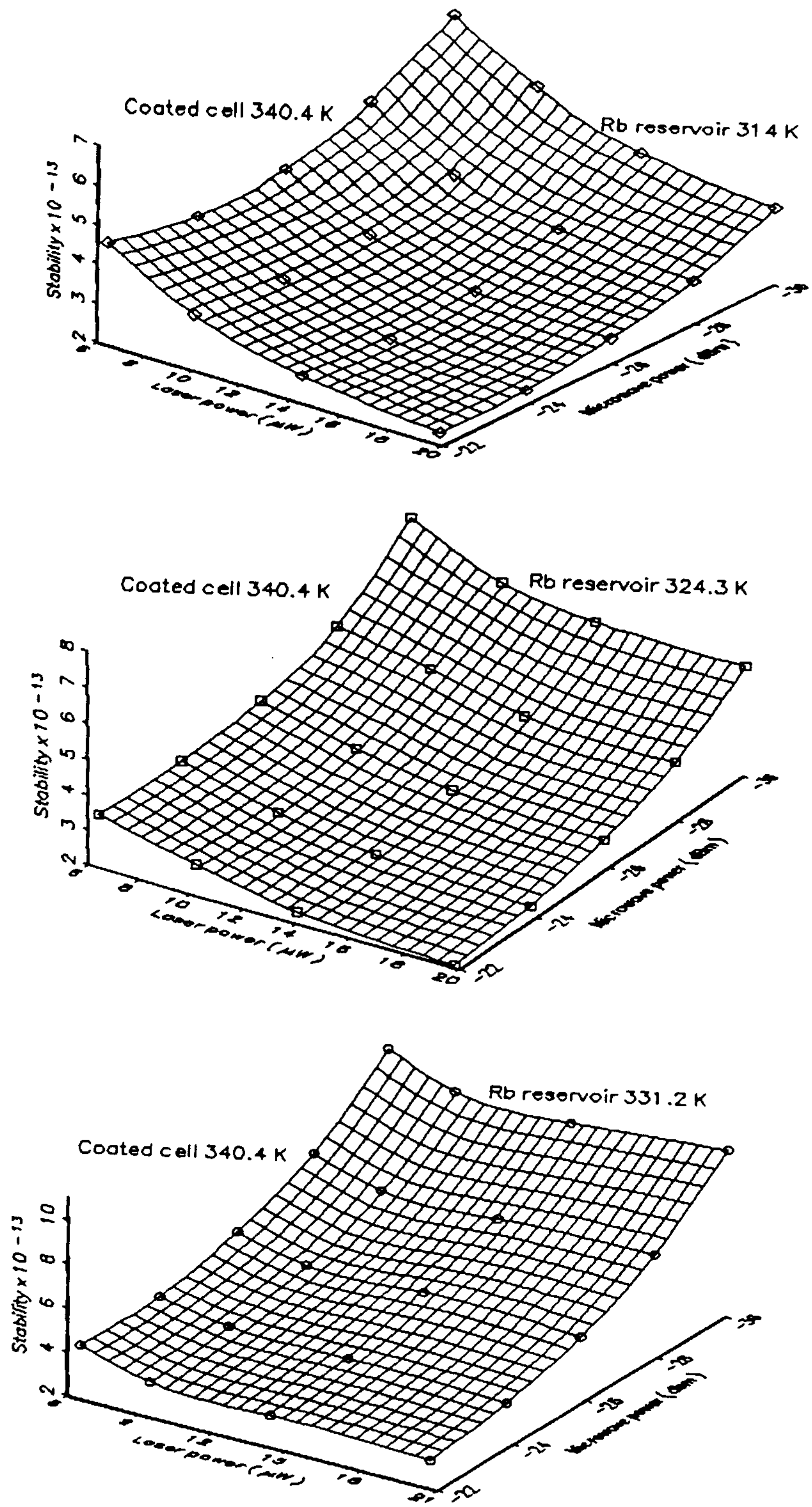

Fig. 4. Evaluated stability vs. microwave and optical power. The stability is calculated from measured noise current and discriminator slope; $\sigma_y(\tau) \equiv [1/\sqrt{2}] \cdot [i_n/D\nu_o] \cdot \tau^{-1/2}$, [14].

The reduced linewidth inherent in an extended-cavity laser provides the desired FM noise control. We need only servo the frequency to a feature in the rubidium spectrum to attain long-term frequency control. We choose a Doppler compensated, saturated-absorption scheme in an external, evacuated rubidium cell. This scheme can be implemented in a way that requires no extra optics from a simple Doppler interrogation of the rubidium resonance, Fig 5. The system uses the Fresnel reflections from the exit window of the cell to generate the probe beams. By differential detection of the two, nonoverlapping beams there is first-order cancellation of the Doppler absorption and the saturated absorption lines stand out clearly against a flat background; Fig 6. A full discussion of the laser FM control and its influence on the clock stability through the light shift effect will be presented in a future publication.

In addition to adequate AM and FM noise control on the laser, the interrogating microwave radiation must have exceptionally low phase noise.[12] The actual results we achieved in the experiments with a commercial physics package were limited by this effect. To solve this problem, we have developed a new synthesis scheme which is expected to support standard operation down to $\sigma_y(\tau) = 2 \times 10^{-14}\ \tau^{-1/2}$.[13]

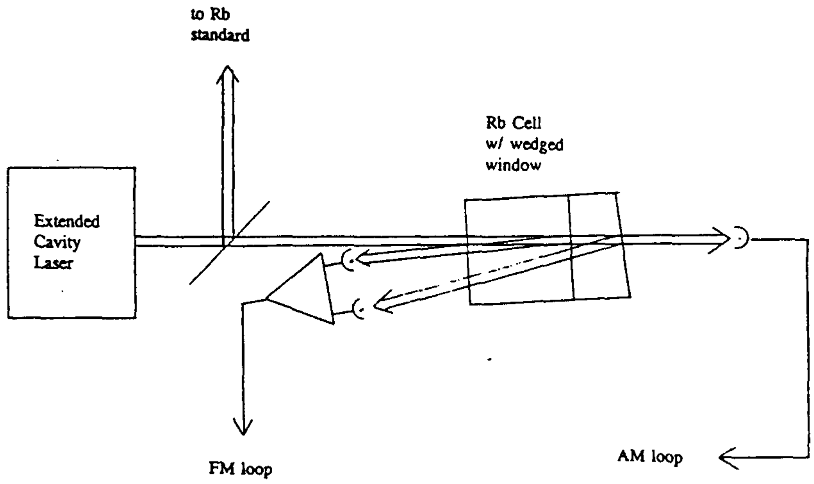

Fig. 5. Schematic for obtaining saturated absorption spectra from very simple layout.

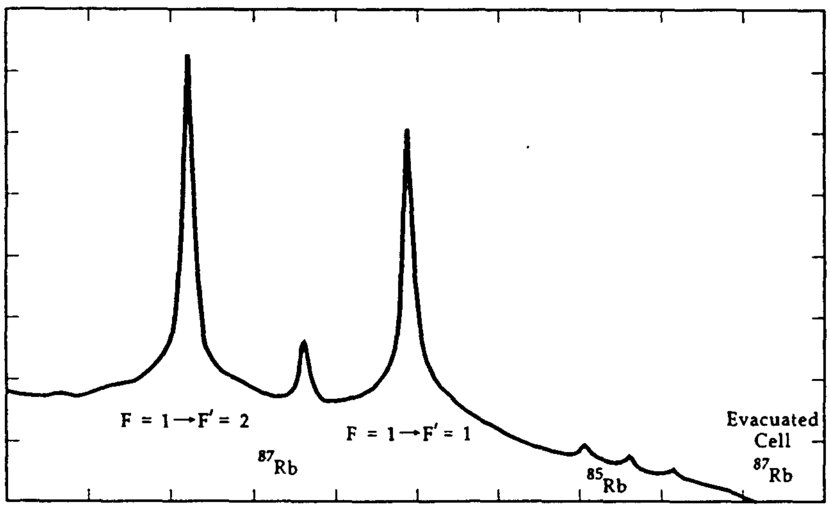

Fig. 6. Saturated absorption signals obtained in an evacuated ^{87}Rb cell. A small residual of ^{85}Rb can be seen as the closely spaced triplet in the lower right of the plot.

4. CONCLUSIONS

Our results are summarized in Table 1 along with those of other researchers. The measured stability of a commercial standard operated with our line-narrowed laser is a factor of 3 better than with its original lamp and is limited by phase noise in the microwave radiation. With an AM loop on the laser and adequate phase noise control in the microwave synthesizer, our measurements indicate that a short-term stability of $\sigma_y(\tau) \approx 4 \times 10^{-13}\ \tau^{-1/2}$ can be achieved in this standard. Optimizing the physics package for this new system should yield still further improvements. In an evacuated, wall-coated cell in a TE_{011} cavity we have measured line Q and S/N ratios commensurate with a $\sigma_y(\tau) = 2 \times 10^{-13}\ \tau^{-1/2}$. With improved magnetic field control and a refined AM loop on the laser, we think this can be reduced to $\sigma_y(\tau) \leq 5 \times 10^{-14}\ \tau^{-1/2}$.

Table 1. Summary of experimental results on laser pumped rubidium cell standards.

Source	laser, linewidth, lock technique	cavity and cell type	Measured $\sigma_y(\tau)$	Projected $\sigma_y(\tau)$ based on measured Q and S/N
ref 2	A	TE_{111}, Buffer gas, Mixed isotopes	$\approx 2 \times 10^{-11}\tau^{-1/2}$ $\tau \leq 100$ s	
ref 3	B	TE_{111}, Buffer gas, Mixed isotopes	$\approx 10^{-10}\ \tau^{-1/2}$ $\tau \leq 10$ s	
ref 4	A	Buffer gas, ^{87}Rb		[a] $\approx 2 \times 10^{-11}\tau^{-1/2}$
ref 7	A	TE_{011}, Buffer gas, mixed & ^{87}Rb		[a] $\approx 3 \times 10^{-12}\tau^{-1/2}$
ref 8	A	same as ref 7 single		[b] $\approx 8 \times 10^{-13}\tau^{-1/2}$
this work	C	same as ref 2	$\approx 4 \times 10^{-12}\tau^{-1/2}$ $\tau \leq 30$ s	[c] $\approx 4 \times 10^{-13}\tau^{-1/2}$
this work	C	TE_{011}, Evacuated, wall coated, ^{87}Rb		[d] $\approx 2 \times 10^{-13}\tau^{-1/2}$

A: Solitary laser, D_2 line (780 nm), linear absorption lock, $\Delta\nu_{laser} \approx 40$ MHz

B: Solitary laser, D_2 line, free running frequency, $\Delta\nu_{laser} \approx 400$ MHz.

C: Extended cavity laser, D_1 line (795 nm), saturated absorption lock, $\Delta\nu_{laser} \approx 0.1$ MHz.

[a] Based on measured line Q and S/N combined through the relationship $\sigma_y(\tau) = 0.2/[Q \cdot S/N]$.

[b] Based on measured line Q and S/N combined through the relationship $\sigma_y(\tau) = 0.11/[Q \cdot S/N]$.

[c] Based on measured stability rescaled for available AM noise control in the laser.

[d] Based on measured noise and discriminator slope $[\sigma_y(\tau) \equiv (1/\nu_o\sqrt{2})(i_n/D)\tau^{-1/2}]$ [14].

5. REFERENCES

1. J. C. Camparo and R. P. Frueholz, "Fundamental stability limits for the diode-laser-pumped rubidium atomic frequency standard," J. Appl. Phys. vol. 59, pp. 3313-3317, 1986.
2. R. E. Drullinger, C. Szekely, and J. C. Camparo, "Diode-laser-pumped, gas cell atomic clocks," in Proc. 1992 IEEE Freq. Control Symp., pp.104-107, Hershey, PA 1992.
3. L. L. Lewis and M. Feldman, "Optical pumping by lasers in atomic frequency standards," in Proc. 35th Ann. Freq. Control Symposium, pp. 612-624, Ft. Monmouth, 1981.
4. C. H. Volk and J. C. Camparo, "Lasers diode pumping in atomic clocks," in Aerospace Report No. ATR-82(8498)-1, pp. 55-60, 1982.
5. J. T. Liu, P. Thomann, L. Zhang, and G. Busca, "Studies of a laser diode pumped Rb standard," in Proc. 4th European Frequency and Time Forum, Neuchatel, March 1990.

6. Motoichi Ohtsu, Minoru Hashimoto and Hidetaka Ozawa, "A highly stabilized semiconductor laser and its application to optically pumped Rb atomic clock," in Proc. 39th Ann. Freq. Control Symposium, pp. 43-54, Philadelphia 1985.
7. Minoru Hashimoto and Motoichi Ohtsu, "Experiments on a semiconductor laser pumped rubidium atomic clock." IEEE J. Quant. Elect., vol. QE-23, pp. 446-451, 1987.
8. Minoru Hashimoto and Motoichi Ohtsu, "Modulation transfer and optical stark effect in a rubidium atomic clock pumped by a semiconductor laser," J. Opt. Soc. Am. B, vol. 6, pp.1777-1789, 1989.
9. This cell and cavity were kindly lent to us by Hugh Robinson of Duke University.
10. R. W. Fox, H. G. Robinson, A. S. Zibrov, N. Mackie, J. Marquardt, J. Magyar and L. W. Hollberg, "High-sensitivity spectroscopy with diode lasers," in these proceedings.
11. L. Hollberg, R. Fox, N. Mackie, A. S. Zibrov, V. L. Velichansky, R. Ellingsen, and H. G. Robinson, "Diode lasers and spectroscopic applications," in Tenth International Conference on Laser Spectroscopy, ed. M. Ducloy, E. Giacobino and G. Camy, pp. 347-352, World Scientific, 1992.
12. See for example C. Audoin, V. Chandelier and N. Dimarcq, "A limit to the frequency Stability of passive frequency standards," IEEE Trans. Instr. Meas., vol 40, pp. 121-125, 1991.
13. J. P. Lowe, F. L. Walls and R. E. Drullinger, "Ultra-high stability synthesizer for diode Laser pumped rubidium," in Proc. 1992 IEEE Frequency Control Symp., pp. 183-187, Hershey, PA 1992.
14. William J. Riley, "A rubidium clock for GPS," Proc. of the 13th Precise Time and Time Interval (PTTI) Applications and Planning Meeting, pp. 609-630, 1981