Quartz optical cells with alkali-metal vapour for aerospace

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Abstract. This work for the first time analyses the impact of cosmic radiation on quartz cells with rubidium vapour and buffer gas, as well as the ensuing change in stability of atomic frequency standards (AFS) relying on such cells. It is demonstrated that the main effect consists in variation of partial pressure of nitrogen, which is a part of the buffer gas mix. This leads to degraded AFS stability. It was established by modelling that this effect is not significant because material degradation of the AFS stability is only likely to happen over a long period of time, as long as several decades. It can be concluded on the basis of the proposed analysis that a gas cell with rubidium vapour and buffer gas is the most reliable element of a satellite-borne AFS and that it is less affected by exposure to ionising radiation than electronic components of AFS.

1. Introduction

Atomic frequency standards (AFS) using narrow spectroscopic resonances as a reference are often installed in space-based equipment [1, 2]. Their application domains are multifarious: from high-speed laser communications [3, 4] and global satellite navigation systems (GLONASS, GPS, Galileo) [5, 6] to deep space studies [7]. The core of an AFS is an optical cell containing an alkali metal. When the cell is heated up to its working temperature (~60 °C) the alkali metal vapour interacts with optical radiation passing through the cell and create a reference spectroscopic resonance. Operation of optical cells in space-borne AFS poses extra stringent requirements related to specific environmental factors in space. First of all, among these factors are the effect of ionising radiation and wide swings of the ambient temperature. In addition, AFS are subjected to significant acceleration and vibrations during the space vehicle launch. Sensitivity of optical cells to space environment factors is determined by the materials of the cell and its design. There are various cell fabrication technologies [8, 9] using different materials for the cell casing and different ways of sealing off the internal cell volume. One of the newest technologies for fabrication of miniature cells for compact atomic clocks uses optical contact [10] and is compatible with a broad choice of optical materials. Ref. [10] discusses results of testing done on a batch of 40 cells fabricated according to this technology and providing relatively high atomic clock stability. The proposed technology is simple and may be implemented in common lab conditions, which is conceptually compatible with approaches used in manufacture of space CubeSat nanosatellites. Development of simpler technologies for fabrication of atomic clock components, as well as complete clocks for inexpensive CubeSat vehicles is important for deployment of space-based networks containing thousands and tens of thousands of nanosatellites for high-speed internet [11, 12].

It is of considerable interest to study the impact of open-space factors upon a cell with alkali-metal vapour, which is fabricated according to the newest technology relying on direct optical contact. The

present work analyses the effect of adverse open space factors (first of all, cosmic radiation) upon the parameters of optical cells with alkali-metal vapour and upon performance of atomic clock using them.

2. Cell design

The proposed optical cell is a sandwich of three optical elements made of quartz (Figure 1). The central part of the cell is a 5-mm long tube with the outer diameter of 8 mm and 2-mm thick wall. The ends of this tube are capped by direct optical contact with 2-mm thick quartz windows having the diameter of 8 mm. The internal sealed volume of the cell contains 1.5 μL of metallic rubidium and is filled with an argon/nitrogen mix at low pressure (48/32 Torr).
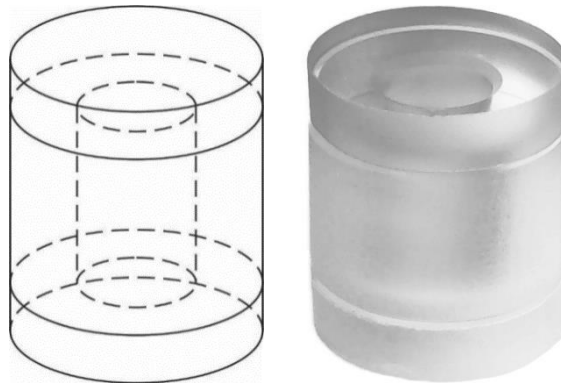

Figure 1. Design of the proposed cell with alkali-metal vapour: schematic view (left) and photo (right).

3. Effect of ionising radiation

Cosmic ionising radiation (or cosmic rays) is one of the main specific adverse factors of the open space, which may lead to degradation of materials and performance of satellite-borne systems [13]. Ionising radiation affects gas cells in several ways:

   a) *effect of ionising radiation on the cell material*

Ionising radiation may affect transparence [14–17] of quartz used in the cell windows, as well as cause luminescence of quartz material. As it was shown in [18], transparence of quartz glass for pumping radiation at 795 nm does not change by more than 10% over 10 years on a low Earth orbit. Sensitivity of quartz glass to ionising radiation may be dramatically reduced (by 2–3 orders of magnitude and even more) by adding cerium oxides to the glass mix [19, 20]. Luminescence of glass elements of the cell [21] has practically no effect on operation of an atomic frequency standard due to relatively low spectral power density of the luminescence radiation whose wavelengths are far away from those of commonly used for pumping atomic frequency standards.

   b) *effect of ionising radiation on structural strength of the cell*

Direct optical contact used in the technology for fabrication of the studied gas cell was earlier used in order to join elements of monolithic laser gyroscopes and gyrometers utilised in spacecraft orientation systems [22]. Many years of successful satellite-borne operation of these devices confirms insignificant effect of ionising radiation on the strength of direct optical contact, which determines the structural strength of the studied cell.

   c) *effect of ionising radiation on the cell contents*

The cell contains 1.5 μL of metallic rubidium, which evaporates and fills it with rubidium vapour, as well as a mix of argon and nitrogen gases. Under normal conditions, rubidium reacts with neither argon nor nitrogen. However, ionising radiation may destroy the strong bond of the nitrogen (N_2)

molecule and that, in turn, may lead to formation of two chemical compounds of rubidium and nitrogen, rubidium nitride (Rb_3N) and trinitride (RbN_3) [23].

Compounding of rubidium and nitrogen may lead to reduction of pressure of both rubidium and nitrogen. According to the technology covered in [10], rubidium is introduced into a cell as a micro-droplet, and its amount significantly exceeds what is needed for a high-contrast spectroscopic resonance. Therefore, interaction of rubidium with nitrogen does not affect the rubidium vapour pressure. On the contrary, it does reduce the nitrogen pressure and hence, modifies the pressure ratio of the gas mix in the cell. The ratio of the partial pressures of the gas mix determines the temperature at which the linear shift of the reference resonance frequency is nullified [24, 25]. This point is optimal and is used as the working temperature of the cell. This means that change of nitrogen pressure inside the cell will lead to the corresponding shift of the optimal cell temperature. Figure 2 presents temperature dependencies of the linear frequency shift of the reference resonance at a fixed partial argon pressure (48 Torr) and different partial nitrogen pressures (32, 29, 26, and 23 Torr). It can be seen that a change of ~10 Torr in the nitrogen pressure can lead to a respective change of the optimal working temperature of the cell, at which the linear shift of the reference resonance frequency is nullified (i.e. the reference resonance frequency shift equals 1 in relative units), by as much as ~50 °C. For the studied cell, the working (and optimal) temperature is 62 °C at the component partial pressure ratio of the buffer gas $\eta = P_{Ar}/P_{N2} = 48$ Torr/32 Torr = 1.5.
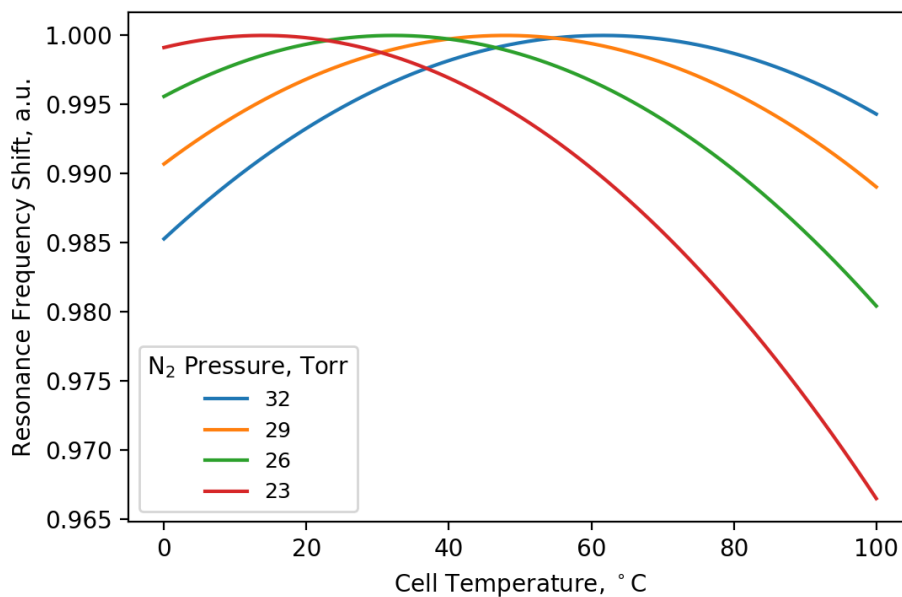

Figure 2. Dependence of the linear frequency shift of the reference resonance at fixed argon pressure of 48 Torr and nitrogen pressure of 32, 29, 26, and 23 Torr.

Let us estimate the relative rate of nitrogen molecule ionisation v in a cell under action of ionising radiation. Ratio v of nitrogen molecules N_{ion} ionised over 1 second to the total number of nitrogen molecules in the cell N_0 is:

$$v = \frac{N_{ion}}{N_0} = \frac{J_{ion} \cdot S \cdot L \cdot n}{N_0}$$

where J_{ion} – value of ionising particle flux, S – cross section area of the internal cell volume, L – length of the internal cell cavity, n – number of ion pairs generated by each ionising radiation particle over a unit path. At $N_0 \approx 2.5 \cdot 10^{16}$, $J_{ion} = 10^6$ cm$^{-2} \cdot$ s^{-1} (peak value of the ionising particle flux through 1 cm^2 over 1 second in the Earth radiation belt during solar flares [26]), $S \approx 0.125$ cm^2 (cross

section area of the studied cell), $L = 0.55$ cm (length of the internal cell cavity), $n \approx 3500$ cm^{-1} – number of ion pairs generated by each ionising particle over unit length of 1 cm [26], the value of v comes to:

$$v \approx 10^{-8}$$

Thus, during 1 second under the highest possible ionising particle flux, approximately 10^{-8} fraction of the total nitrogen molecules may react with rubidium. Hence, the highest rate of nitrogen pressure drop may amount to 10^{-8} s^{-1}.

As it was mentioned earlier, variation of nitrogen pressure inside the cell gives rise to a corresponding change in the optimal cell temperature, which will differ from the temperature set point determined at the start of the AFS operation and not adjusted afterwards. It is because of the discrepancy between the working temperature of the cell and the current optimal temperature that the AFS stability degrades over time.

Let us now estimate the effect of lowering nitrogen partial pressure on the AFS stability. To do that, we will define the Allan deviation over an interval from 1 to 10,000 seconds $\sigma(\tau)$ of the signal $f(t) = W(t) + F(T) \cdot k(T_{work} - T_{opt})$, where f(t) – corresponds to the frequency of the reference resonance of the AFS, $W(t)$ – white noise with the root-mean-square deviation (RMS) of $5 \cdot 10^{-11}$ over 1 second (typical value for rubidium frequency standards), $F(T)$ – flicker noise of the cell temperature around the working set point T_{work} with RMS of 0.01 °C (in existing frequency standards, this parameter is significantly lower and does not exceed 1 mK), $k(T_{work} - T_{opt})$ – the value of the derivative of the dependence of the reference resonance frequency shift upon the working temperature T_{work} of the cell with the optimal temperature T_{opt}. Shown in Fig. 3 are the dependencies of the AFS Allan deviation calculated from the parameters of the studied cells at different partial nitrogen pressures in the range of 32–8 Torr.
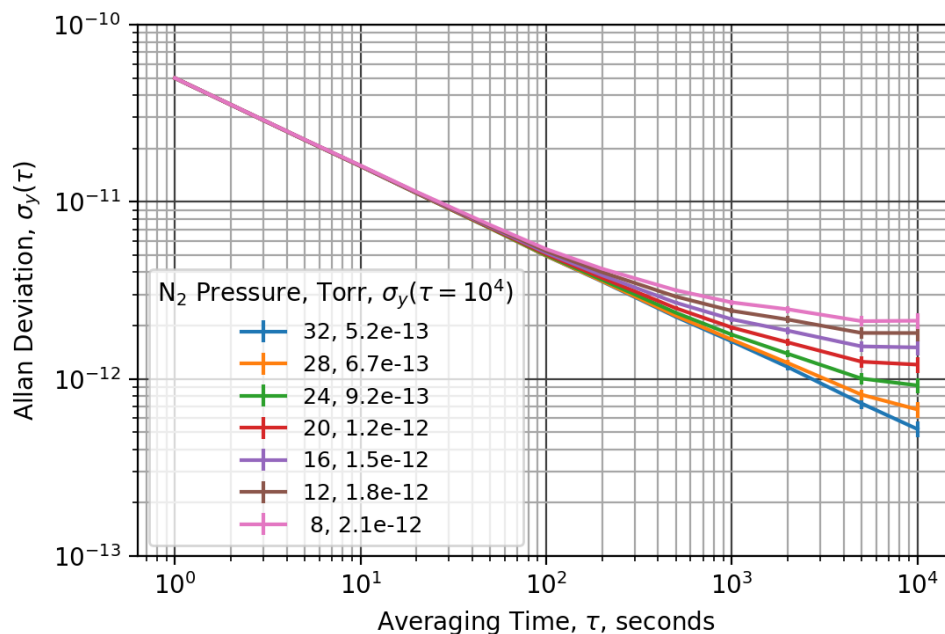

Figure 3. AFS Allan deviation with cells at partial argon pressure of 48 Torr and partial nitrogen pressure ranging from 32 to 8 Torr and the cell temperature fluctuations of 0.01 °C around 62 °C.

Figure 3 demonstrates that over times in the vicinity of 10^4 seconds, AFS stability may vary almost as much as my order of magnitude as the partial nitrogen pressure ranges between 32 and 8 Torr. Let us now calculate the time it will take the nitrogen pressure dropping at the rate of 10^{-8} s^{-1} to degrade the Allan deviation, for instance, by a factor of 2 over 10^4 seconds (typical time of Allan deviation

reduction with exponent $\tau^{-1/2}$ for rubidium AFS [27]). From the dependencies given in Figure 3 it follows that the Allan deviation will grow by a factor of 2 when the partial nitrogen pressure drops to ~22 Torr. Given the highest estimated relative rate of nitrogen depletion defined above, this will occur in $t = -\ln(\frac{32\ \text{Torr}}{22\ \text{Torr}})/v \approx 1.2$ years.

In our calculations, we used the peak value of ionising particle flux during solar flares. However, the total duration of these flares does not exceed several per cent per year [28]. Correspondingly, our estimation will be tens of times longer. Besides, ionising radiation gives rise to two mutually opposite processes: compounding of nitrogen and rubidium and their dissociation into the initial components. Rubidium nitride is an unstable compound, and rubidium trinitride is actively decomposed under the action of ionising radiation [29]. Therefore, the effect of ionising radiation on the contents of the optical cell may lead to noticeable reduction of AFS stability. This, however, will likely take a relatively long time, as long as several decades.

4. Conclusion

The conducted study explains the mechanisms of influence of cosmic radiation on quartz optical cells with rubidium vapour and buffer gas, as well as the consequent variation of AFS stability. The major effect of cosmic radiation on a cell with rubidium and buffer gas is related to dissociation of nitrogen molecule leading to formation of compounds of rubidium and nitrogen, which leads to reduction in nitrogen pressure inside the cell. In its turn, dropping nitrogen pressure in the cell may result in noticeable worsening of AFS stability, albeit over a very long time: at the minimum, several decades will be needed in order for AFS stability to drop by a factor of 2. It will not be an overstatement to say that a quartz optical cell with rubidium vapour and buffer gas is the most reliable element of an AFS, and that it is less affected by ionising radiation that the electronic components of the AFS.

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