Compact Diode-Laser Based Rubidium Frequency Reference

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Abstract—**The performance of a simple microwave frequency reference based on Raman scattering in an atomic vapor is examined. This reference has the potential to be compact, low-power, and insensitive to acceleration. Several design architectures have been evaluated with a table-top experiment in order to guide the future development of a compact system. Fractional frequency deviations of $\leq 5 \times 10^{-11}$ appear to be feasible.**

I. Introduction

A microwave frequency reference that has the potential to be compact, low-power, transportable, and insensitive to acceleration while maintaining moderately good frequency stability is under development at NIST. This reference is based on stimulated Raman scattering (SRS) in Rb vapor related to dark line resonances [1] and coherence-induced gain in atomic systems [2]. SRS is a nonlinear process that couples two atomic states through a two-photon Λ transition. This happens on an atom-by-atom basis: an atom passes from its initial energy state to a different state by absorbing an incident photon and emitting a photon whose frequency is shifted by the frequency difference between the two energy levels. This process, as applied in our experiment, is depicted in Fig. 1. The incident beam, generated by a diode laser tuned near the Rb D1 atomic transition at 795 nm, passes through a small, heated Rb vapor cell. Within the vapor, a second, co-propagating optical field is generated by SRS, shifted from the incident field by the ground state hyperfine splitting of the atom (3.036 GHz for ^{85}Rb and 6.835 GHz for ^{87}Rb). These two fields are then focused onto a high-speed photodetector, and the resulting RF beat note becomes the signal on which the frequency reference is based. The different design configurations described here use this beat note in different ways.

The baseline design goals for this reference are a volume of $3 \times 3 \times 9$ cm^3, a power consumption of less than 1 W, and a fractional frequency instability of 10^{-11} at one day. We hope that the use of SRS will provide a fractional frequency insensitivity to acceleration below 3×10^{-12}/g (where g = 9.8 m/s^2). Applications for these devices include timing synchronization in telecommunications, global positioning system (GPS) receivers for use in adverse environments, and frequency calibration of laboratory instrumentation. The final device might occupy an intermediate niche somewhere between quartz crystal oscillators and traditional atomic frequency standards.

The present work is intended to be an initial, quick test of the conceptual basis for the project in order to guide the future development of a compact device. We present here preliminary, table-top evaluations of several different system designs using commercially available parts.

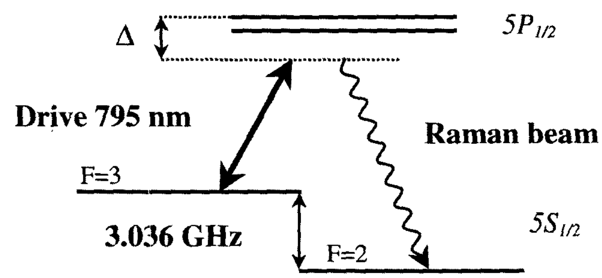

Fig. 1. Level diagram for ^{85}Rb showing relevant optical fields.

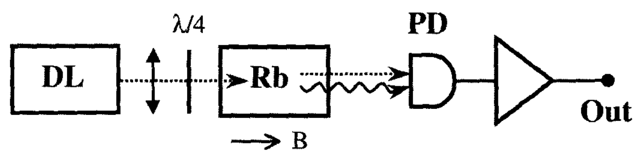

Fig. 2. Basic Raman scheme. DL, diode laser; PD, photodiode; B, magnetic field.

II. Design Configurations

A. Basic Scheme: Open-Loop Raman System

The basic experiment is shown in Fig. 2. Light from a two-section distributed Bragg reflector (DBR) diode laser [3] lasing at 795 nm was focused through an optical isolator and a quarter-wave plate into a small cell. The cell contained natural Rb at its vapor pressure, along with 4×10^3 Pa of Ne, and was heated to between 70 and 90°C. An axial magnetic field of $\leq 10^{-4}$ T was applied to the cell in order to split the Zeeman lines and resolve the magnetic

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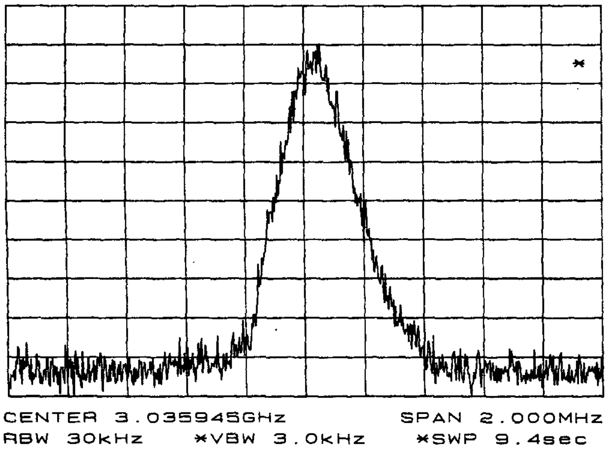

Fig. 3. Raman beat note for the $\Delta m = 0$ transition in open loop configuration. Vertical scale is 2 dB/div.

field independent $\Delta m=0$ resonance. The laser was tuned within 1 GHz of the F=3 D1 ^{85}Rb transition, and the laser power at the cell window was about 2 mW. The wave plate was adjusted for circular polarization. Within the cell, a Raman-shifted field was generated, which was then focused, along with the original laser field, onto a high-speed photodetector. The output RF signal at 3.036 GHz was then amplified and used as the reference frequency.

A typical output spectrum is shown in Fig. 3 and plays some role in all of the designs considered here. The Raman signal sits ~10 dB above a broad background, probably originating from FM-AM laser noise conversion in the atomic vapor [4]. The signal itself had a typical FWHM ~150 kHz, although widths as small as 70 kHz were observed for specific combinations of laser tuning and cell temperature. We think that this width is mostly due to power broadening reduced by propagation [5], and transit-time broadening; the laser beam was tightly focused inside the cell. The large width of this signal made it less than ideal for use as the frequency reference. Initial tests to divide this signal down to lower frequencies with simple commercial prescaler chips proved unsatisfactory, although further work needs to be done in this direction. This simple configuration was also troubled by laser-light-induced shifts that will need to be controlled. The main advantages are simplicity, very low required part count, and anticipated insensitivity to acceleration. The small amount of associated electronics also would aid considerably in the design of a compact, low-power package.

B. Closed-Loop Raman Oscillator

In order to achieve higher signal-to-noise ratio at the output, a closed-loop configuration, shown in Fig. 4, was adopted. The beat note from the RF pre-amplifier was amplified further, then was sent back to the laser injection current. With enough amplification, a microwave loop oscillation condition was established that narrowed the output signal enormously. The signal-to-background-noise ratio improved to ~60 dB with a 1 kHz resolution bandwidth. We anticipate that the closed-loop architecture will require a rigid structure and low loop delay times to reduce acceleration sensitivity, as changes in the loop length caused by vibrations are translated directly into frequency fluctuations of the oscillator. This frequency pulling is reduced by the Rb line Q compared to effective Q of the feedback delay. Nevertheless, even with an approximately 2 m long table-top system, a fractional frequency instability of 5×10^{-9} for measurement times between 0.01 s and 1 s was obtained.

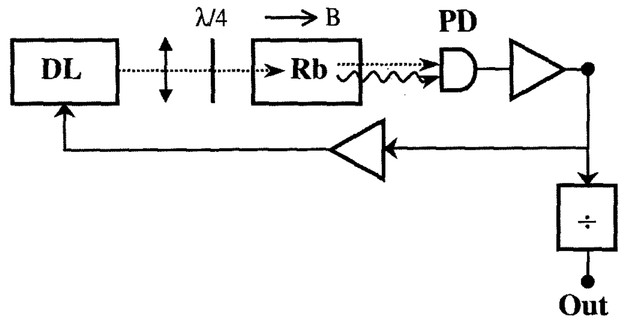

Fig. 4. Closed loop Raman oscillator, which includes feedback into the laser injection current.

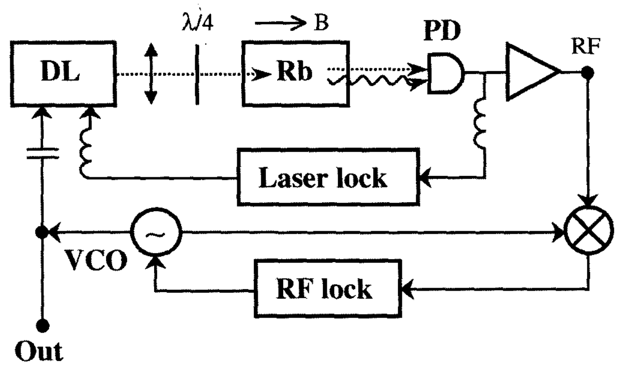

Fig. 5. External oscillator configuration. VCO, voltage controlled oscillator.

C. External Oscillator Locked to Raman Signal

To reduce problems associated with laser-light-induced Stark shifts, and to get the required microwave gain, a configuration was implemented in which an external oscillator was frequency-locked to the Raman resonance without a closed RF feedback loop. This configuration is shown in Fig. 5. An external oscillator was used to modulate the laser injection current at 3.4 GHz, one half of the ^{87}Rb hyperfine splitting. In this case we used a voltage-controlled crystal oscillator (VCXO) synthesized up to RF, but it easily could be replaced by a low-power voltage-controlled oscillator (VCO). The optical carrier and associated RF sidebands were passed through the Rb cell, and the 3.4 GHz modulation frequency was recovered in the fast photodiode. This RF photocurrent was amplified and mixed with the original modulating signal to produce an output at DC. The external oscillator frequency then was scanned around 3.4 GHz. The resulting mixer output contained a narrow feature (FWHM ~600 Hz) associated with Raman processes in the Rb vapor, superimposed on a broad background resulting from phase shifts in the RF path. At low laser power this narrow feature consists of a "dark line" resonance between the upper and lower modulation sidebands enhanced by Raman gain [6]–[8]. The VCXO was tuned onto the narrow resonance, and the error signal was fed into the crystal voltage control in order to stabilize the crystal to the Raman resonance.

In order to suppress oscillator frequency changes arising from drifts in the laser wavelength, the laser was locked to the ^{85}Rb Doppler absorption signal using the DC output from the photodetector (indicated by "Laser lock" in Fig. 5). The stabilized external oscillator frequency then was measured by beating it against a 3.04 GHz dielectric resonator oscillator (DRO) phase-locked to a hydrogen maser. The resulting intermediate frequency (IF) at 377 MHz was sent to a counter and recorded as a function of time. Typical frequency data as a function of time are shown in Fig. 6. Fig. 6(a) shows that the oscillator's shorter-term frequency fluctuations are of order 0.5 Hz (~10^{-10}), probably due to nonoptimal locking of the VCXO and to counter-associated noise. The long-term frequency fluctuations, shown in Fig. 6(b), were dominated by thermally induced drifts of order of 10 Hz on time scales of a few thousand seconds. These data were taken without active temperature control of the Rb cell or the apparatus. The Allan deviation was calculated from this measured frequency data and is shown in Fig. 7. While the fractional frequency stability remains below 10^{-10} out to about 100 s measurement time, it increases rapidly at longer times due to the thermal effects (temperature changes approximately ±0.5°C). The data shown here are good, but not atypical, results of our table-top system. We have explored a number of configurations with different locking schemes, modulation frequencies, and laser powers for both ^{85}Rb and ^{87}Rb. These parameters are mutually interacting and often can be traded one against the other for certain performance goals. We anticipate, however, that improved engineering of the RF system will reduce these temperature-related difficulties substantially.

D. RF Power Detection

A slightly modified scheme is presented in Fig. 8. The mixer was replaced with a microwave power detector to avoid RF phase-dependent variations in the DC level of the signal background. Removing this phase dependence also should eliminate a potential source of vibration sensitivity. The laser injection current was modulated at half the frequency of the ground state hyperfine splitting of either Rb isotope. With appropriate choice of RF amplifiers

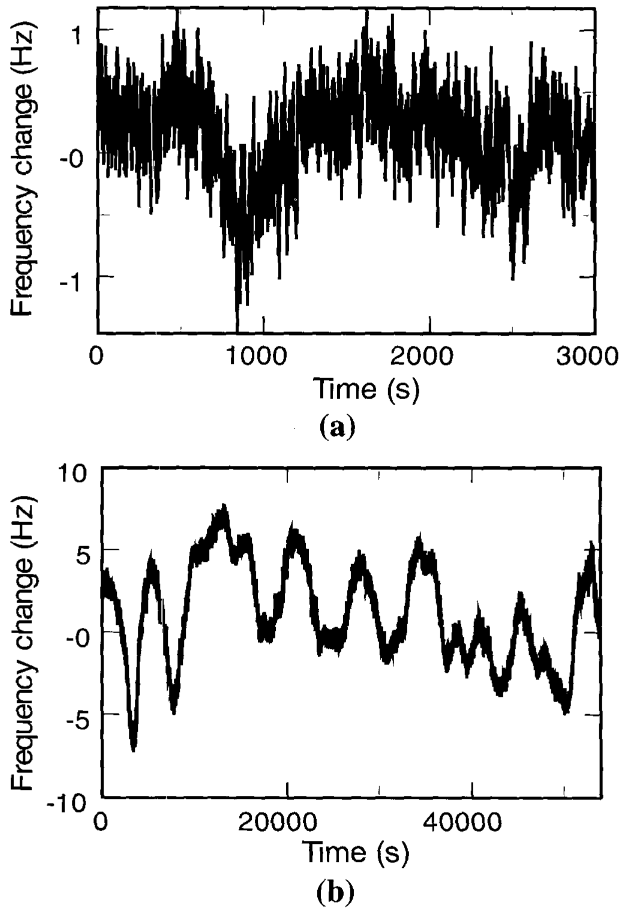

Fig. 6. Oscillator frequency change as a function of time. (a) Short-time data, (b) long-time data showing thermally driven fluctuations.

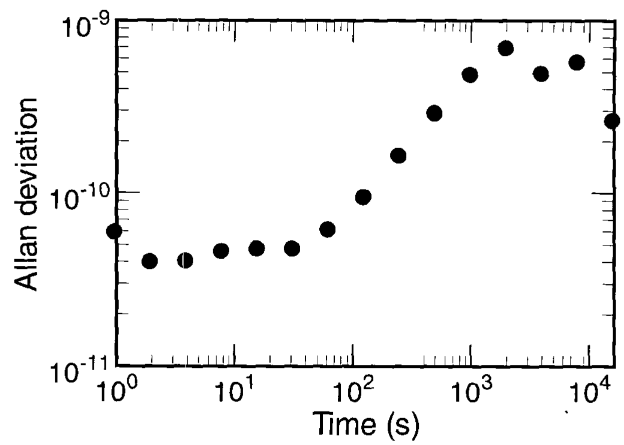

Fig. 7. Allan deviation of external oscillator configuration.

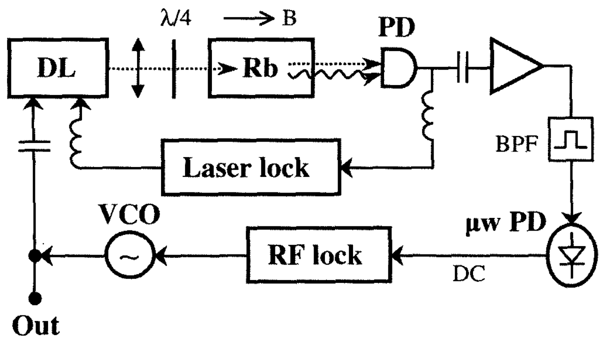

Fig. 8. RF power detection scheme. BPF, band-pass filter; μw PD, microwave power detector.

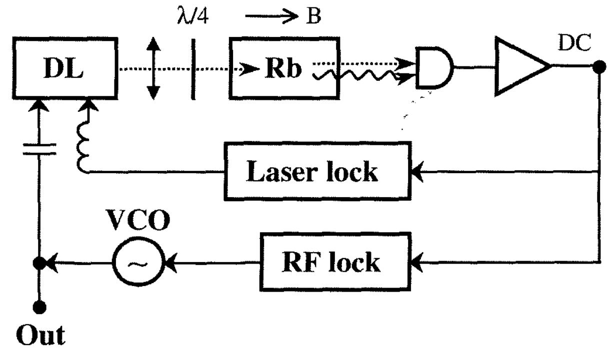

Fig. 9. DC detection configuration.

and band-pass filters, the microwave power was measured at the frequency corresponding to the hyperfine splitting, at which a signal was created by the beat note between the two RF sidebands. The output of the power detector then was used to lock the VCXO. The choice of different modulation and detection frequencies resulted in reduced cross-talk between the input and the output. The laser frequency was locked in-between the two ^{85}Rb Doppler absorption lines, with an optical power range incident upon Rb of 50 μW to 1 mW. The frequency stability obtained with this configuration was similar to the data shown above. The main limitations were Stark shift and power broadening caused by the strong laser carrier tuned near the Rb transition. Depleting the carrier power by increasing the laser modulation index at the microwave frequency would reduce these effects. Also, more power would be transferred into sidebands, which would yield a higher signal-to-noise ratio to lock the VCO.

E. DC Detection

The fast photodiodes used in all of the above configurations have a small photosensitive surface ($\varnothing \sim 50$ μm), which poses a problem for vibration insensitivity. This could be avoided by substituting the fast photodiode with a large-area DC photodiode and measuring the change in DC light level. Other benefits of this scheme, shown in Fig. 9, are simplicity of design, no need for microwave amplifiers, and direct access to absorption signal. However, limitations are that the useful signal sits on a large DC background and detection is at a low Fourier frequency, which usually means excess noise. Performance of this type of configuration is now under study.

III. Discussion

The designs discussed here present several advantages for a compact frequency reference. The device clearly could be made compact and have low power consumption. The diode laser used in the table-top experiment dissipates about 200 mW, which is adequate for a system with a power budget of 1 W. We also expect that the open loop and external oscillator designs will be insensitive to acceleration, because the signal is derived exclusively from an atomic point process. In principle, therefore, the frequency does not depend at all on the physical length of any component. We will make measurements on this aspect of the device performance in the near future.

There also are disadvantages with this type of oscillator. It requires optical complexity usually not required in microwave frequency references: a laser tuned to the atomic resonance and a high-speed photodetector. Although there is no fundamental reason why these need to be unreliable or expensive components, the devices used in this table-top experiment cost several thousand dollars. The closed-loop configuration almost certainly will require some kind of microwave phase cancellation within the loop in order to reduce the sensitivity to acceleration. The laser-induced Stark shifts are significant in some configurations, but they can be reduced to an acceptable level with appropriate design.

All of these designs also appear compatible with the use of vertical-cavity surface-emitting lasers (VCSELs) [9], [10]. These devices typically require about an order of magnitude less power than conventional lasers due to their low threshold and operating currents. In addition, their high modulation bandwidth would enable equivalent sideband generation with a lower power RF amplifier for both the closed loop and the external oscillator schemes. Their somewhat broader line width is not expected to cause significant broadening of the Raman resonance line because the Raman signal generated in the vapor is phase-coherent with the driving field, and only the relative phase between the two is important for the beat note. Therefore, we hope to try VCSEL technology in this system in the near future.

IV. Conclusions

We have explored a large number of system configurations for a compact microwave reference based on stimulated Raman transitions in Rb vapor. Aspects that have been addressed are: open-loop versus closed-loop operation, whether an internal VCO is required, whether a laser frequency servo is required, and how such a servo might be implemented. Allan deviations in the range of a few times 10^{-11} have been measured on time scales around 100 s; increasing instability on longer time scales appears to be thermal in origin and is likely to be improved with better mechanical, thermal, and RF engineering. We expect the development of a prototype compact device in the near future.

Acknowledgments

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Fred L. Walls (A'93–SM'94) was born in Portland, OR, on October 29, 1940. He received the B.S., M.S., and Ph.D. degrees in Physics from the University of Washington, Seattle, in 1962, 1964, and 1970, respectively. His Ph.D. thesis was on the development of long-term storage and nondestructive detection techniques for electrons stored in Penning traps and the first measurements of the anomalous magnetic (g-2) moment of low energy electrons.

From 1970 to 1973, he was a Postdoctoral Fellow at the Joint Institute for Laboratory Astrophysics in Boulder, CO. This work focused on developing techniques for long-term storage and nondestructive detection of fragile atomic ions stored in Penning traps for low energy collision studies. Since 1973, he has been a staff member of the Time and Frequency Division of the National Institute of Standards and Technology, formerly the National Bureau of Standards in Boulder. He is presently Leader of the Phase Noise Measurement Group and is engaged in research and development of ultra-stable clocks, crystal-controlled oscillators with improved short- and long-term stability, low-noise microwave oscillators, frequency synthesis from RF to infrared, low-noise frequency measurement systems, and accurate phase and amplitude noise metrology. He has published more than 150 scientific papers and articles. He holds five patents for inventions in the fields of frequency standards and metrology.

He received the 1995 European "Time and Frequency" Award from the Societe Francaise des Microtechniques et de Chromometric for "outstanding work in the ion storage physics, design and development of passive hydrogen masers, measurements of phase noise in passive resonators, very low noise electronics and phase noise metrology." He is the recipient of the 1995 IEEE Rabi Award for "major contributions to the characterization of noise and other instabilities of local oscillators and their effects on atomic frequency standards" and the 1999 Edward Bennet Rosa Award for "leadership in development and transfer to industry of state-of-the-art standards and methods for measuring spectral purity in electronic systems." He has also received three silver medals from the US Department of Commerce for fundamental advances in high resolution spectroscopy and frequency standards, the development of passive hydrogen masers and the development and application of state-of-the-art standards and methods for spectral purity measurements in electronic systems. Dr. Walls is a Fellow of the American Physical Society, a Senior Member of the IEEE, a member of the Technical Program Committee of the IEEE Frequency Control Symposium, and a member of the Scientific Committee of the European Time and Frequency Forum.