A compact microwave frequency reference using diode lasers[1]

N. Vukičević, A. S. Zibrov, L. Hollberg, F. Walls and J. Kitching
Time and Frequency Division, National Institute of Standards and Technology
M.S. 847.10, 325 Broadway, Boulder CO 80303
Tel: (303)-497-6353, Fax: (303)-497-7845, E-mail: natasa@boulder.nist.gov

A compact microwave frequency reference that uses a diode laser to excite stimulated Raman transitions in a small Rb vapor cell is being developed. The system's simplicity and use of advanced semiconductor laser and photodetector technology allows it to be compact and power-efficient, while maintaining a reasonable degree of long-term stability and a potentially high degree of insensitivity to environmental perturbations. Baseline design goals are a volume of 3x3x9 cm^3, power consumption of less than 1 W and a fractional frequency instability of 10^{-11} at one day.

Compact microwave frequency references have a number of important potential applications in the areas of telecommunications, global navigation and instrumentation. For example, such devices might be installed in cellular telephone networks in order to maintain timing synchronization without the need for a reference timing signal common to all nodes. A fractional frequency inaccuracy of 10^{-10} at one day would likely be adequate for this application, but insensitivity to large temperature changes, humidity and vibrations is essential. Compact, power-efficient, vibration-insensitive frequency references could also be used in global positioning system receivers in order to acquire a GPS signal lock more quickly and maintain the lock in adverse environments. Finally, many common laboratory instruments, such as frequency synthesizers, counters and spectrum analyzers might benefit from compact, inexpensive atomic frequency references to replace or enhance commonly used quartz reference oscillators.

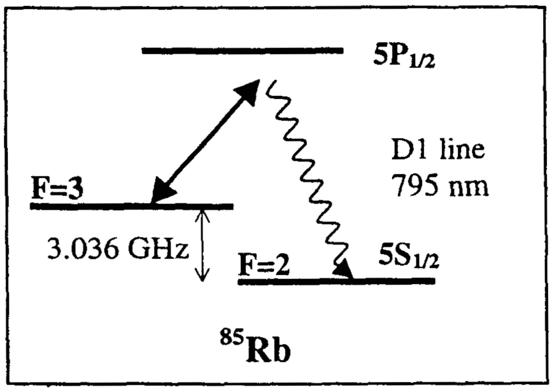

Figure 1: Basic optical field configuration.

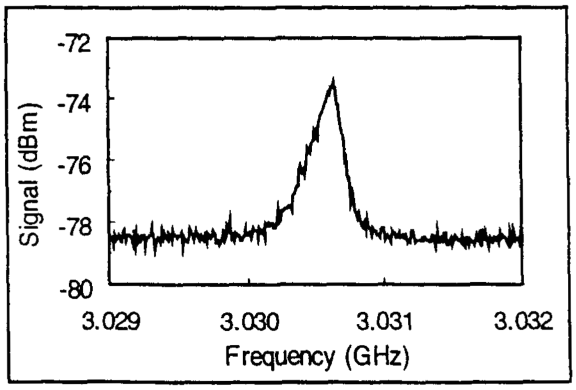

Figure 2: Raman beatnote for unmodulated laser.

The compact Rb oscillator described here is based on atomic coherence-induced gain observed in a previous simple experiment[2]. The basic optical field configuration and the relevant atomic energy levels are shown in Figure 1. Light from a distributed Bragg reflector (DBR) diode laser at 795 nm is focussed through a miniature, heated ^{85}Rb vapor cell. Within the cell, stimulated Raman scattering (SRS) generates a second optical field, co-propagating with the first, but shifted by the hyperfine frequency of the atom. These two optical fields are focussed onto a high-speed

Reprinted from Advanced Semiconductor Lasers and Their Applications Conference, 1999 Technical Digest,

photodetector resulting in a beat note at the 3.036 GHz hyperfine splitting. In one initial design implementation, this signal, shown in Figure 2, is simply amplified and used as the frequency reference output. While this configuration has the advantage of simplicity, could fit into an extremely small package, and is expected to be acceleration insensitive, the output frequency is fairly broad (FWHM ~ a few hundred kilohertz) and troubled by laser light-induced shifts that will need to be controlled. Nevertheless, a fractional frequency instability of 1×10^{-9} between 0.01 s and 1 s was obtained.

In a refinement of the basic design, shown in Figure 3, the laser injection current is directly modulated at the hyperfine frequency with a voltage-controlled oscillator (VCO). In the laboratory experiments described here, a crystal oscillator is used but will be replaced eventually by a VCO. This modulation provides an additional optical frequency to the Rb cell that is then amplified by SRS. The width of the resulting resonance at 3.036 GHz is narrowed to ~800 Hz. The photodetector output is then mixed with the original modulating signal and the resulting error signal is fed back to the VCO stabilizing it to the atomic resonance (Figure 3, RF servo). In order to reduce laser frequency-induced fluctuations in the beat note frequency, a laser frequency servo is also implemented using the detector DC photocurrent (Figure 3, DC servo). The locked VCO frequency is monitored in time; Figure 4 shows a typical Allan deviation, with fractional frequency fluctuations $< 1 \times 10^{-10}$ for averaging times $1 \leq \tau \leq 300$ s. The small remaining frequency excursions are due to uncontrolled thermally-induced frequency drifts.

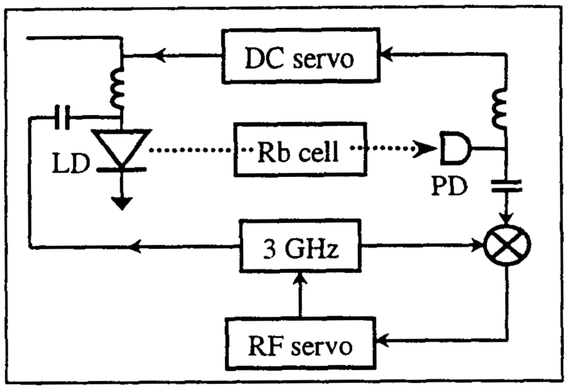

Figure 3: Refined experimental setup showing RF lock and laser frequency lock. LD: Laser Diode, PD: Photodiode.

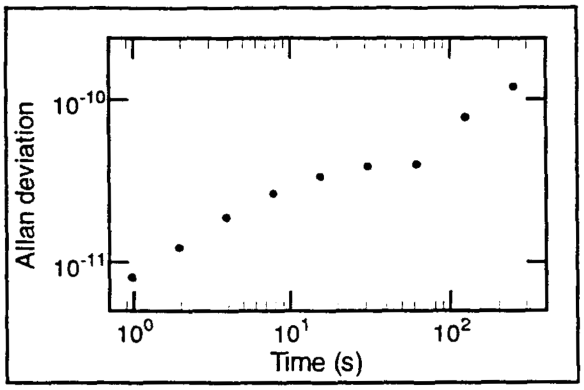

Figure 4: Allan deviation of compact Rb frequency reference.

The two-section DBR laser[3] used here was chosen because of its reasonably narrow spectral linewidth (~1 MHz) and its tunability combined with a compact, monolithic design. While this laser has a reasonably low electrical power consumption (<200 mW), a considerable advantage could be gained by replacing it with a vertical cavity surface-emitting laser (VCSEL)[4]. A typical operating current of several milliamperes for these devices results in a power consumption value about an order of magnitude smaller than that for edge-emitting lasers. Their high modulation bandwidth would also be a significant advantage in this application, since a lower power RF amplifier would then suffice to put modulation sidebands on the laser. Preliminary evaluations of VCSELs show two possible drawbacks, larger linewidth (several tens of MHz) and high sensitivity of wavelength to current variations (~100 times higher than edge-emitting Fabry-Perot lasers).

In summary, preliminary table-top experiments have demonstrated the feasibility of a compact, low power, atomic frequency reference with a fractional frequency instability of $< 1 \times 10^{-10}$. While sensitivity to environmental perturbations continues to be a problem with the current unoptimized system, improved RF and structural design and modest temperature control are expected to reduce these difficulties substantially. Re-engineering of the system into a small package is currently underway.

---

[1] Contribution of NIST. Not subject to copyright.

[2] A. S. Zibrov, et al., Proc. 5th Symposium on Frequency Standards and Metrology, J. C. Bergquist, ed., World Scientific, 1996.

[3] T. Hirata, M. Maeda, M. Suehiro and H. Hosomatsu, IEEE J. Quantum Electron. **27**, 1609, 1991.

[4] High wallplug efficiency lasers at 850 nm have recently been reported in R. Jager, et al., Electron. Lett., **33**, 330, 1997; also see C. Affolderbach, et al., submitted to Appl. Phys. B, 1999 for spectroscopic applications of VCSELs.