Ultra-Small Atomic Clocks based on Coherent Population Trapping and Micromachined Vapor Cells*

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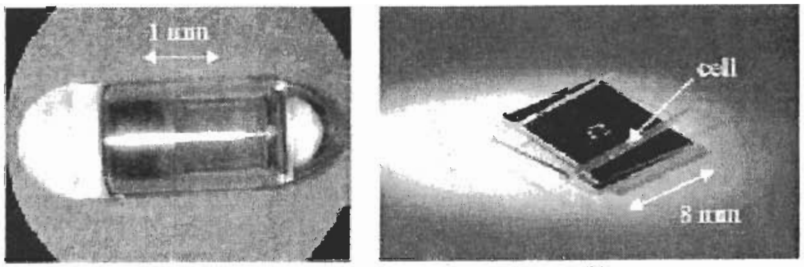
A new generation of highly miniaturized vapor-cell atomic frequency references is being developed based on micromachined silicon and glass structures. The physics packages of these frequency references are anticipated to be a few cubic millimeters in size and to dissipate less than 10 mW of electrical power, while retaining the long-term stability and insensitivity to environmental perturbations characteristic of atomic standards. The frequency references are based on coherent population trapping[1] (CPT) resonances in atomic vapors, which are excited by use of a modulated diode laser. The CPT design allows the physics packages to be small and simply aligned while providing short-term frequency stability comparable to those seen for conventional microwave excitation. However, the technology of making highly miniaturized vapor cells is also a significant challenge. We discuss recent results on the fabrication of ultrasmall atomic vapor cells and present designs of miniature physics packages based on such cells.

Atomic vapor cells with interior volumes less than about 1 mm^3 were fabricated using two main methods. The first involved hollow-core Pyrex[2] optical fibers sealed with light from a 10 W CO_2 laser[3]. These fibers had an exterior diameter of 1.6 mm and a wall thickness of ~200 μm. The CO_2 laser light was focused onto the end of the glass fiber, melting the glass, which was drawn toward the fiber axis by surface tension, thereby sealing the fiber with a glass bead which can serve as a lens to couple light into the cell. Alkali atoms along with a buffer gas were then introduced into the fiber from the open end, which was then sealed in the same manner as the first. The resulting vapor cells were about 4 mm long and 1.6 mm in diameter, with an interior volume of about 2 mm^3. A photograph of one such cell is shown in Fig. 1a.

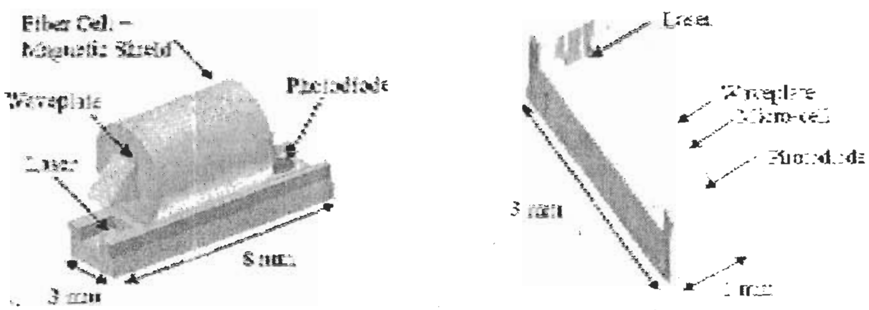
A second method of fabricating cells was developed based on anodic bonding[4] of Pyrex glass and silicon wafers. In this procedure, square holes ~ 1 mm in size were first etched in a silicon wafer, 350 μm thick. This wafer was then anodically bonded to a Pyrex wafer using a combination of elevated temperature and applied high voltage. The resulting preform was then placed inside a vacuum system, and alkali atoms and a buffer gas were introduced through the chemical reaction $BaN_6 + 2CsCl \rightarrow BaCl_2 + 3N_2 + 2Cs$. A second Pyrex wafer was then bonded onto the top of the preform to seal the Cs and buffer gas inside the cell. The resulting cell had an interior diameter of 1.5 mm and a length of 350 μm but scaling to smaller sizes is straightforward. A photograph of such a cell is shown in Fig. 1b. The presence of Cs and a buffer gas appropriate for narrowing the atomic transition linewidth was verified in both cells by use of optical absorption and narrow CPT resonances have also been observed.



(a) (b)

Fig. 1. (a) A Cs vapor cell based on CO_2 laser fusion of hollow-core Pyrex fiber. (b) A Cs vapor cell fabricated by anodic bonding of glass and silicon.

These cells could be used in highly miniaturized physics packages, designs for two of which are shown in Fig. 2. These designs have volumes near a few cubic millimeters. The physics package design shown in Fig. 2b could be assembled at the wafer level and then diced into individual physics packages, permitting a large reduction in cost and assembly time.



(a) (b)

Fig. 2. Designs for miniature atomic clock physics packages based on ultra-small atomic vapor cells.

References

1. See, for example E. Arimondo, in Progress in Optics XXXV, E. Wolf (1996), ed. Elsevier: Amsterdam, p. 257.
2. Specific product is named only for technical clarity and does not constitute or imply endorsement by NIST. Other products may be found suited just as well to this application.
3. S. Knappe, V. Velichansky, H. G. Robinson, J. Kitching and L. Hollberg, Rev. Sci. Instrum., **74**, 2003.
4. G. Wallis and D. Pomeranz, J. Applied Phys., **40**, 3946, 1969.