NIST on a Chip: Realizing SI units with microfabricated alkali vapour cells

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Abstract. We describe several ways in which microfabricated alkali atom vapour cells might potentially be used to accurately realize a variety of International System (SI) units, including the second, the meter, the kelvin, the ampere, and the volt, in a compact, low-cost "chip-scale" package. Such instruments may allow inexpensive *in-situ* calibrations at the user's location or widespread integration of accurate references into instrumentation and systems.

1. Introduction

Precision metrology underlies a broad range of modern technology including communications, satellite-based navigation and positioning, manufacturing, and electrical instrumentation. Since the 1990s, there has been a rapid increase in the use of portable, battery-operated electronics and related technologies that include telecommunications (cellular telephones), computing (laptop computers), and even space (cubesats). Such systems require low-cost, low-power and highly miniaturized components that can be mass-produced and integrated easily into new instruments and devices. At NIST, we are currently exploring the possibilities for the development of low-cost, easily manufactured, low-power SI-traceable references suitable for deployment to users for a broad range of *in-situ* calibration purposes. The vision for such instruments is shown in figure 1, although it is unlikely that one chip will incorporate all references. A similar vision has been articulated at the National Physical Laboratory in the United Kingdom [1]. In particular, we are considering possibilities related to microfabricated alkali vapor cells, which were first demonstrated in our group in 2003 [2]. We propose that five SI units (four base units and one derived unit) could potentially be realized using such alkali vapor cells.

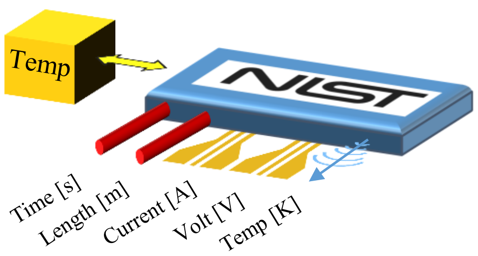


Figure 1. Concept of a possible chip-scale implementation of an SI-traceable set of references (Colour online).

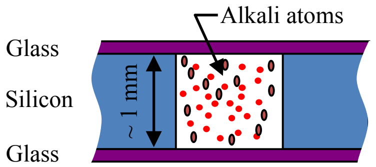
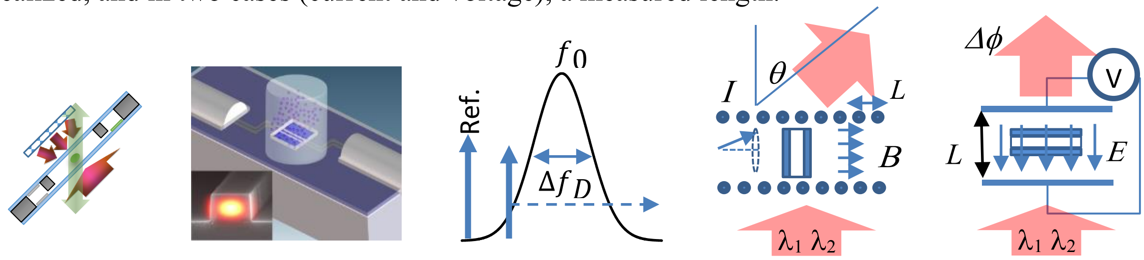


Figure 2 Microfabricated alkali vapour cell design (Colour online).

Microfabricated alkali vapour cells [2] have by now become a fairly well-developed technology, routinely used in commercial atomic clock products [3] and being developed for a number of other technologies such as magnetometry. The basic cell structure is shown in figure 2. A cavity is etched into a polished silicon wafer using standard micromachining processes and glass, bonded to the top and bottom surfaces, confines the alkali atoms to the interior of the cell.

2. Realization of Units

Figure 3 shows a number of ways in which atomic spectroscopy in microfabricated alkali vapour cells can be used to realize a variety of SI units. In all cases, the frequency of some atomic transition is measured in order to realize the unit. The relation between the measured frequency and the specific unit is mediated by a set of fundamental constants, presumed to be known more accurately than the unit will be realized, and in two cases (current and voltage), a measured length.



$$t = \frac{1}{f_{Cs}}$$ (a)

$$L = N\frac{c}{f_{opt}}$$ (b)

$$T = \frac{mc^2}{2k_B}\left(\frac{\Delta f_D}{f_0}\right)^2$$ (c)

$$I = \frac{2L}{\mu_0}\frac{\hbar}{g\mu} f_L$$ (d)

$$V = \sqrt{\frac{2hL^2}{\alpha_0}|f_s|}$$ (e)

Figure 3. Measurements of alkali atoms confined in vapour cells, which could lead to realizations of a number of base SI units. (a) A time and frequency standard based on the measurement of the hyperfine frequency of laser-cooled atoms similar to conventional fountain clocks; (b) a length standard based on a laser locked to an optical transition in atoms for which the frequency has been measured; (c) a temperature standard based on Doppler thermometry; (d) a current standard based on the measurement of Zeeman shifts and a diffraction-grating measurement of length; (e) a voltage standard based on DC Stark shifts and an interferometric measurement of length (Colour online).

2.1. Time

Chip-scale atomic clocks [4] have been extensively developed and are beginning to see broad utility in the real world. However, because of the buffer-gas pressure shifts, CSACs require calibration after being fabricated and assembled and the output frequency drifts at a rate of near 10^{-8}/yr [3]. As a result, the SI-traceable uncertainty in the frequency of an uncalibrated commercial CSAC is in the range of 10^{-7}.

We are therefore beginning work to develop a microfabricated platform, shown in figure 2(a) for the creation of laser-cooled atoms in order to realize interaction-free measurements of the Cs hyperfine transition. This platform is based on the standard microfabricated cell fabrication method described above, but with the absence of an intentionally introduced buffer gas and with non-evaporable (or evaporable) getter pumps to maintain the vacuum. A major challenge to such a device is maintaining a vacuum sufficiently low, typically below 10^{-7} Torr, to enable the production of large quantities of cold atoms. Getter pumps can support ultra-high vacuum [5] in combination with other pumps but generally do not pump either He or CH_4. As a result we plan to use aluminosilicate glass as the window material, which is known to have He permeation rates orders of magnitude below [6], for example, borosilicate glass, in order to reduce the He permeation into the cell. We expect lifetimes of months to years by use of glasses with the lowest He permeation rates. A similar proposal was presented in [7].

As with other types of laser-cooled atomic clocks, such an approach enables long interaction times while avoiding collisional broadening and shifts typical of buffer-gas confinement. We anticipate using pulsed coherent population trapping to interrogate the cold atoms [8] in order to avoid the use of a microwave cavity. This approach does introduce additional systematics associated with the first-order Doppler shift and an AC Stark shift, but recent experimental evidence [9, 10] suggests these shifts can be reduced to below 10^{-13} for a Ramsey time of 10 ms, consistent with atoms falling 0.5 mm in free-fall with appropriate design choices. Light needed for this device could be produced with a modulated vertical-cavity surface emitting laser with optical feedback from an external reflector, which both narrows the linewidth and enhances the modulation efficiency at certain modulation frequencies [11].

2.2. Length

It is well-established that because the speed of light is defined as a fixed constant, lasers stabilized to atomic transitions with known optical frequencies become SI-traceable standards of length via interferometry and the relation

$$L = N\frac{c}{f_{\rm opt}}, \tag{1}$$

where N is the number of fringes counted as the interferometer mirror separation moves a distance L, $f_{\rm opt}$ is the optical frequency of the interferometer laser (measured with respect to the SI second) and c is the speed of light. Previous work has established a number of suitable references [12], both in the visible and near-infrared and a telecommunications wavelengths [13]. The integration of appropriate atoms with chip-based single-mode photonics may ultimately allow highly miniaturized wavelength references compatible with complementary metal-oxide-semiconductor (CMOS) electronic and photonic fabrication methods.

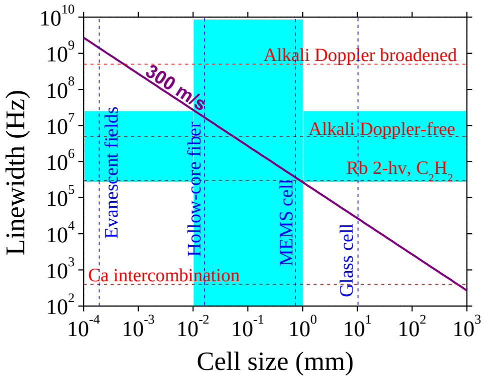


Figure 4. Transit time broadening in a room-temperature thermal vapour of atoms (Colour online).

Transit-time broadening imposes an important limitation on the wavelength reference performance: figure 4 shows this broadening for atoms moving at a typical thermal velocity of 300 m/s as a function of the size of the interaction region. Also drawn in the figure are a number of confinement/interaction platforms that have been used to allow the interaction of the light with atoms (glass cells, microfabricated (MEMS) cells, hollow-core fibers and evanescent fields) as well as a number of atomic transitions suitable as wavelength references. We target the size range between 10 µm and 1 mm, which is compatible with current methods of fabricating silicon-glass alkali vapor cells; the corresponding transit time broadening is 100 kHz to 10 MHz suggesting the use of optical references based on rotational-vibrational transitions in molecular gases, and multi-photon and Doppler-free transitions in alkali atoms.

There appear to be two clear alternatives for integrated atom-photonic systems. The first is to use silicon photonics with light at a wavelength (usually 1.3 µm – 1.5 µm) below the silicon bandgap, combined with molecular transitions in this wavelength range. Both C_2H_2 and HCN have both been investigated [14, 15] as wavelength standards for the telecom band. The strengths of this approach are: a well-developed manufacturing platform for Si photonics and a large number of integrated photonics components already demonstrated [16]; compatibility with the standard CMOS fabrication process; compatibility with optical fiber communications; narrow atomic lines; and many useful transitions. The main disadvantage is that the molecular absorption cross-sections at this wavelength range are quite weak, which results in small signals. An additional difficulty related specifically to miniaturization is transit-time broadening, which reaches the natural linewidth characteristic of molecular transitions of about 300 kHz at a cell length scale of 1 mm; cell sizes smaller than this will not be able to fully realize the advantages of the narrow transition. In addition, the two-photon non-linear absorption in silicon at this wavelength range results in lower Q-factors for optically resonant structures, resulting in difficulty generating frequency combs and limitations on non-linear optical interactions within the material.

The second alternative is to use silicon-nitride photonics [17], transparent at wavelengths down to 300 nm, with alkali vapor cells. There are a number of strengths of this approach including high optical cross-sections for alkali atoms; well-developed microfabricated cell fabrication; CMOS process compatibility; potential for integration with microfabricated frequency combs [18]; and the possibility of optically pumping the atoms. The main weaknesses are broader lines, the lack of free carriers in SiN that enable fast switching, and difficulties incorporating electrostatic actuation for moving components.

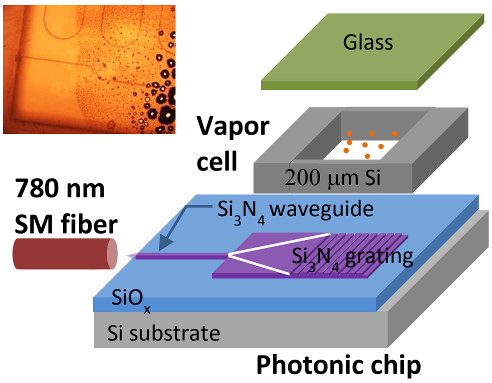


Figure 5. Design for photonically coupled alkali vapor cell. Inset: first such vapor cell fabricated at NIST showing SiN waveguides and alkali atom droplets condensed on the inside wall of the cell (Colour online).

Optical frequency references based on saturated absorption spectroscopy in alkali atoms currently achieve stabilities well below 10^{-12} at one second [19] and near 10^{-12} at one day [20]. Accuracies of this type of reference have been established to about 10^{-10} [21], limited largely by uncontrolled Zeeman shifts. Saturated absorption resonances have also been observed in on-chip hollow waveguides [22] and hollow-core optical fibers [23] and similar Doppler-free resonances are observed in thin glass cells [24]. Saturated absorption spectra have also been observed in microfabricated alkali vapor cells [25, 26]. A final interesting case is the possibility of using SiN photonics to interrogate the Rb two-photon transition at 778 nm for which accuracies 5×10^{-12} [27] have been observed.

In figure 5, we show one possible design, in which light confined in a SiN waveguide is expanded via diffraction in the slab before being coupled into the cell with a diffractive grating output coupler. The conversion from a small optical mode to a larger one allows for the measurement of narrower transition linewidths. The inset in figure 5 shows the first such cell fabricated at NIST. Narrow-linewidth light sources for such a wavelength reference could be a ring-cavity semiconductor laser, microresonator-based Brillouin laser [28], a linewidth-narrowed vertical-cavity surface emitting laser [11] or a vertical-cavity extended cavity laser with macroscopic cavity length.

2.3. Temperature

It is anticipated that in the near future, the Kelvin will be redefined by setting Boltzmann's constant to a fixed value and associating the energy $k_B T$ with, for example, the motional energy of atoms in a gas. The measurement of Doppler widths, Δf_D, in molecular and atomic gases can thus be used as an accurate measurement of temperature via the relation [29]

$$T = \frac{mc^2}{2k_B}\left(\frac{\Delta f_D}{f_0}\right)^2, \quad (2)$$

where mc^2 is the rest energy and f_0 the transition frequency of the atom or molecule being measured. Over the last decade, a number of groups have carried out Doppler thermometry experiments in molecules in order to measure Boltzmann's constant. Uncertainties in k_B of 4×10^{-5} have been achieved [30], with projections of ultimate uncertainties in the 10^{-6} range.

As discussed above, the measurement of molecular transitions in compact vapor cells is challenging because of the small absorption cross-sections of the molecules in the near-infrared wavelength range. We therefore propose to realize an accurate thermometer using electronic transitions in alkali atoms [31]. This approach has the advantages of higher absorption cross-sections and reduced collisional effects but suffers from different systematics including optical pumping, unresolved hyperfine structure and a more limited temperature range of utility due to the change in vapor pressure with temperature.

2.4. Current and Voltage

Atomic vapors can also be used to realize the ampere and the volt via Larmor and DC Stark frequency shifts. Atomic g-factors relate the Larmor precession frequency f_{L} to the strength of the magnetic field, B, by $f_L = (g\mu/\hbar)B$ where μ is the nuclear or Bohr magneton as appropriate. Many nuclear and atomic electronic g-factors are known, traceable to the SI [32] to about 10^{-7} and hence atomic vapor cells can be used to define accurately a magnetic field. From elementary electrostatics, it is known that an infinite current sheet with a current density per unit length of i creates a magnetic field that is independent of distance from the sheet given by $B = (\mu_0/2)i$. If this current sheet is implemented using lithographically-defined metallic traces spaced by a distance L and a vapor cell is placed near this planar surface (see figure 2(d)), the current I can be determined in terms of the measured Larmor precession frequency by the relation

$$I = \frac{2L}{\mu_0}\frac{\hbar}{g\mu}\, f_{\mathrm{L}}. \tag{3}$$

The wire spacing, L, which can be on the order of micrometers, can be measured accurately using techniques of grating spectrometry. The major technical challenge appears to be dealing with fringing fields and magnetic shielding. For the latter, AC current measurements may alleviate some of the difficulty.

Finally, in a manner similar to current, measurements of the DC Stark shift in Rydberg or Rydberg-like atoms provides a route to realizing the volt. The DC Stark shift is given as $f_{\mathrm{S}} = -(\alpha_0/2h)E^2$ and the DC polarizabilities, α_0, of some atoms have been measured accurately; the polarizability of the neutral Yb atom, for example, has been measured to near 10^{-5} in optical clock experiments [33] and similar techniques should enable improvements on the 0.1 % uncertainties for shorter-wavelength two-photon transitions in alkali atoms [34]. For an atomic vapor cell placed between two parallel plates separated by a distance L (see figure 2(e)), the voltage on the plates can therefore be determined with respect to the measured Stark shift from

$$V = \sqrt{\frac{2hL^2}{\alpha_0}|f_{\mathrm{S}}|}\,. \tag{4}$$

In this case, the plate separation can be determined (again using a chip-scale wavelength reference) via interferometry. The shift itself is measured using optical spectroscopy of two-photon transitions and a reference cell (with no applied fields) to stabilize the optical frequency. Major technical challenges here are fringing fields and charge build-up on surfaces, similar to those mentioned above for the realization of the ampere. In addition, however, the two-photon transitions often occur at wavelengths for which there are no convenient diode lasers and hence some laser development may be required to ultimately realize a compact, low-power voltage reference in this manner. Similar ideas are being developed for RF electric field measurements [35].

3. Conclusion

We have described a number of ways in which microfabricated alkali vapor cells might be used to realize compact, potentially easily manufactured, SI-traceable references of frequency, wavelength, temperature, current and voltage. All units are realized by some type of frequency-based measurement (RF, optical or microwave) of atomic energy levels. If additional challenges (light sources, packaging, thermal control, wafer-level fabrication, etc.) can be addressed, such references could be used to provide embedded calibration capability across a broad range of instruments and systems.

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