COMPACT MICROWAVE FREQUENCY REFERENCE BASED ON COHERENT POPULATION TRAPPING†

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A simple, compact and low-power microwave frequency reference based on CPT resonances in Cs vapor is described. The 14 cm^3 physics package exhibits a resonance width of 620 Hz at 4.6 GHz, a short-term fractional frequency instability of $1.3\times10^{-10}/\sqrt{\tau/(s)}$, and dissipates less than 30 mW, not including temperature control. We discuss the prospects for extreme miniaturization to sub-millimeter dimensions.

1 Introduction

Atomic frequency references and quartz-crystal oscillators are, in some sense, complimentary technologies. Atomic frequency references have good accuracy and long-term stability but are large, complex and expensive to build. Quartz-crystal oscillators, on the other hand, have poor accuracy but superb short-term stablity, and are small, simple and inexpensive. A significant gap exists, both in performance and design, between the two types of frequency reference, as shown in Table 1. There are two obvious appoaches to bridging this gap: to make quartz crystals better (and probably larger and more expensive) or to make atomic clocks cheaper and simpler (and probably less accurate).

Table 1. Comparison of frequency references.

	Accuracy	$\sigma_y(1\ s)$	Size	Power	Cost
Atomic Reference	10^{-10}	3×10^{-11}	100 cm^3	10 W	$2,000
Quartz-crystal oscillator	10^{-7}	10^{-12}	10 cm^3	1 W	$100

Applications for compact atomic clocks (or high-performance quartz crystals) are numerous, ranging from the military [1] to advanced telecommunications [2] and instrumentation. Military applications include fast-acquisition GPS receivers, anti-jam communications systems, and advanced identification and surveillance technology. These tend to require more compact devices of lower power. Commercial applications, such as telecommunications network synchronization and laboratory instrumentation, mostly require devices of lower cost. We describe here our efforts to design and build compact atomic clocks for these kinds of applications. We have focused on using coherent population trapping (CPT) rather than a conventional optical-microwave double-resonance design due to the simplicity and increased potential for extreme miniaturization and low-power operation.

2 The CPT-Clock

Research on coherent population trapping [3,4] is increasing for use in a variety of applications from atomic clocks [5,6] to magnetometers [7], although no

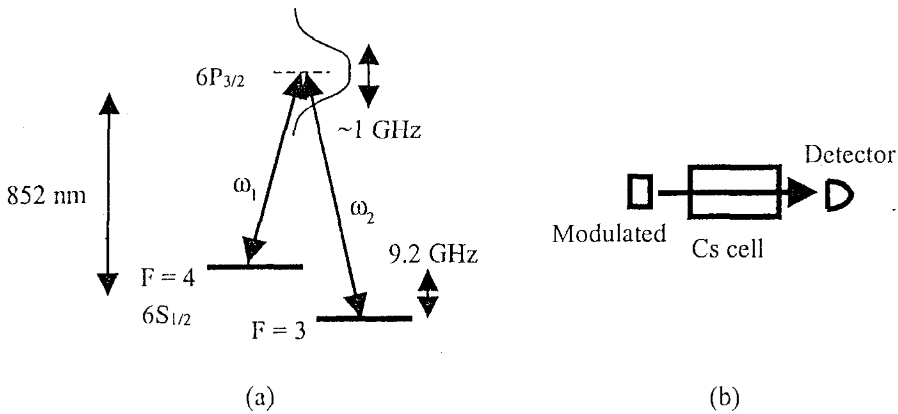


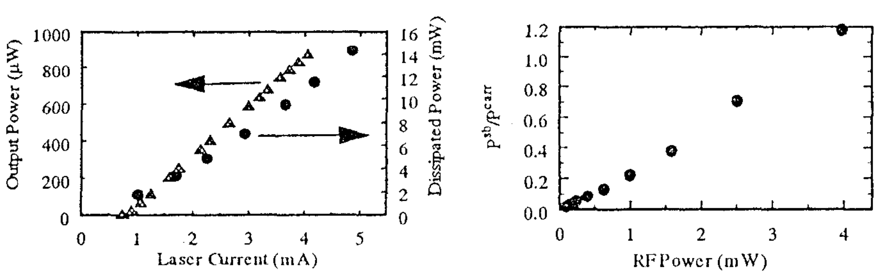
Figure 1. An atomic clock based on CPT.

commercial systems have yet been brought to market. In a CPT clock, the atomic microwave resonance is probed using only optical fields, separated in frequency by the atomic ground state hyperfine transition splitting and tuned to be simultaneously in resonance with an optical transition. The fields are passed through a thermal vapor of atoms and the DC absorption is monitored as a function of the difference frequency between the fields. When this difference frequency exactly equals the atomic hyperfine splitting, a change in the absorption occurs: atoms are optically pumped into a coherent superposition of the ground states for which quantum interference prevents the absorption of light [8].

In our system [9], the current of a semiconductor laser is modulated at the first sub-harmonic of the hyperfine frequency such that the two first-order sidebands are resonant with the atomic levels, as shown in Figure 1. The frequency of the modulation signal, which is derived from a crystal oscillator and synthesizer, is then locked to the atomic absorption line using the transmitted power through the cell. It is interesting and important that, with this method, no microwave fields are applied to, or detected from, the atoms. Both the atomic excitation and the state detection are done with only optical fields. Although not used in our implementation of the CPT-clock, the CPT superposition state has a magnetic moment oscillating at the hyperfine splitting frequency, which can also be detected [10] (with a microwave cavity, for example) to determine whether the microwave frequency is on resonance.

3 Clock Design

Several aspects of the clock design are important for miniaturization and low-power operation. The first of these is the choice of laser: we use here a vertical-cavity surface-emitting laser (VCSEL). VCSELs are ideal for a number of reasons. First, they operate with very low input power. The laser threshold current is typically below 1 mA for single-transverse-mode devices, and the operating current is under 5 mA, so that only ~ 10 mW of DC power is required to run the device (see Figure 2a). Because of the high modulation bandwidth, the RF power required to produce large first-order optical sidebands is also quite low, about 5 mW, as shown in Figure 2b. Finally, the stable single-mode operation and device reliability are promising features for commercial implementations. Although not yet commercially available, single-transverse-mode VCSELs are made routinely in research labs at the 852 nm D2 transition wavelength of Cs.



(a) (b)

Figure 2. (a) The VCSEL output power and DC electrical power dissipated in the device as a function of injection current and (b) the power in one first-order optical sideband at 4.6 GHz, as a fraction of the power in the carrier, plotted as a function of RF power injected into the laser.

The microwave transition linewidth, which is normally broadened by collisions of the atoms with the cell walls and the Doppler effect, is reduced with the addition of a buffer gas (typically a few kPa of Ne or N_2 for a centimeter-scale cell) to the cell. Larger pressures of buffer gas isolate the Cs atoms more effectively from the cell walls but introduce pressure broadening and reduce the signal strength. In the cells used in the experiment, a combination of Ne and Ar buffer gases, with a total pressure of ~ 5 kPa, was used to reduce the cell's temperature coefficient.

A circularly-polarized optical field, created with a quarter-wave-plate between the laser and the cell, was used to excite the CPT resonance. The laser frequency was locked to the optical absorption line to reduce the effects of long-term laser frequency drifts on the clock frequency. A longitudinal magnetic field of ~ 10 μT was applied to the cell to separate the $m_{F=3}=0 \rightarrow m_{F=4}=0$ transition from those involving other ground-state Zeeman levels and some magnetic shielding protected the cell from external fields. The laser current was modulated with enough RF power so that about one-half of the optical power was contained in the two first-order sidebands. Each sideband contained ~ 50 μW/cm^2 in a beam ~ 4 mm in diameter. This was sufficient to see a CPT resonance without the use of a lock-in. Locking to the CPT resonance was accomplished by modulating the frequency of the quartz-crystal oscillator source and demodulating the photodiode's output with a lock-in amplifier and feeding back into the crystal varactor voltage.

4 Experimental Results

4.1 Table-top system

A table-top system was constructed to test the basic method and investigate the limits to the clock performance. In this system a cell of diameter 25 mm and length 20 mm was used. A typical CPT resonance is plotted in Figure 3. The resonance width was 106 Hz (at 4.6 GHz) and the change in power on resonance is about 0.3 % of the total optical power.

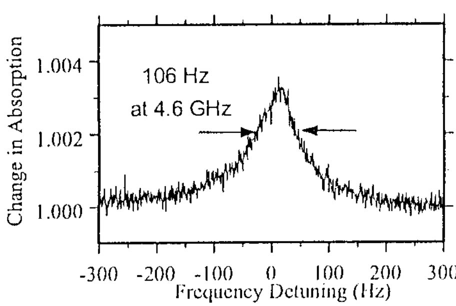


Figure 3. A typical CPT resonance.

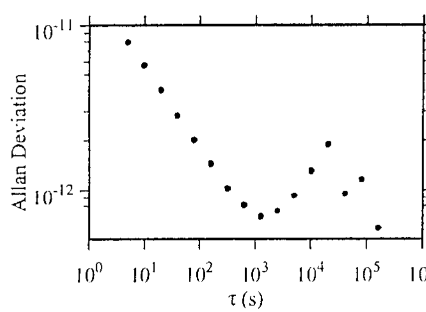


Figure 4. Allan deviation for table-top system

When the cell was actively temperature-stabilized and the synthesizer locked to the atomic resonance, the output frequency of the synthesizer at 4.6 GHz was measured as a function of time. The Allan deviation calculated from this time-series data is shown in Figure 4. The short-term fractional frequency instability, characterized by the Allan standard deviation, was $1.6\times10^{-11}/\sqrt{\tau/(s)}$, and bottomed out near 10^{-12} at 1000 s. The short-term instability was due to several noise sources: laser (shot) noise, linear and non-linear FM-AM conversion noise

[9], and noise due to optical pumping [11]. The long-term instability is believed to be caused by residual fluctuations in cell temperature, but was not extensively investigated. The fractional shift of the CPT resonance with optical power was $\sim 10^{-10}/(\mu W/cm^2)$, and the fractional shift with temperature was $< 4\times10^{-11}$ /K.

4.2 Compact System

A compact version of the system was designed and built; a photograph is shown in Figure 5. The support manifold was machined out of a high-permeability material to shield the cell from external magnetic fields. A cell with an inside diameter of 4 mm and length 25 mm was used. The full device measured 6.6 cm × 1.6 cm × 1.3 cm, not including connectors. The DC power dissipation was < 30 mW, without thermal control.

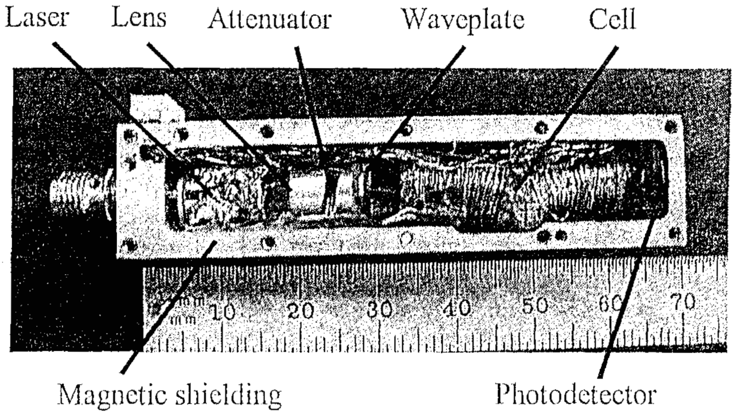


Figure 5. Compact CPT clock.

Because of the smaller cell size, the CPT resonance, shown in Figure 6, was wider than that of its table-top counterpart, and measured 620 Hz at the operating intensity. We believe that about one-half of this width results from the decay of the polarization diffusion mode due to the cell walls. The remainder is most likely pressure and power broadening. The Allan deviation measured with the system locked is shown in Figure 7. The somewhat larger short-term instability of $1.3\times10^{-10}/\sqrt{\tau/(s)}$ reflects the increased resonance width, while we believe the increased long-term instability is due to the lack of active temperature control of the cell.

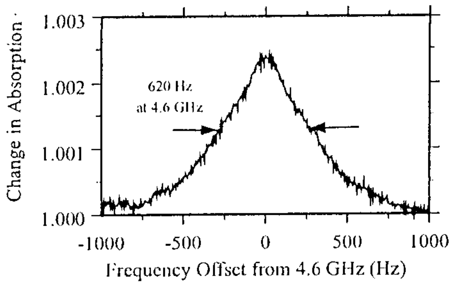


Figure 6. A CPT resonance in the compact system.

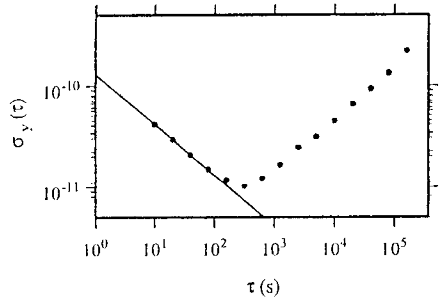


Figure 7. Allan deviation of compact system.

5 Further Miniaturization

A unique advantage of the CPT-resonance clock is the prospect for further miniaturization. In conventional double-resonance clocks, a microwave cavity is used to confine the microwaves in the vicinity of the atoms and to avoid Doppler shifts due to the motion of the atoms along the direction of the field propagation. The microwave cavity must be near the size of the microwave wavelength in order to be resonant, and miniaturization to much below 1 cm appears difficult. In the CPT design, no microwave cavity is required and the miniaturization is limited fundamentally by the wavelength of the optical radiation. This feature is critical for miniaturization to sub-millimeter dimensions.

The design of the cell containing the Cs atoms involves a trade-off between size and performance. For a given cell size, there is a specific buffer-gas pressure that optimizes the performance of the clock. At low pressures, collisions of the atoms with the cell walls reduce the atom Q-factor, while at high pressures, more frequent collisions with the buffer gas atoms do the same. As the cell gets smaller, therefore, the optimum buffer gas pressure increases and the optimized short-term stability of the clock is degraded correspondingly. The effectiveness of wall coatings, another technique commonly used to reduce the effect of wall collisions on the hyperfine decoherence, also depends on the

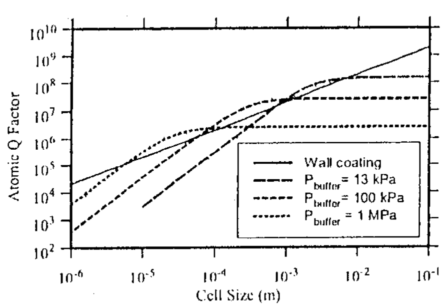


Figure 8. Atomic Q-factors for a wall-coated cell (1000 bounces), and a buffer-gas cell with several buffer gas pressures.

cell size. The calculated [12] optimum atomic Q-factors are proportional to the cell's characteristic dimension and are plotted in Figure 8. The smaller Q-factors at small dimensions result in increased instability of the frequency reference. The precise value of the Allan deviation depends ultimately on a number of additional factors such as optical power, cell temperature, signal height, and relevant noise sources.

6 Conclusion

A compact frequency reference physics package based on CPT-resonances in Cs vapor has been described. This device measures 6.6 cm × 1.6 cm × 1.3 cm, dissipates less than 30 mW not including temperature control and has a short-term fractional frequency instability of $1.3\times10^{-10}/\sqrt{\tau/(s)}$. Prospects for future miniaturization are excellent, in part because of recent advances in VCSEL technology and because no microwave cavity is required in the CPT design. The main limitation to performance under extreme miniaturization will be the effects of atoms colliding with the walls of a very small cell. However, we believe an instability of less than 10^{-9} at one second should be possible with a millimeter-scale cell. Such a device is likely to lead to a number of new applications.

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