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Production of miniature glass cells with rubidium for chip scale atomic clock

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Abstract

The main advantage of chip scale atomic clock (e.g., Knappe (2008)) (CSAC) over quartz-oscillators is the higher long-term stability. It is provided by non-aging resonance of unperturbed atoms. However it is not a simple task to suppress all possible perturbations. Hence, metrological properties of resonance depend on the way in which ensemble of atoms is localized in space and protected. The paper describes a technology of small all-glass Rb cells production. The sealing of cells is made with radiation of a CO_2 lasers. The cells will be utilized in Rb CSAC based on the phenomenon of coherent population trapping (CPT). (Pat. No RU 2014101361)

*Keywords:*rubidium vapor cell, laser welding, coherent population trapping

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1. Introduction

Many civil and military applications rely on compact and stable frequency reference. Chip scale atomic clock based on CPT (Vanier (2005)) have small volume and stability of the order 10^{-11}… 10^{-12} per hour and fit well the requirements. The CSAC do not incorporate cumbersome microwave cavity or a resonance lamp with large energy consumption. Thus, they compete successively with traditional Rb clocks in fields where weight, mass and consumption are critical.

One of the main units of CSAC is a physical package that contains small cell with atoms of alkali and buffer gases. The paper describes a new technology of small all-glass cells fabrication with ^{87}Rb atoms and buffer gases.

2. Main approaches in fabrication of alkali vapor cells

2.1. Glass blowing technique

It is difficult to produce small-size cells with a characteristic dimension of less than 5 mm and reasonable optical quality of windows by glass-blowing technique (Knappe, Velichansky et al. (2003)). Typically the dimensions of such cells are additionally increased by piece of tube that remains after off-sealing a sell.

2.2. Silicon-Pyrex technologies

Here cells are produced by anodic bonding of silicon body with pyrex windows (Petremand et al. (2012)). The internal volume of such cells can be as small as 1 mm3. The windows preserve optical quality in the sealing. However, combination of different materials in the cell restricts some of possible applications. The direct detection of fluorescence that gives additional degree of freedom in controlling the operation of a cell (Hasegawa et al. (2011)) is hindered as silicon walls of a cell are opaque for resonance radiation. Other drawbacks of a hybrid cell are the following: 1. The windows of a cell should be heated with a thin layer of metal deposited on the glass. Otherwise metal inside a cell will condensate on the window since thermal conductivity of pyrex is lower than that of silicon. Inhomogeneous magnetic field of the current that flows through such a heater increases width of the CPT resonance and is particularly detrimental in magnetic field sensors. Applying a grid of thin bifilar conductors decreases the cross-section area of the laser beam. 2. Some laser-pumped nuclear-magnetic resonance gyroscopes involve atoms with non-zero quadropole moment of the nucleus. High symmetry of a cell is needed in this case so as to prevent strong interaction of nuclei with electrical field near the walls of a cell. 3. The extended time of anodic bonding (several hours at ~ 300˚C) inevitably results in filling of a cell with additional gas evolving from the surface during the process.

3. Vapor cell fabrication process

We propose a technique of all-glass cell production which does not involve expensive manual labor of glassblower. Fabrication of glass with CO_2 radiation has been proposed by L. Hollberg and was first described in Knappe et al. (2003). The cell was formed from a single piece of a tube by fusion of the ends of tubes with CO_2 laser radiation. The external surface of the window had spherical shape of high quality; however the internal surface could not be properly controlled. As a result further development of this technique has been given up.

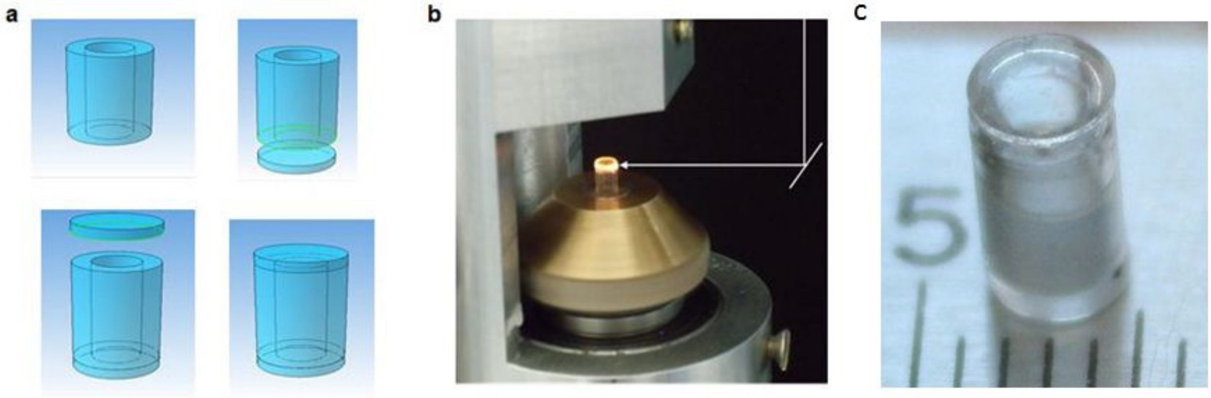

Fig. 1. (a) Main steps of cell fabrication; (b) Production of the preform; (c) Sealed miniature glass cell with Rb and buffer gases (Dimensions in SI).

Our technique relies on welding of separately made cylindrical glass body of a cell and caps which serve as windows. The length and diameter of tube are 5 and 3.4 mm, respectively, while thickness of the wall is 0.7 mm. The windows have the same diameter and thickness of 0.5 mm (Fig. 1a). The first window is welded to the body in the open atmosphere producing a cartridge-shaped preform. Radiation of CO_2 laser is focused on the junction of the cap and the body (Fig. 1b). The diameter of the hot spot is in the range of 0.5 − 0.7 mm. The cylinder and the window rotate around the axis with angular velocity of two turns per second. The process of welding has three stages: preheating, intense heating lasting for 15 seconds, and annealing. The total time takes less than 1 minute. The produced preforms after leak-testing and cleaning are put into seats of circular table inside a vacuum chamber shown on Fig. 2. Second windows are placed close to each preform, the chamber is closed and the air is pumped off.

The degassing of preforms and windows starts at pressure of 10^{-6} Torr and proceeds for 6 hours at 150 ˚C. A stream of cold N2 vapor that passes through hermetic tubing under circular table is used to cool down the preforms. At the same time we start heating a dispenser which consists of a glass tube containing Rb metal and a capillary pipe with a deep scratch made on it. We start to move the dispenser when its temperature attains 200 ˚C. The capillary comes to abut and breaks at the scratch. After that the dispenser is positioned just about the preform and covers its internal walls with a thin layer of Rb. Rotation of the table allows filling of all preforms in the chamber. It is followed by filling the chamber and preforms through the leaks with Ar and Ne buffer gases. A special facility moves the second window on top of the filled preforms. The place in the chamber where welding of the second window occurs provides rotation of the preform about its axes. The CO_2 laser radiation is sent to the junction of the second cup and the preform through the ZnSe window of the vacuum chamber. All rotations and translations in the vacuum chamber are made outside with commercial leak-proof facilities.

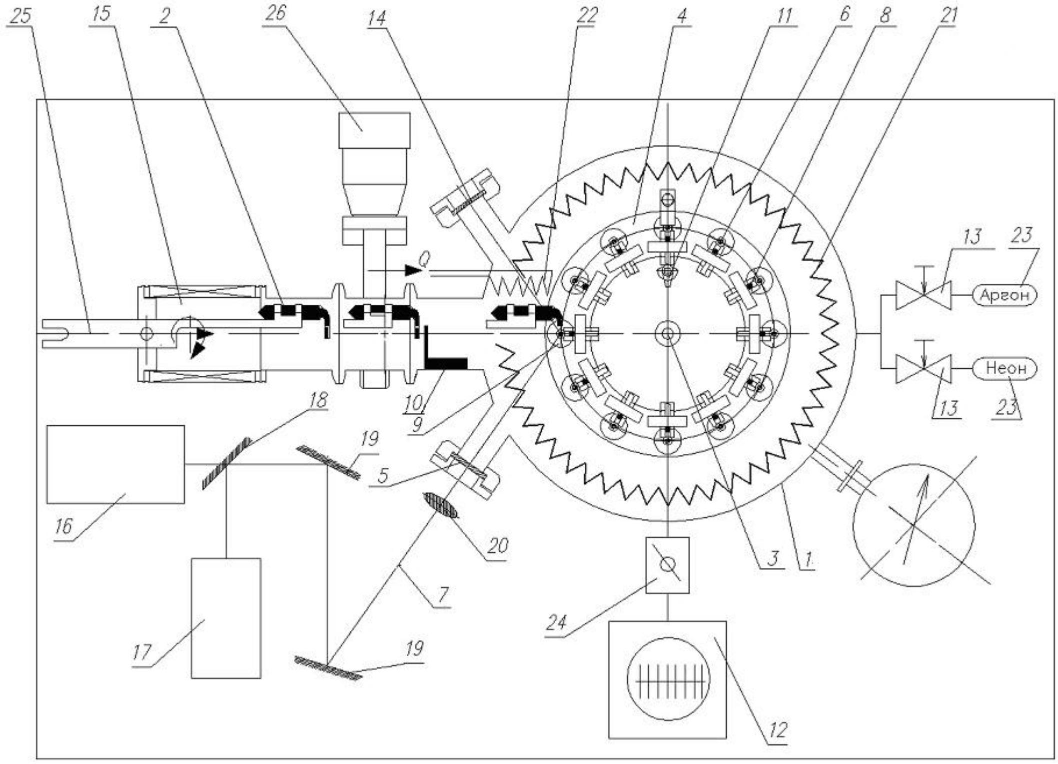

Fig. 2. The facility for filling and sealing of miniature all-glass cells. Conventions: 1 – vacuum chamber, 2- dispenser of an alkali metal , 3 – gadget rotating the circular table, 4 – circular table, 5 – ZnSe window, 6 – preform, 7 – path of a CO_2 laser beam, 8 – cap for preform, 9 – gadget rotating the cell, 10 – wall for breaking a capillary pipe of a dispenser, 11 – facility covering the preform with a cap, 12 – vacuum pump, 13 – precision valve, 14 – viewing window, 15 – hermetic chamber for a dispenser, 16 – CO_2 laser head, 17 – visible guide-laser head , 18 – translucent plate, 19 – mirror, 20 – focusing lens, 21 – heater for the degassing of preforms, 22 – heater of a dispenser, 23 – reservoir with inert gas , 24 – gate valve, 25 – manipulator of a dispenser, 26 – gate valve.

The laser welding of glass parts takes much shorter time than anodic bonding of pyrex and silicon, however it is performed at higher temperature needed to melt the glass. The question which of these techniques results in smaller contamination of the gases in cells needs long-term studies. A problem that is encountered in the welding at the reduced pressure of buffer gases (< 300 Torr) is the formation of bubbles in the melted glass. The welding regime has to be delicately adjusted so as to provide leak-proof sealing without overheating of the glass. Since the gas inside the cell is also heated during welding, part of it goes out and real pressure in the finished cell is smaller than pressure in the chamber. The difference was estimated by the pressure shift of the CPT resonance. For that purpose the cells were filled with pure Ne or Ar gases. The ratio of the pressure in the chamber to that in the cell was found to be 1.3 and 1.6 for Ar and Ne respectively. The ready cells (Fig.1c) after visual inspection and testing by Rb absorption signal were annealed for 30 hours at 100 ˚C. The annealing accelerates saturation of the walls with rubidium and neutralization of water and hydrogen since alkalis are excellent getters.

4. Fabrication results and conclusions

A cell fabricated according to the described process is shown in figure 1c. We found that there is no significant change in polarization of the transmitted beam in our cells. We have decreased temperature coefficient of resonance frequency of the CPT resonance to the value smaller than 0.3 Hz per ˚C by optimizing the ratio of partial pressures of the two buffer gases. Allan deviation of the clock signal obtained with one of our cells is shown on figure 3. One can see that for the measurement times between 100 seconds and 20 000 seconds Allan deviation does not exceed 10^{-11}. Standard electronic devices were used in this measurement. The cell was placed into specially designed physical package of 20 mm in diameter and 20 mm of height. The package provided temperature stabilization and the proper magnetic field inside the shield. The CPT resonance used for stabilization was displayed with bichromatic radiation of a VCSEL laser located in the same package. We conclude that the developed technology can provide high-quality cells for CSACs.

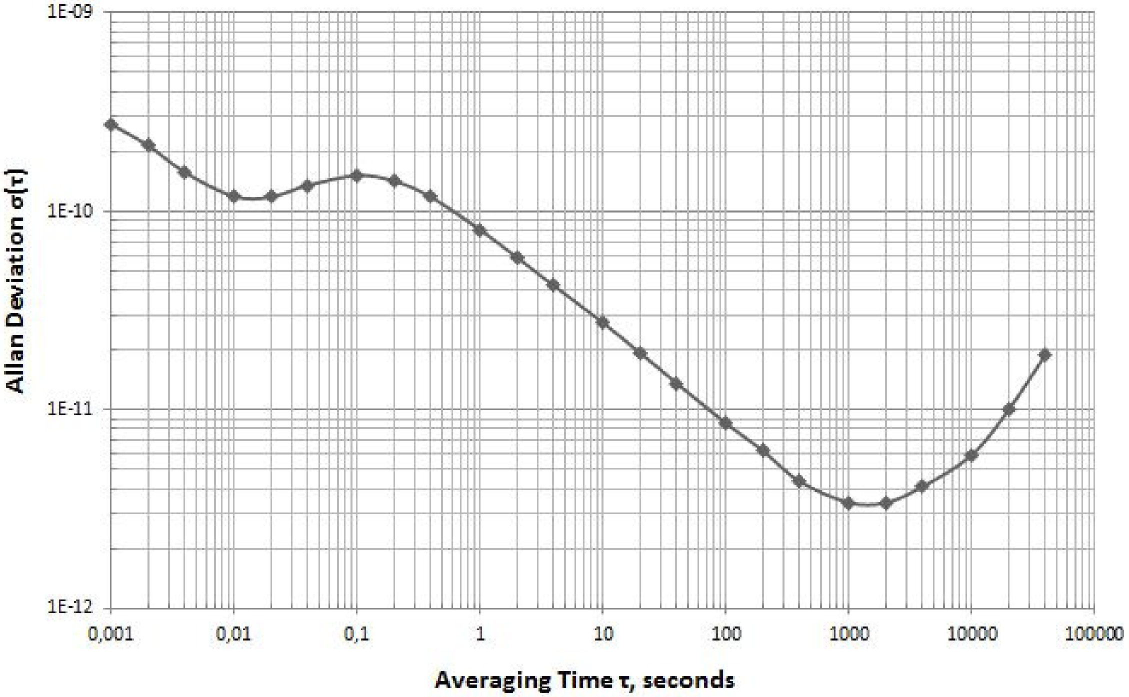

Fig. 3. Allan Deviation plot captured by Symmetricom's Allan Deviation and Phase Nose Test 5120 with Hydrogen Maser as a reference.

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