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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 $\leq 5\times10^{-11}$ appear to be feasible.

1. 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]. A diode laser is tuned near the Rb D1 atomic transition at 795 nm and passed through a small, heated Rb vapor cell. Within the vapor, a second, co-propagating optical field is generated by SRS, shifted from the first field by the ground state hyperfine splitting of the atom (3.036 GHz for ^{85}Rb), as shown in *Figure 1*. These two fields are then focussed 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 below use this beat note in different ways.

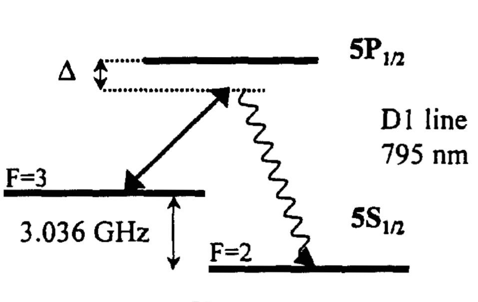


Figure 1: Level diagram for ^{85}Rb showing relevant optical fields.

The baseline design goals for this reference are a volume of $3\times3\times9$ 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 position 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.

2. DESIGN CONFIGURATIONS

2.1 Basic Scheme: Open-Loop Raman System

The basic experiment is shown in *Figure 2*. Light from a two-section distributed Bragg reflector (DBR) diode laser [3] lasing at 795 nm was focussed 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 °C and 90 °C. An axial magnetic field of $\leq10^{-4}$ T was applied to the cell in order to split the Zeeman lines and resolve the magnetic field independent $\Delta m=0$ resonance.

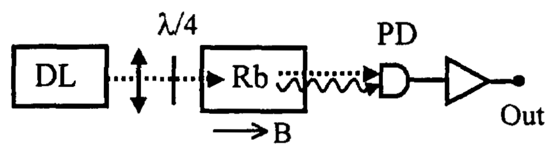


Figure 2: Basic Raman scheme. DL: diode laser, PD: photodiode.

In this configuration 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 focussed, 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 *Figure 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 focussed 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 would also aid considerably in the design of a compact, low-power package.

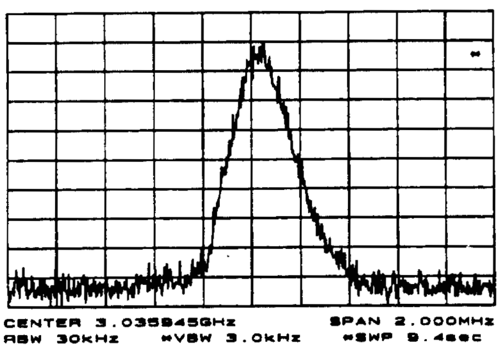


Figure 3: Raman beat note for the $\Delta m=0$ transition in open loop configuration. Vertical scale: 2 dB/box

2.2 Closed-Loop Raman Oscillator

In order to achieve higher signal-to-noise ratio at the output, a closed-loop configuration, shown in *Figure 4*, was adopted. The beat note from the RF pre-amplifier was amplified further and was then sent back to the laser injection current. With enough amplification, a microwave loop oscillation condition was established which 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, since 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.

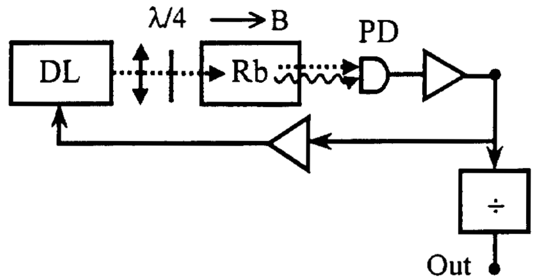


Figure 4: Closed loop Raman oscillator which includes feedback into the laser injection current.

2.3 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 *Figure 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 could easily 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.

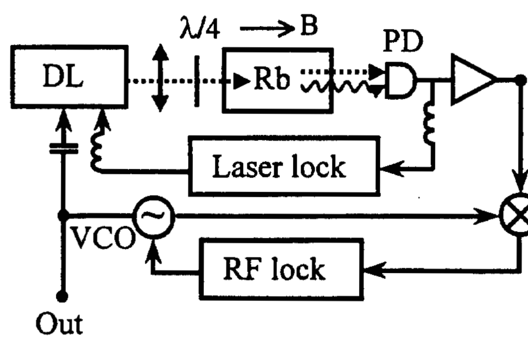
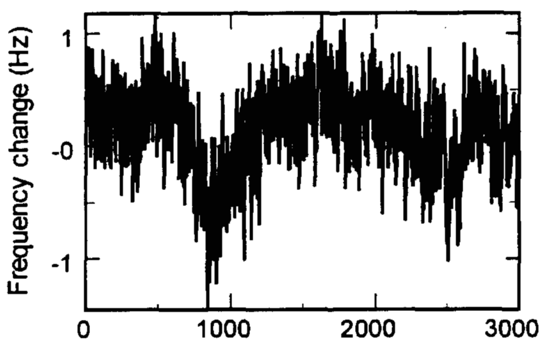


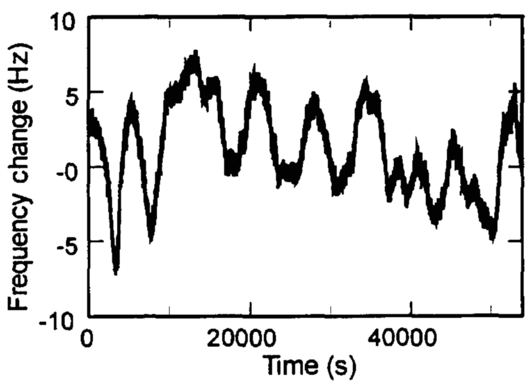
Figure 5: External oscillator configuration. VCO: voltage controlled oscillator

This RF photocurrent was amplified and mixed with the original modulating signal to produce an output at DC. The external oscillator frequency was then 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][7]. 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 *Figure 5*). The stabilized external oscillator frequency was then 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 *Figure 6*. *Figure 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 *Figure 6*(b), were dominated by thermally induced drifts of order of 10 Hz on time scales of a few thousand seconds.



(a)



(b)

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

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 *Figure 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.

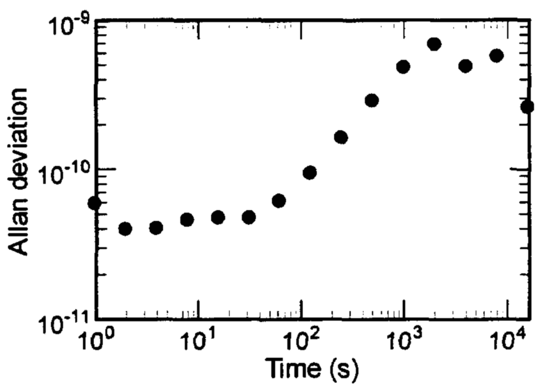


Figure 7: Allan deviation of external oscillator configuration.

3. DISCUSSION

The designs discussed above present several advantages for a compact frequency reference. The device could clearly 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 are also 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. While 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 will almost certainly require some kind of microwave phase cancellation within the loop in order to reduce the sensitivity to acceleration. Finally, laser-induced Stark shifts are significant in some configurations, but can be reduced to an acceptable level with appropriate design.

However, all three designs also appear compatible with the use of vertical-cavity surface-emitting lasers (VCSELs) [8][9]. 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 since 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. We therefore hope to try VCSEL technology in this system in the near future.

4. 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.

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