# Reliability characteristics of microfabricated Rb mini-lamps for optical pumping in miniature atomic clocks and magnetometers

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## ABSTRACT

With the rising need for microfabricated chip-scale atomic clocks to enable high precision timekeeping in portable applications, there has been active interest in developing miniature (<few cm$^3$), chip-scale alkali vapor lamps, since vapor plasma discharge sources are currently the standard for optical pumping in double-resonance clocks. We reported in 2012 a first microfabricated chip-scale Rubidium dielectric barrier discharge lamp. The device's preliminary results indicated its high potential for optical pumping applications and wafer-scale batch fabrication. The chip-scale plasma light sources were observed to be robust with no obvious performance change after thousands of plasma ignitions, and with no electrode erosion from plasma discharges since the electrodes are external. However, as atomic clocks have strict lamp performance requirements including less than 0.1% sub-second optical power fluctuations, power consumption less than 20 mW and a device lifetime of at least several years, it is important to understand the long-term reliability of these Rb planar mini-lamps, and identify the operating conditions where these devices can be most reliable and stable. In this paper, we report on the reliability of such microfabricated lamps including a continuous several month run of the lamp where the optical power, electrical power consumption and temperature stability were continuously monitored. We also report on the effects of temperature, rf-power and the lamp-drive parasitics on the optical power stability and discuss steps that could be taken to further improve the device's performance and reliability.

**Keywords:** dielectric barrier discharge, rubidium, double resonance, atomic clock, plasma discharge, lifetime

## 1. INTRODUCTION

Rubidium discharge lamps have been widely used for developing compact (100-1000 cm$^3$) double-resonance atomic clocks, where they are used for optically pumping the Rb atoms in a reference cell for high precision time keeping (clock uncertainty <$10^{-12}$) through microwave interrogation techniques. There has recently been a lot of interest in developing miniature (<few cm$^3$) clocks, to improve the performance of highly portable applications such as GPS receivers, but the predominantly available inductively-coupled glass-blown Rb discharge lamps could not be scaled down for use here, due to their high-power consumption (several watts) and non-planar high-volume geometry. Laser diodes (VCSELs) were used instead as they are compact and power efficient but they have several undesirable characteristics including a strong temperature dependence of the output wavelength, and ageing effects. A planar mm-scale Rb light source might be more suitable for the desired miniature-scale clock as they would extend the characteristic advantages of a Rb discharge lamp (such as intrinsically correct light wavelengths of the Rb D1/D2 lines required for optical pumping and very low-frequency drifts with time), and avoid the limitations of a VCSEL. With our partners in a Swiss consortium developing chip-scale atomic clocks, we have recently reported on a chip-scale planar microfabricated capacitively coupled Rb dielectric barrier discharge (DBD) lamp prototype[3]. This development proved the feasibility of low-power mm$^3$ Rb DBD lamps and these light sources were further optimized by changing the electrode geometry and buffer gas pressure[4], to achieve several µW of optical power on the desired Rb D line (minimum power required for optical pumping) with higher power efficiency. However, the microfabricated Rb light source can only be used for atomic clocks or magnetometers if it can function reliably and with high stability for at least several years. Also, the long-term reliability studies of a microfabricated Rb plasma light source have never been previously reported in literature. Hence, the long-term performance and reliability aspects of the microfabricated Rb DBD lamp were investigated and the operating conditions that can maximize the stability and lifetime of the light source are reported here in this paper.

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Dielectric barrier discharges (DBDs) are characterized by the presence of one or more electrically insulating layers in the current path between two conducting electrodes[5] and have been used in several applications including ozone generation and excimer lamps[6]. While these discharges have many general advantages including non-equilibrium plasma operation over a wide pressure range, they offer two specific advantages for this light source application: (1) the current through the discharge gap is limited because of the dielectrics, and (2) no electrodes are in contact with the plasma. These aspects enable low-power operation of a light source by allowing a low sustaining ac voltage, and also eliminate the problem of electrode erosion, which is otherwise a major lifetime limiting process. Hence, this lamp design was chosen where a capacitively-coupled Rb plasma discharge can be sustained in the discharge gap using external parallel electrodes with high power efficiency in the rf range[7].

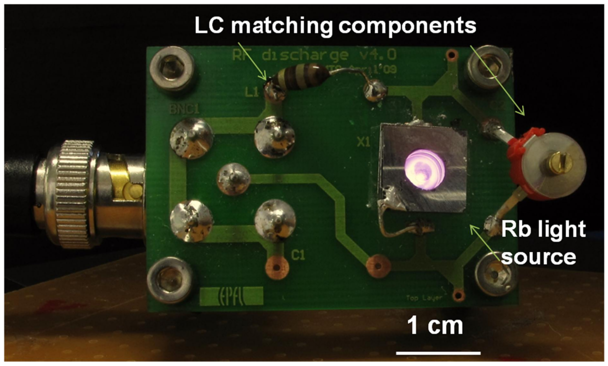


Figure 1. Our microfabricated Rb light source (square chip on right), connected to an LC impedance matching circuit on a PCB and powered by an RF signal (coaxial cable on left), emitting a visible glow discharge.

## 2. THE RB DBD LIGHT SOURCE AND SOME RELIABILITY ASPECTS

When we reported the first microfabricated Rb DBD plasma lamp[3], the long-term performance limiting factors specific to the miniature lamp-cell were unexplored and needed investigations for its potential application in miniature Rb clocks. The parameters that primarily affect the lifetime and long-term performance of a given light source are: (1) the hermeticity of the Rb cell, (2) the input rf power to the cell, (3) input frequency, (4) the cell temperature and (5) p.d, the product of buffer gas pressure (p) and discharge gap length (d).

First, the Rb cell needs to be highly hermetic for a long device lifetime and a consistent and stable light source performance. Higher rf power or lower frequencies leads to higher electron oscillations leading to higher erosion of inner dielectric surfaces from electron bombardment. Higher cell temperature, due to both external cell heating and self-heating, will increase the rate of Rb diffusion into the walls leading to degradation of the light source performance and a reduced device lifetime[8]. The p.d determines the electron energy in the discharge gap and hence the breakdown mechanism for a given set of input conditions and thus plays an important role in determining both the rate of dielectric wall erosion and Rb diffusion (for a given set of conditions, the dielectric erosion rate would have an insignificant dependence on the type of transparent dielectric but the Rb diffusion rate would change measurably due to the different types and arrangement of ions in the dielectric[9]). Rb vapor cells can also contain condensed liquid Rb droplets on the inner dielectric walls, which can lead to large number of Rb surface discharges if the electron oscillation amplitude is equal or more than the discharge gap length. The surface discharges lead to both optical power fluctuations and higher Rb diffusion into the dielectric walls. Hence, after considering all these above factors, appropriate p.d and drive frequency values were identified[4] and chosen for a long-term monitoring experiment to evaluate the Rb DBD lamp's long-term performance and reliability. The results of this experiment are discussed in the next section before which the necessary Rb lamp-cell properties and the fabrication process are mentioned below.

### 2.1 Microfabricated Rb DBD lamp-cell

The Rb lamp-cells (cell dimensions: 1x1x0.3 $cm^3$, discharge gap dimensions: 5 mm diameter and 2 mm height cylindrical geometry) were microfabricated and hermetically-sealed through the anodic bonding technique[10] (illustrated in Figure 2). This was a challenge for creating such miniature Rb cells with volumes on the order of a $mm^3$, principally due to the highly reactive nature of Rb with oxygen (and hence ambient air) and high diffusivity with most metals. Several successful bonding techniques compatible with Rb filling have been reported in the past, for instance[11-13], but these cells have always been used as reference cells in miniaturized atomic clocks, but not as light sources - in part due to the additional complexity of igniting a stable plasma.

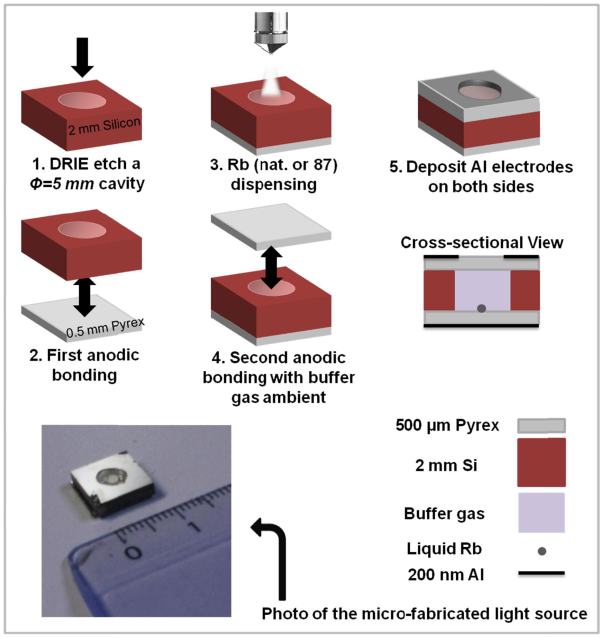


Figure 2. Microfabrication process flow of the Rb DBD lamp-cell where the bonding steps are conducted in a pressure-controlled environment and the Al electrodes are deposited using evaporation

## 2.2 Rb lamp-cell hermeticity

The first reliability aspect of the device is the hermeticity of the Rb lamp-cell. The hermeticity of the anodically bonded cells was studied by monitoring the concentration of Rb atoms in an anodically bonded Rb cell (only cell, no plasma ignition) with time, using laser absorption spectroscopy measurements. The normalized Rb absorption data plot recorded from one of the anodic bonded Rb cells for more than 17 months is shown in Figure 3. The cells produced by this sealing technique have been found to be highly hermetic with an almost non-existent leak rate for more than 2 years, and have also been tested at 180 °C for several months with similar results.

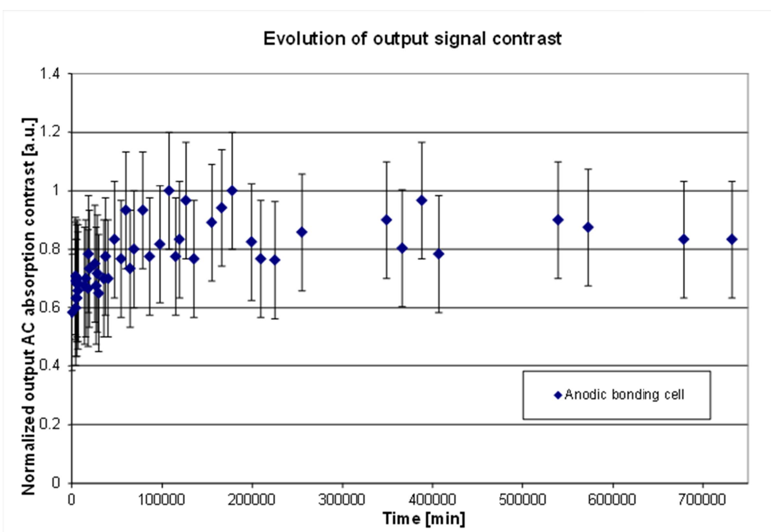


Figure 3. The normalized Rb absorption vs. time for a Rb cell hermetically sealed by the anodic bonding techniques showing the almost constant concentration of Rb atoms inside the cell with time

# 3. LONG-TERM OBSERVATIONS OF THE RB DBD LAMP

Several Rb cells were microfabricated for this research, where the discharge gap length was always 2 mm with low-pressure (between 2 and 70 mbar) Argon as buffer gas. The first set of observations from the various Rb lamp-cell discharge tests over the last 2.5 years is that the Rb lamp-cells were very robust with no significant change in performance after: (1) being ignited thousands of times and (2) heated to more than 100 °C hundreds of times. We expect that these cells can emit discharges continuously for several years after choosing suitable input conditions, based on the observations presented in this section.

## 3.1 Rb DBD lamp lifetime test

An experiment was setup for long-term monitoring of an ignited Rb light source (natural Rb cell with 70 mbar Argon pressure): we logged the stability of the output optical power ($P_{op}$), as well as all other parameters of interest (temperature of the cell - $T_{cell}$, input electrical forward power to the (load) cell and drive circuit - $P_f$, measured reflected power from the load - $P_r$). The experimental setup is illustrated in Figure 4, and the entire light source setup was fully covered with black sheets to eliminate any background light noise.

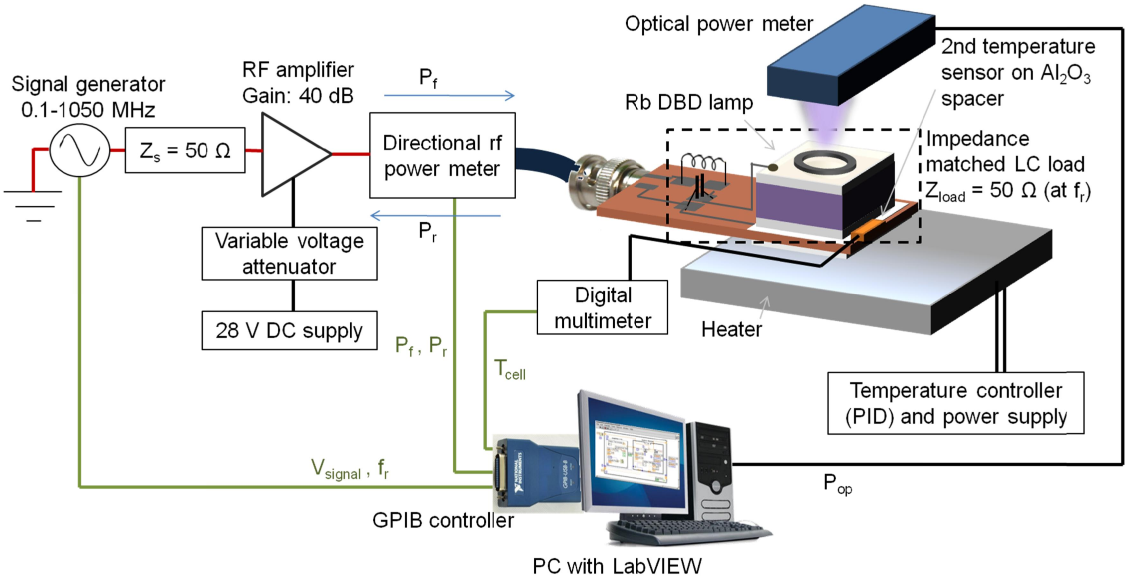


Figure 4. A schematic illustration of the Rb lamp long-term test setup. The red lines are 50 Ω BNC coaxial cables, green lines are GPIB cables and black lines are standard laboratory cables/wires.

The load (Rb cell and LC drive circuit) was impedance matched to 50 Ω (for maximum power transfer from the 50 Ω source) at 17.1 MHz ($f_r$) and the forward power from the rf amplifier (1028-BBM1C3KAJ, 10 W CW power, Empower systems) was PID feedback controlled using LabVIEW, to give a constant RF output power (this was necessary because the output power amplitude of the rf amplifier was found to drift with time, hence an external control was needed to ensure steady input conditions for the Rb lamp under test). The lamp was ignited and the initial conditions were chosen to emit an optimal $P_{op}$ of 100 μW when heated (using heater H1) to 100 °C. As 90-120 °C is the relevant operation temperature range for the Rb light source, 100 °C was chosen for this experiment which corresponded to a Rb D2 output of 6 μW. A 4 mm thick $Al_2O_3$ spacer was placed between the Rb cell and the heater surface (to remove the observed capacitive interference at closer separations) and the photodiode was positioned around 1 cm away from the top electrode for the same reason. The exact position was set in such a way that the optical power reading from there was 25 μW when it was 100 μW if measured right above the electrode surface. A high-power rating inductor (3 A current rating) with a high temperature tolerance was used in the LC-stage for this experiment to avoid the inductor failing due to over-heating effects during the long-term operation. Figure 5 shows the optical power recorded (one data point every 20 seconds) for the long-term experiment, with the initial conditions set as mentioned above and this corresponded to a PID-controlled input forward power of 1.25 W to the LC-stage. The experiment ended after 6 months, because the bottom cell electrode interconnect became unsoldered and the wire connecting the chip to the PCB thus disconnected most probably due to the continuous heating effects (100 °C) from the nearby heater. The interconnect was then resoldered and the lamp was re-ignited to confirm that the Rb lamp was still indeed functional, with an observed performance that matched the last recorded data point and hence the test was confirmed to be hindered only due to an external mechanical soldering defect and not anything because of the Rb lamp-cell.

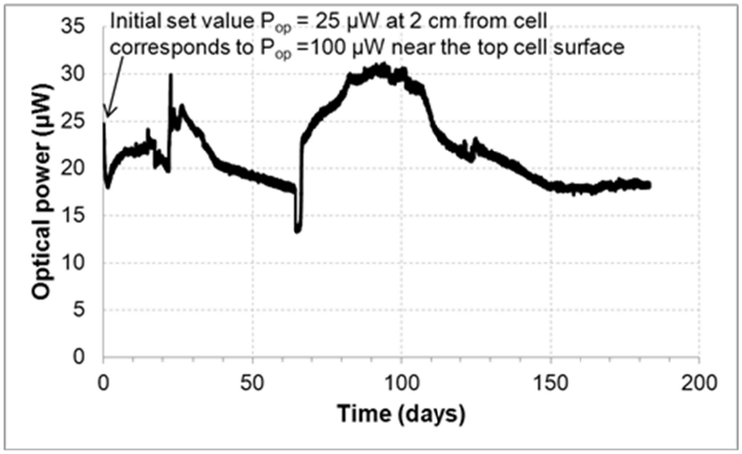


Figure 5. The measured emitted optical power from the Rb lamp-cell during the Rb DBD lamp lifetime test. The lamp was initially set to emit 100 μW of optical power (corresponding to 25 μW from the position of measurement. The lamp was still fully functional after the test.

The first observation from this lifetime test was that the Rb lamp operates without any problems for at least six months, emitting a stable 100 μW of total optical power at 100 °C (corresponds to 6 μW of Rb D2 line power). The short-term (sub-second) fluctuations in the optical power were found to be less than 0.2% (which is in the acceptable range for the atomic clock applications[14]). As seen from the figure, there were drifts in the optical power over time and it has not been possible to determine with certainty the specific causes for the observed behavior. Several possible reasons were identified, based on the observations made from various lamp experiments, which are thought of as the main causes for the observed fluctuations: (1) the resistance change of the inductor (in the LC drive circuit) with time due to long-term heating effects, (2) solder interconnects losing their integrity which leads to changes in the power coupled to the lamp and (3) Rb diffusion into the inner glass walls leading to a lower transmission of light from the Rb-lamp. (1) and (3) can possibly explain gradual and consistent changes in the optical power but (2) can result in erratic and random changes. This is because such behaviors were observed many times before in other lamp tests when the interconnects were not 'perfectly' soldered to the electrodes. The measured reflected power, shown in Figure 5, shows a steady drift after around 100 days possibly indicating the failing solder interconnect. The solder used was 100% Indium, which is a good choice as it wets the Pyrex surface well but an additional non-metallic mechanical support should probably make the interconnect more stable and avoid any unpredictable power coupling losses and optical power fluctuations.

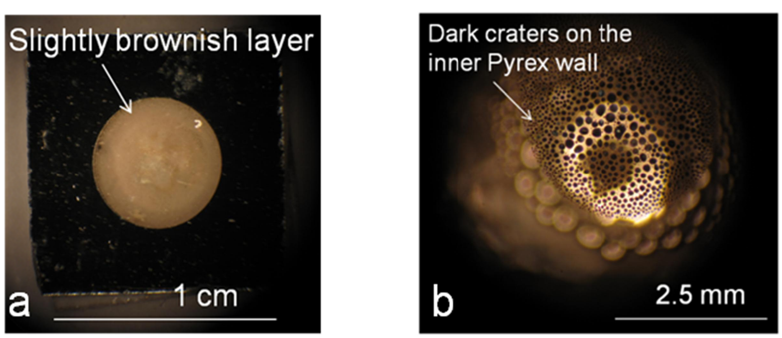


Figure 6. (a) The Rb lamp-cell after the 6-months lifetime test showing a slightly brownish thin layer on the inner dielectric wall indicating possible Rb diffusion in the Pyrex walls (b) Dark craters observed on the inner Pyrex wall after several months of plasma operation in a Rb lamp-cell. The surface discharges formed on liquid Rb droplets are the most likely cause of these slightly eroded dark craters.

### 3.2 Effect of plasma discharges on the Pyrex walls

Figure 6a shows a picture of the Rb lamp-cell after the 6-month lifetime test showing the mildly brownish layer formed on the inner Pyrex wall. This is most probably due to the Rb atoms diffused into the wall over time (similar to the observations reported by other groups[8]). This layer causes increased Rb self-absorption leading to Doppler broadening of the emitted Rb D lines and also overall reduced transmission of the D line power[15]. However, as the Rb lamp is intended to be operated at low power (10 μW Rb D output), this would most probably not be a limiting factor for its use in an atomic clock application (as seen from Figure 5, the optical power emitted after 6 months is still in the same range as the initially set value), but a slight degradation in the clock performance can be expected due to the possible Rb D line Doppler broadening.

Placing electrodes external to the discharge gap (electrodeless) avoids a major lifetime-limiting problem of electrode erosion from plasma discharges. However, the inner dielectric walls are in contact with the discharges and hence get slightly eroded with time. The erosion rate should primarily depend on the input rf power and the drive frequency. When the electron oscillation amplitude is significantly smaller than the discharge gap length ($f_r$>10 MHz for most Rb cells here), most of the discharges are contained within the discharge gap with minimal DBDs occurring on the dielectric surface. For lower drive frequencies or high input power, the wall erosion will be much higher due to the significant amount of surface discharges leading to wall erosion. Separate set of experiments were not performed to study this phenomenon as all Rb cells were tested at several frequencies and power levels. However, some fundamental visual observations have been made and an example picture of a Rb lamp-cell photographed using an optical microscope with focus on the inner dielectric wall after several months of operation is reported here in Figure 6b. From visual observations, some etching of the dielectric layers was observed where dark shallow spots that would reduce the output transmission are seen. The dark spots are most probably high concentrations of diffused Rb originating into the glass wall. The intensity of the spots were higher with a higher presence of liquid Rb in the cells, especially when the light source was operated for hundreds of hours (not necessarily continuously) at the drive frequency less than ~8 MHz. This is because of the higher number of electrons bombarding the liquid Rb present on the dielectric wall at lower drive frequencies and this leads to an increased presence of Rb vapor atoms with high energy eventually diffusing into the nearby dielectric walls. When the light source was predominantly operated at a higher frequency (such as in the lifetime test), a Rb thin film was formed rather than dark spots with no visually observable Pyrex erosion.

## 4. CONCLUSIONS

Reliability aspects of microfabricated Rb DBD light sources were investigated and reported. The light source emitted in the relevant optical power range required for low-power optical pumping in atomic clocks and it was found to operate without any functional problems for at least six months, emitting a stable 100 μW of total optical power at 100 °C (corresponds to 6 μW of Rb D2 line power). The light source was fully functional after the test indicating that it has high potential to operate without significant degradation for several years. A brownish thin film layer is formed on the inner Pyrex wall after prolonged operation which would possibly result in a slight degradation in the optical pumping performance with time. This could probably be reduced by changing to a better-suited glass substrate, like the SCHOTT 8436 glass type. Surface discharges due to condensed Rb droplets on the inner dielectric walls and microdischarges occurring over the dielectric surface increase optical instability and the rates of erosion of the dielectric surface and Rb diffusion. Hence, to significantly reduce these effects, the cell p.d and drive frequency values have to be chosen such that the electron oscillation amplitude is lower than the discharge gap length. The microfabricated plasma light sources are thus expected to operate with high stability for several years, enabling a new class of very compact atomic clocks and quantum sensors.

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