Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

ATOMIC VAPOR CELLS FOR MINIATURE FREQUENCY REFERENCES

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Abstract – **We report on the fabrication of millimeter-sized vapor cells and their performance in atomic clocks based on coherent population trapping (CPT). We discuss two fabrication techniques. The first one is based on hollow-core pyrex fibers, fused with a CO_2 laser or micro-torch, and the second one involves anodic bonding of micro-machined silicon wafers to pyrex. Key aspects of the discussion are the performance of the cell in frequency references, the potential for further miniaturization of the cells and the ability to manufacture them on a large scale with reproducible performance.**
Keywords – Frequency reference, atomic vapor cell, miniaturization

We discuss progress towards developing chip-scale atomic frequency references for portable, low power applications such as global positioning system (GPS) receivers and wireless communications systems. As a passive reference, the atomic resonance is used to steer and provide long-term stability to the local micrwave oscillator. Frequency stabilities below 10^{-11} at one day are desired. It has been estimated that this can be achieved in cells with dimensions of a millimeter [1]. The whole frequency reference should have a volume of less than 1 cm^3, with a physics package of approximately 3 mm^3. To reach the best frequency stability, the interior volume of the cell should occupy the largest possible fraction of the physics package.

Most of the approaches for developing these miniature references use coherent population trapping (CPT)[2]. The physics package of a CPT cesium clock is shown in Fig. 1. A vertical-cavity surface-emitting laser (VCSEL) is current-modulated at half the ground state splitting of the cesium atoms. The light is circularly polarized, and sent through a vapor cell, and the transmitted power is detected on a photodiode. When the modulation frequency is chosen such that the two first order modulation sidebands are exactly resonant with the atomic transitions from the two ground state components to the excited state, the atoms will be pumped into a so-called coherent dark state. This gives rise to a reduced absorption. The signal can then be fed back to the local oscillator to lock it to this resonance. CPT spectroscopy makes it straightforward to scale the frequency reference to smaller length scales using a simple optical setup. However this may be challenging with the conventional approach based on optical pumping, where the design of a microwave cavity or antenna of sub-millimeter size at several gigahertz is complicated.

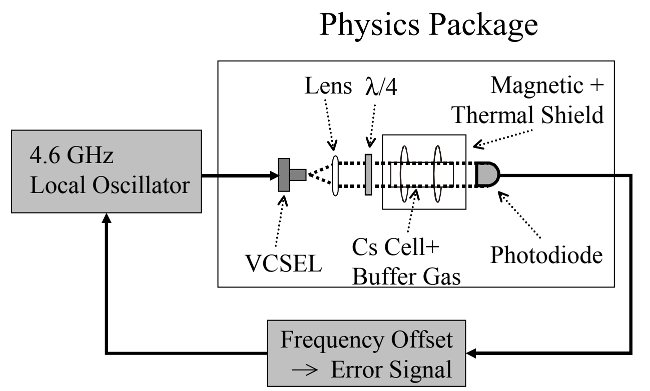

Fig. 1: Experimental setup of the CPT clock.

The vapor cell is perhaps the most challenging part in the development of a physics package of only a few cubic millimeters in size. Besides being small, the cell must be filled with an alkali metal and a buffer gas, and hermetically sealed. The buffer gas is used to prevent the cesium atoms from colliding with the cell walls too frequently, because collisions broaden the resonance line and reduce the line Q. In addition, the cell material should be transparent to the laser light that is resonant with an optical transition in the atoms. In order to obtain sufficiently high densities of the vapor, the cell must withstand temperatures up to 130°C in chemically aggressive alkali vapor.

We are investigating various means of fabricating small cells, including a novel way of fusing hollow-core glass fibers with CO_2 laser light[3]. Fig. 2 shows a vapor cell fabricated from a hollow-core glass fiber using a CO_2 laser. It has an interior volume of approximately 5 mm^3 and an exterior volume of approximately 15 mm^3. The cell is made by focussing a laser beam onto the end of a hollow-core glass fiber. Light from the CO_2 laser (of wavelength 10 μm) is strongly absorbed by the glass, leading to highly localized heating, which melts the fiber. With this method it is possible to form lenses on both ends, allowing a laser beam

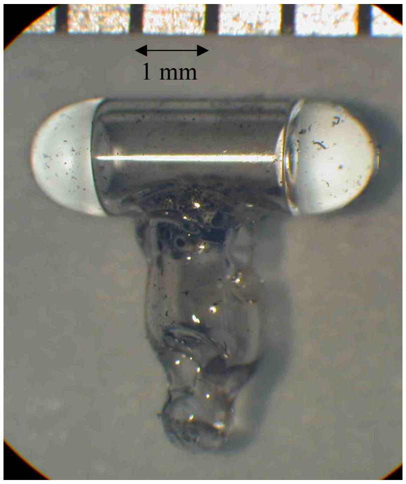

Fig. 2: Cesium cell made from a hollow-core pyrex fiber with a CO_2 laser.

to be collimated inside the cell without additional optics. A filling tube is attached to the cell preform by means of the same CO_2 laser, and used to fill the cell with cesium and a buffer gas before being sealed. We implemented some cells into the physics package of a microwave frequency reference based on CPT spectroscopy. We measured Q-factors above 10^7 and an unoptimized reference gave a frequency instability of $5.3 \times 10^{-10}/\tau^{1/2}$.

In order to dispose of the filling tube, which occupies half the total cell volume, the procedure above is modified slightly. The fiber is filled with a buffer gas with a pressure of a few tens of kPa; the smaller difference between the pressure inside the fiber and that outside allows the formation of a useful lens as the glass melts. Such a fiber cell without filling tube is shown in Fig. 3. First, the nice lens on the right hand side is made in air. The lens on the left hand side is formed after the cell is filled with cesium and 20 kPa of neon. It is good enough to couple 40% of the laser light through the cell.

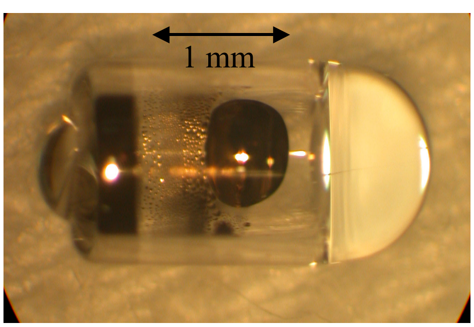

Fig. 3: Cesium cell without filling tube made with a CO_2 laser.

Another approach to the small vapor cell design is based on micro-machined silicon wafers. This approach has the potential of batch fabrication at the wafer level, which makes production easy and inexpensive. It should be possible to scale the cells down to sub-millimeter size (Fig. 4).

This cell was made by drilling a hole through a silicon wafer of 375 µm thickness. Then, a piece of pyrex wafer is anodically bonded on top at 300°C and 1000 V [4] . To fill the cell with cesium, a mixture of BaN_6 and CsCl is inserted into the silicon hole. Inside a vacuum system, a second pyrex wafer is placed over the hole. The cell is then heated to 120 °C to perform the reaction and produce cesium metal. The cell is heated further and is then bonded shut under nitrogen atmosphere by anodic bonding at 500 to 1000 V. The interior of the cell in Fig. 4 has a radius of 750 µm and a length of 375 µm. The CPT resonances measured in these cells with widths of a few kilohertz.

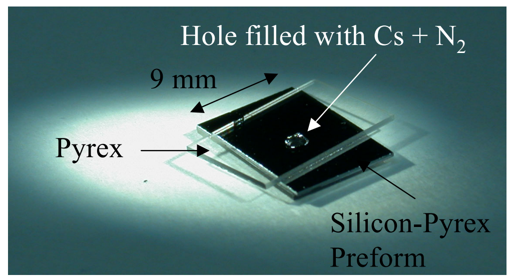

Fig. 4: Cesium cell produced by micro-machining of silicon wafers and anodic bonding. It has an inner radius of 750 µm and a length of 375 µm.

We are currently developing miniature physics packages to incorporate these cells. One goal for the reference containing the micro-machined cells is to design it so that all components can be manufactured and assembled at the wafer level. Volumes of a few cubic millimeters seem feasible with current techniques.

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