

Miniature vapor-cell atomic-frequency references

J. Kitching,^{a)} S. Knappe, and L. Hollberg

Time and Frequency Division, The National Institute of Standards and Technology,
M.S. 847.10, 325 Broadway, Boulder, Colorado 80305-3328

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We propose a sub-millimeter-scale vapor-cell atomic-frequency reference based on a micromachined vapor cell, all-optical excitation, and advanced diode-laser technology. We analyze theoretically the performance of such a device as a function of cell size. Initial measurements on small-scale vapor cells support the theoretical treatment. © 2002 American Institute of Physics. [DOI: 10.1063/1.1494115]

Quantum-mechanical transitions in atoms have long been used as references for highly stable frequency standards. Compared to mechanical oscillators based on, for example, quartz crystals, atoms are less sensitive to external perturbations such as temperature changes, and also have much lower frequency drift rates. The use of atomic clocks in some applications requires reducing their size, power consumption, and cost. The smallest commercial atomic clocks built to date have physics packages with volumes near 1 cm^3 ,^{1,2} a total power dissipation near 1 W, and cost a few hundred dollars. Their long-term fractional frequency instability (over about one day) is near 10^{-11} , substantially lower than that of quartz crystal oscillators. Current applications for such devices include the synchronization of telecommunications networks³ and advanced global positioning system (GPS) receivers.⁴

Attempts to further miniaturize the frequency reference component of atomic clocks have encountered a number of difficulties. One is the construction of ultrasmall glass cells by use of conventional glass-blowing techniques. Another has to do with the microwave cavity required to excite the atoms by means of a conventional optical-microwave double-resonance technique. In order for typical microwave field modes to be resonant, the cavity dimension must be as long as the wavelength of the microwave radiation. This wavelength is roughly 1 cm and it is not clear how to reduce the size of a frequency-standard physics package significantly below this value by means of a conventional cavity design. We propose to solve these difficulties using a combination of micromachining technology and all-optical excitation.^{5,6} The design described below is a roadmap for the realization of an atomic-frequency-reference physics package with submillimeter dimensions, capable of a long-term frequency instability significantly lower than that achieved with state-of-the-art quartz crystal oscillators.

The basic frequency reference design, shown in Fig. 1(a), is based on our previous work.⁷ Alkali atoms such as Rb or Cs are confined as a vapor in a miniature cell that is designed to be transparent to radiation at the wavelength of a specific optical transition in the atom. The atomic hyperfine transition, on which the frequency reference is based, is

probed with light from a current-modulated diode laser. The current modulation creates a number of sidebands on the optical spectrum of the laser's output. When the modulation frequency is near the frequency of the ground-state hyperfine splitting, two frequency components of the optical spectrum can become simultaneously resonant with the two optical transitions from the hyperfine-split ground state to the excited state. This forms a Λ system, and a coherence between the ground states is excited through the phenomenon of coherent population trapping (CPT) (Ref. 8) [see Fig. 1(b)]. The detected signal is the change in absorption of the optical radiation as the laser modulation frequency is scanned near the frequency corresponding to the hyperfine splitting. Because of the exceedingly long radiative decay time of these ground states, the coherence can be very long lived, resulting in a narrow transition suitable for a microwave frequency

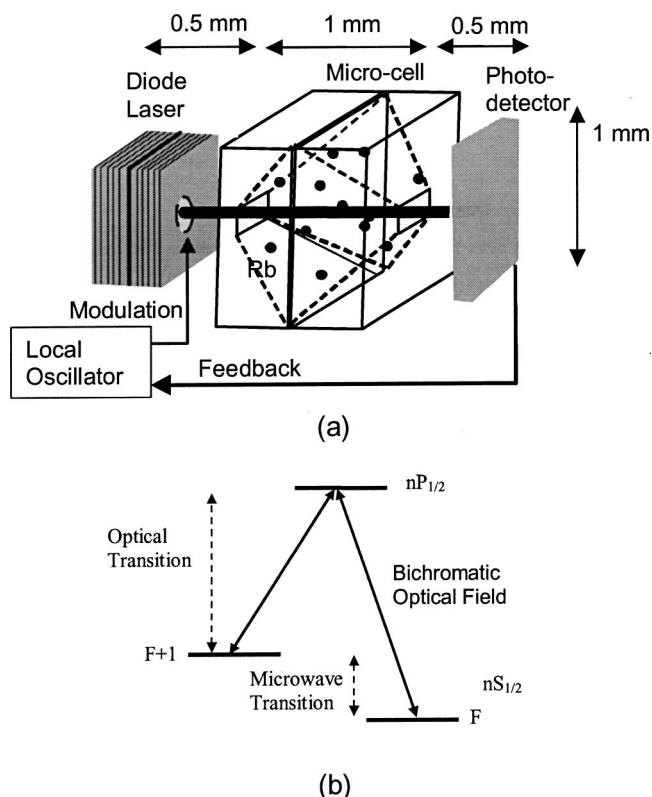


FIG. 1. (a) Basic design for a sub-millimeter-scale atomic clock and (b) the atomic level scheme and optical tunings for all-optical excitation.

^{a)}Also at: JILA, The University of Colorado, Boulder, CO 80309; electronic mail: kitching@boulder.nist.gov

reference. Broadening of the microwave transition due to transit-time effects, collisions of the atoms with the cell walls, and the Doppler effect can be reduced significantly with either a buffer gas or a wall coating.⁹

In contrast to frequency references based on conventional optical-microwave double resonance, this all-optical design does not require a microwave field to be directly applied to the alkali atoms. As a result, the cell size is no longer limited by the wavelength of the microwave radiation. There are associated benefits regarding power dissipation (for thermal control) and cost.

We propose the extension of this technique to subcentimeter size scales using micromachining technology. Processes for selective chemical etching of Si-based materials to form complex, sub-millimeter-scale structures are well known.¹⁰ Advantages of such machining techniques, in addition to the size reduction, include: the ability to simultaneously fabricate many units, a high degree of machining and materials uniformity leading to good frequency reproducibility, and low overall cost per unit. Packaging techniques also exist for sealing a controlled environment (vacuum or gas) inside a small enclosure for long periods of time.¹¹ It, therefore, appears possible to effectively seal a vapor of alkali atoms, along with a buffer gas if desired, in such a compact structure. Issues related to the reactivity of the atoms with the surface and the associated lifetime of the cell remain to be addressed. The combination of a small cell, a diode laser, and compact Si photodetector would allow the construction of a physics package such as that shown in Fig. 1.

We turn now to an estimation of the fundamental limits to the performance of compact frequency references as a function of size. We proceed by evaluating theoretically the frequency instability, as determined by the Allan deviation. The Allan deviation is given in terms of the atomic resonance Q factor and detection signal-to-noise ratio (S/N) as¹²

$$\sigma_y = \frac{\chi}{Q(S/N)\sqrt{\tau}}, \quad (1)$$

where τ is the integration time and χ is a parameter of order unity related to the method of interrogation of the resonance signal. The goal, then, is to determine the Q factor and signal-to-noise ratio for the frequency reference as a function of cell size, for transitions narrowed with either buffer gas or wall coating.

When a buffer gas is used, the frequency width of the atomic microwave resonance is determined by both collisions with the buffer-gas atoms and diffusion to the cell walls. If the cell's dimension is much larger than the mean-free path of alkali atoms in the buffer gas, the atomic Q factor is related to the lowest-order diffusion mode and is given by⁹

$$Q_{\text{bg}} = \frac{f_0}{\Delta f_{\text{bg}}} = \frac{\pi f_0}{\gamma_k + \frac{D\xi^2}{R^2}}, \quad (2)$$

where f_0 is the resonance frequency; Δf_{bg} is the full width at half maximum (FWHM) of the transition; γ_k is the coherence decay rate due to collisions with the buffer-gas atoms;

D is the diffusion constant of the alkali atoms in the buffer gas; R is the cell size; and ξ is a constant of order unity related to the geometry. For the relevant range of operating conditions, γ_k and D are, respectively, proportional and inversely proportional to the buffer-gas pressure. When a wall coating, rather than a buffer gas, is used to narrow the resonance width, the atomic Q factor becomes⁹

$$Q_{\text{wc}} = \frac{\pi f_0}{\zeta \alpha_k \bar{v}} R, \quad (3)$$

where ζ is another geometrical constant of order unity; \bar{v} is the mean atom velocity; and α_k is the probability of hyperfine decoherence for an atom upon collision with a cell wall; it has been assumed for simplicity that the entire cell is illuminated by the optical pumping light.

The intrinsic Q factors in Eqs. (2) and (3) are reduced by two additional effects: spin-exchange collisions between alkali atoms⁹ and power broadening by the optical field used to pump the atomic system.¹² These effects can be included as

$$\frac{1}{Q_{\text{tot}}} = \frac{1}{Q_{\text{intrinsic}}} + Bn_{\text{alkali}} + CI_{\text{opt}}, \quad (4)$$

where n_{alkali} is the number density of alkali atoms; I_{opt} is the incident optical intensity; and B and C are constants.

We next estimate the maximum detection signal-to-noise ratio, the detected signal is proportional to the absorbed optical intensity it can be written $S = \beta I_{\text{opt}} A (\alpha L)$, where β is the fractional change in atomic absorption when the microwave-modulated light is applied; A is the cross-sectional area of the light beam; α is the absorption coefficient of the atoms; and L is the length of the cell; it has been assumed that the cell is optically thin. Assuming shot-noise-limited detection, the noise is given by¹³ $N = \sqrt{2h\nu P_{\text{trans}}} = \sqrt{2h\nu I_{\text{opt}} A (1 - \alpha L)}$, where P_{trans} is the power transmitted through the cell and $h\nu$ is the energy of one optical photon.

The expressions for the signal and noise can then be combined with Eqs. (4) and (1) to obtain an expression for the Allan deviation that is a function of the two main configurational parameters, n_{alkali} and I_{opt} . For a given cell size, the Allan deviation can be optimized with respect to these two parameters. We take n_{alkali} to be such that the optical thickness of the atomic sample is a constant, w , independent of length, L : $n_{\text{alkali}} = w/(\sigma_{\text{abs}} L)$. Here, σ_{abs} is the cross section for absorption of light by the atoms. It is then straightforward to find an optimum value for I_{opt} . The final result for the optimized Allan deviation, as a function of cell size, is

$$\sigma_y^{\text{opt}} = \frac{2\sqrt{2}\chi}{\sqrt{\pi\beta w}\sqrt{\tau}} \sqrt{h\nu C} \frac{1}{R} \sqrt{\frac{1}{Q_{\text{intrinsic}}} + \frac{Bw}{\sigma_{\text{abs}} L}}. \quad (5)$$

With the use of the expressions for the intrinsic Q factors for transition widths narrowed by a buffer gas [Eq. (2)] and wall coating [Eq. (3)], the optimized Allan deviation is plotted as a function of cell size in Fig. 2. It can be seen that buffer-gas cells and wall-coated cells perform comparably over a wide range of cell sizes. The change in slope for the buffer-gas curve near $R = 2$ mm is related to the change in the dominant decoherence mechanism from collisions with cell walls (at small cell dimensions) to collisions with buffer-gas atoms (at

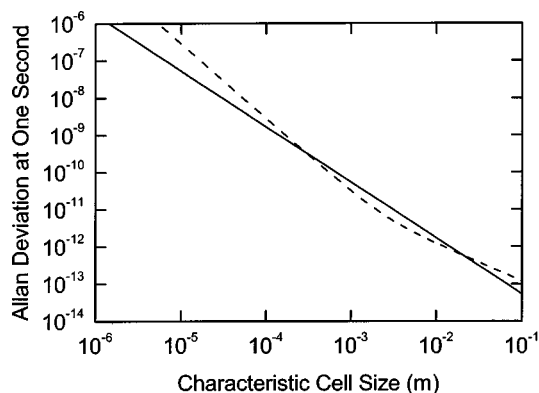


FIG. 2. Allan deviation as a function of characteristic cell size for a wall-coated cell with $\alpha_k=0.002$ (solid line) and a buffer-gas cell with $p_{\text{buffer}}=10$ kPa (dashed line). Parameters used are: $\beta=0.1$, $w=0.1$, $B=3.7 \times 10^{-20} \text{ cm}^3$, $C_{\text{wall coated}}=1.5 \times 10^{-7}/(\mu\text{W}/\text{cm}^2)$ and $C_{\text{buffer gas}}=7.3 \times 10^{-9}/(\mu\text{W}/\text{cm}^2)$.

large cell dimensions). For a constant buffer-gas pressure, frequency references based on buffer-gas cells have performance inferior to those based on wall-coated cells at very small length scales because of the increasing surface-to-volume ratio. In small cells, the hyperfine decoherence of atoms in a buffer-gas cell becomes dominated by interactions with the (uncoated) walls, which reduce the Q factor significantly more than in a wall-coated cell.

We conclude by reporting a preliminary experimental investigation of CPT resonances in cells of small dimension, based on the experiment in Ref. 7. The injection current of a diode laser was modulated at the first subharmonic of the Cs hyperfine splitting frequency, f_{Cs} ; the two first-order sidebands on the optical carrier were, therefore, separated by f_{Cs} . Light from the laser was circularly polarized with a waveplate and then passed through a glass cell with a vapor thickness ≈ 1 mm and diameter 19 mm and containing Cs and a N_2 buffer gas. The walls of the cell were uncoated and the cell temperature was stabilized near 60°C . The transmitted power was detected with a Si photodiode as the modulation frequency was scanned over the hyperfine resonance. Four cells were used, respectively, containing buffer-gas pressures of 2.6, 5.2, 10.4, and 21 kPa. For each cell, the FWHM of the resonance was measured as a function of optical intensity, and the zero-intensity intercept was found. The atomic Q factor calculated from that width is plotted against buffer-gas pressure in Fig. 3. The solid line is a fit to Eq. (2) with $\gamma_k=n_{\text{N}_2}\sigma_{\text{N}_2}\bar{v}_r$ and $D=D_0[(100 \text{ kPa})/p_{\text{N}_2}]$. Here, n_{N_2} and p_{N_2} are the buffer-gas number density and pressure, σ_{N_2} is the hyperfine decoherence cross section for collisions of the alkali atoms with the N_2 molecules, and \bar{v}_r is the mean relative velocity between alkali and buffer-gas atoms.¹² The fit yields values of $\sigma_{\text{N}_2}=3 \times 10^{-21} \text{ cm}^2$ and $D_0=0.12 \text{ cm}^2/\text{s}$, in rough agreement with those published previously.^{9,12} The main discrepancy between the theory and the experiment, the experimental point at 2.6 kPa, can be explained by the fact that the thickness of this particular cell was somewhat below 1 mm, resulting in a somewhat lower Q factor.

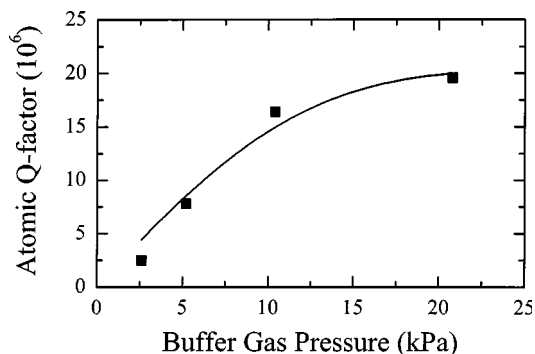


FIG. 3. Atomic Q factor, measured for cells of length ~ 1 mm, as a function of the buffer gas (N_2) pressure (squares). Also shown is a fit (solid line) to Eq. (2).

For a millimeter-scale frequency reference based on Cs in a N_2 buffer gas, the stability would be optimized for a buffer-gas pressure of 25 kPa, assuming that the resonance contrast is independent of buffer-gas pressure. The Q factor for this optimum pressure can then be used in Eq. (5) to determine the fundamental limit to the short-term stability of such a frequency reference if all other parameters were equal to those assumed in the theory. This limit would be roughly 3×10^{-11} at an integration time of 1 s. We note, however, that a variety of other factors including laser FM noise⁷ and broadening of the alkali optical transition due to the buffer gas could significantly degrade the stability predicted from these measurements.

We have analyzed the expected performance of miniature vapor-cell frequency references based on all-optical excitation and a micromachined vapor cell and provided a theoretical scaling relationship for the instability as a function of cell size. Experimental measurements of the Q factors of Cs atoms contained in a millimeter-scale cell with a buffer gas agree with the theoretical predictions.

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