LTCC Integrated Miniature Rb Discharge Lamp Module for Stable Optical Pumping in Miniature Atomic Clocks and Magnetometers

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***Abstract*— We report here on an integrated mini-lamp module (15x26x4 mm^3) with a microfabricated rf-powered Rb dielectric barrier discharge (DBD) lamp (10x10x3 mm^3) positioned on top of a 0.6 mm thick (thickness adjustable) 4-layer LTCC (Low Temperature Co-fired Ceramic) stacked platform containing a serpentine heating resistor design with high heating capacity (up to several hundred degree Celsius) for lamp heating, a fast response DP 5092D PTC temperature sensor for temperature stabilization using PID feedback and a patterned pad layout for the drive circuit components and interconnects. This is the first report of an LTCC integrated Rb mini-lamp module. The novelties of this design include: (1) compact module and independent heating design with thermal isolation of the drive components, (2) very low capacitive interference of the heating elements on the lamp electrodes leading to lower power coupling losses and higher optical power stability during pumping operation, and (3) the components can be batch-fabricated and the module can be independently used for optical pumping in other applications including magnetometers and gyroscopes.**

***Index Terms*— microfabrication, LTCC packaging, chip-scale clocks, dielectric barrier discharge.**

I. INTRODUCTION

Rb vapor discharge lamps (typically spherical, inductively-coupled and glass-blown) are widely used in compact (100-1000 cm^3) double-resonance (DR) atomic clocks and atomic magnetometers for their intrinsically stable and long-term reliable optical pumping for high precision time-keeping and measurement accuracy [1]. With the increasing interest in chip-scale (<few cm^3) DR clocks [2], that would significantly improve the performance of various portable device applications including GPS receivers, there is an active effort in developing a compact, low power, easily integrable and long-term stably emitting Rb lamp which: (1) would avoid the disadvantages of the currently used VCSELs (Vertical Cavity Surface Emitting Laser) [3] in miniature CPT clocks (primary disadvantages are the VCSEL's extreme sensitivity to temperature and ageing effects) and (2) would need much lower power and a simpler drive circuitry than that of the inductively-coupled lamps [4] and make way for a highly space and power efficient module.

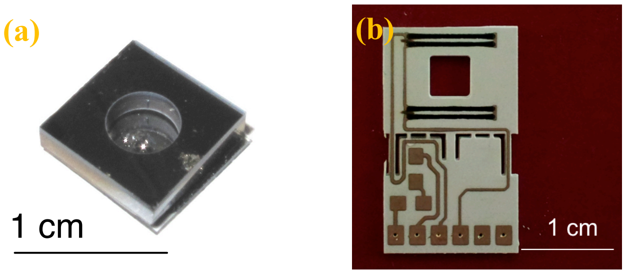

Fig. 1. (a) The microfabricated Rb discharge light source with the top ITO electrode (b) The bottom layer view of the LTCC heater platform showing the PTC sensor and the interconnects through the bridges

The principle challenge and the objective of this research is achieving long-term stable Rb D line power (at least 10 µW needed for optical pumping), with <0.1% sub-second optical power fluctuations, from a miniature integrated lamp module that includes all the necessary peripheral components for stable optical pumping in miniature DR applications. A microfabricated Rb vapor dielectric barrier discharge (DBD) light source prototype was developed [5] for achieving this purpose (cylindrical discharge gap with diameter 5 mm and height 2 mm) which is capable of emitting up to several hundred microwatts of Rb D line power depending on the magnitude of input power, drive frequency and cell-gap conditions. While some of the Rb DBD light source operation conditions have been optimized to produce power-efficient and short-term stable Rb D line power [6], it is important to temperature control the light source at a high enough temperature (typically 100-130 degree Celsius; Rb vapor density increases with increase in temperature) to emit long-term (several years) stable and high intensity of Rb D lines and reduce drifts in optical power. The cell type used in this research is shown in Fig. 1a which has an ITO thin film as top electrode with Al as the bottom electrode.

LTCC (Low Temperature Co-fired Ceramic) technology [7], which allows for high-level integration, easy batch fabrication and compact multi-functional modules, has been used to demonstrate an integrated heater design for rubidium reference cells [8]. It offers many advantages with respect to traditional techniques (thick films on alumina substrates and

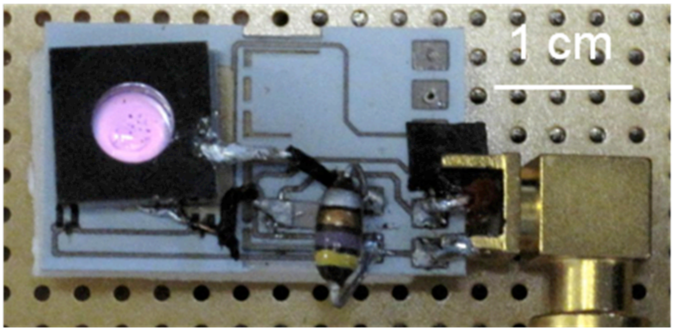

Fig. 2. The LTCC integrated Rb mini-lamp module at operation (lamp powered at 25 MHz)

hybrids) including: (1) excellent 3D structuration, (2) low firing temperatures, (3) possibility to integrate many functions in one same module, and (4) resistance to harsh environments. Here, the advantages of LTCC integration has been extended to develop a lamp platform which comprises of an integrated heater and a thermally isolated rf drive circuit for efficient lamp operation (Fig. 1b). We present here the details of developing the components and the module, indicating the design improvements and the characterization results for optical pumping applications.

II. MODULE COMPONENTS AND DEVELOPMENT

The rubidium mini-lamp module (Fig. 2) is constituted of two primary components: (1) the microfabricated Rb dielectric barrier discharge (DBD) light source, (2) the LTCC heater and drive circuit platform, along with LC drive components and appropriate connectors. In this section, the development of these components and the working mechanism of the module are described.

A. Microfabricated Rb DBD Light Source

The micro-fabricated Rb DBD light source is a stack of three bonded layers: Pyrex (500 µm thick), Silicon (2 mm), Pyrex (500 µm) enclosing a cylindrical cavity containing few microliters of Rubidium and low-pressure buffer gas (15 mbar Ar here), with external parallel thin film deposited electrodes on the top and bottom Pyrex layers. The cavity is created in silicon by a DRIE process and kept hermetically sealed by a two-step anodic bonding process (Fig. 3). A 200 nm thick layer of Al is deposited (by evaporation technique) externally on the Pyrex wall to act as the bottom electrode and a 100 nm thick blanket ITO electrode is deposited (by sputtering) as the top electrode.

The ITO layer has two distinct advantages for this application. The first advantage being high transmission or transparent electrode: ITO allows for the electrode to be directly deposited over the optical window enabling high electric field lines coupling into the discharge gap while being almost transparent (>90% transmittance at the D line wavelengths). The second advantage is that it helps reduce the thermal gradients across the discharge gap. As the ITO layer has a non-negligible surface resistance (with surface resistivity: 40 Ω/sq), some of the input rf power is converted to heat due to resistive losses which helps in top-side heating of the cell and significantly reducing the temperature gradient across the cell. This reduces rubidium vapor condensation on the inner top wall of the light source and hence (1) decreases rubidium self-absorption and Doppler broadening of the Rb D lines and (2) increases the overall transmission intensity and stability of the D lines. The Al layer bottom electrode acts as a light mirror increasing the photon yield through the optical window of the Rb cell.

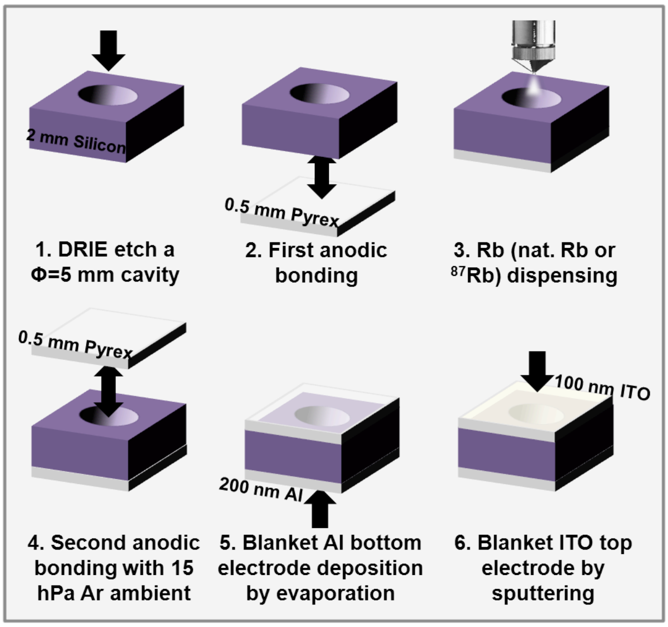

Fig. 3. Microfabrication process flow of the Rb DBD light source. Steps 1 and 2 are performed at wafer level and steps 3 to 6 are done at chip level

B. LTCC Heater and Drive Circuit Platform

The fabrication process of the multi-functional module involves the traditional steps of LTCC technology: laser cutting of green tapes, screen-printing, stacking and lamination, and firing. The final device is 500 µm thick (Fig. 4) and it is composed of 4 layers (intermediate layers can be added depending on thickness requirements). Two different types of LTCC green tapes are used to fabricate the device: the top and the bottom layers consist of the zero (nominally) xy shrinkage

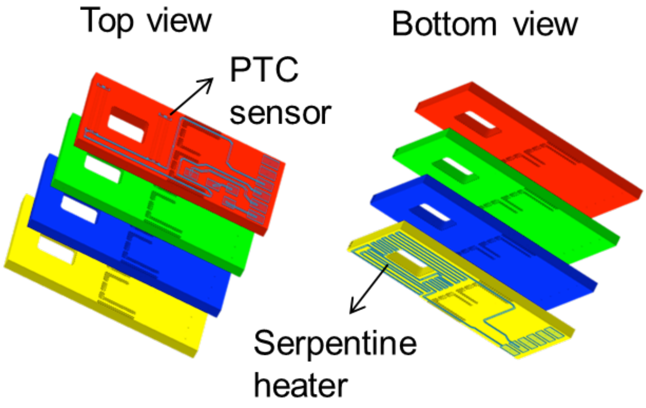

Fig. 4. 3D views of the different layers that constitute the LTCC heater and drive circuit platform

HL2000 (Heraeus, Germany) green tape (50 µm thickness) [9]. The two intermediate layers, added for increasing the thickness and hence the robustness of the platform, consist of DP951 (DuPont, U.S.A) green tape of thickness 254 µm (nominal xy shrinkage is 12.7% when used alone). Using this "sandwich" of HL2000 and DP951 green tapes, the total x shrinkage was 1.079 % and total y shrinkage was 0.844%, because HL tape constrains the shrinkage of DP tape. Thus, almost zero shrinkage was obtained without having to stack many thin HL layers to get the desired thickness - making the fabrication process easy and low-cost.

DP 5092D paste was patterned and screen-printed on the top layer using a shadow mask and mesh screen-printing for the fast-response PTC temperature sensor [10] which is later calibrated before use. Conductive paste (AgPd DP 6146) was used to pattern and screen-print a serpentine heater on the bottom layer. Conducting pads (AgPd) for LC drive components are screen-printed on the top layer where the heater and the pads are thermally isolated with 0.4 mm thick bridges connecting the two sections. A 2 mm thick thermal foam (nominal k = 0.044 W/(m.K) at 25 ^{o}C) (Evonik Industries, Germany) was attached to the bottom layer for thermal insulation and mechanical support. A thin thermally conductive and electrically insulating adhesive layer is used to fix the light source on to the LTCC platform. A thin alumina substrate can also be added as a spacer between the heater and the light source to further reduce capacitive interferences and for homogeneous cell heating.

III. MODULE OPERATION AND RESULTS

The module is operated through two connectors: (1) SMA for the rf input power and (2) D-pin connector for heating and temperature sensing (Fig. 5). The light source is powered at 11.5 MHz (hence requiring a high-frequency connector), which was found to be optimal for the test cell used here (Rb and 15 mbar Ar). Powering the light source in this frequency range allows for the electron oscillation amplitude to be less than the discharge gap length (2 mm), hence reducing fluctuations due to dielectric barrier discharges occurring on the inner dielectric surfaces [6]. As the power required for achieving a given voltage across capacitively coupled electrodes increases with drive frequency, a low drive frequency is preferable for low-power operation and hence 11.5 MHz was chosen as the drive frequency.

The Rb DBD cell is a capacitive load having a high impedance of more than 10 kΩ (~1.5 pF at 11.5 MHz). For maximum power transfer to the light source-load, this load impedance needs to be matched with the source at 50 Ω. However, high voltage amplification is also needed to achieve the electrical breakdown voltage across the electrodes for the least input power. Considering these two requirements for a minimal space and power consuming drive circuit, a series L-C resonant impedance-matching voltage amplifier is used with one capacitor in parallel with the cell and an inductor in series with the capacitor. L-C components are chosen in such a way that the series L-C resonant frequency (f_r) is around 11.5 MHz and the total ESR (Equivalent Series Resistance) of the load (components and the Rb DBD cell) is 50 Ω at f_r. This is done with the help of a vector network analyzer (E5071C Agilent) which plots s11 (scatter parameter) as a function of frequency and hence used for tuning and selecting the L-C components to achieve the required net impedance at f_r. Both SMD and axial components can be used, with SMD components having the advantage of easier assemblage.

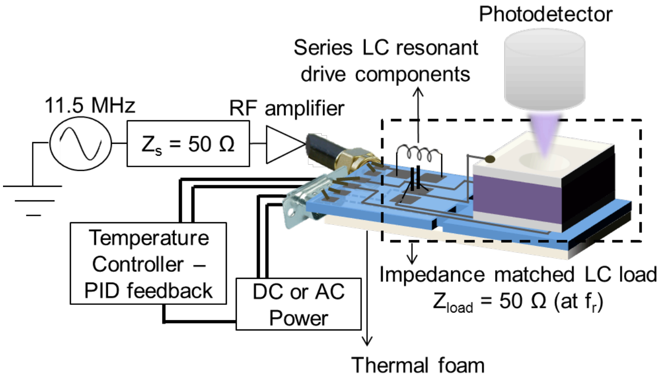

Fig. 5. Schematic of the module operation and test measurement setup

Capacitively coupling rf discharges in planar DBD cells is highly suitable for miniature applications as it enables easy stack integration with other application components when compared to the predominantly used inductively-coupled lamps which uses spiral rf coils. Mini-coils can also be microfabricated inside the discharge gap but it faces the problem of higher power consumption and electrode erosion by the plasma discharges [11].

The heater is powered here by a DC power source whose input voltage is calibrated to the cell temperature readout. The heater can be powered by a DC or an AC power source depending on the target application. For example, in a magnetometer pumping application, a DC powered heater will create magnetic field inhomogeneities when detecting a DC magnetic field while an AC powered heater will avoid this problem. However, for general applications, DC heating is used as it is uncomplicated and more power efficient than AC heating. The corresponding change in resistance of the PTC

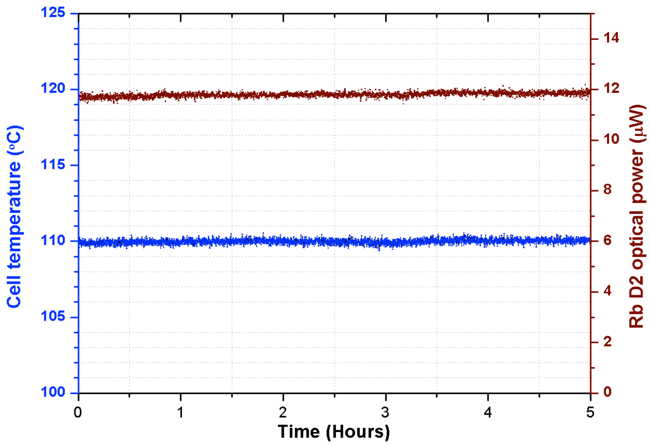

Fig. 6. Cell temperature and Rb D2 optical power measured during a continuous run of 5 hours. Lamp drive frequency: 25 MHz, forward power: 1.1 Watts

sensor with change in temperature is monitored and is fed to the heating power source via a PID (Proportional-Integral-Derivative) feedback controller loop to set and control the temperature and achieve up to less than 0.2 degree Celsius fluctuations with time.

The emitted Rb D2 (780 nm) line optical power and the temperature stability of the Rb lamp-cell recorded over time are shown in Fig. 6. The heater was powered by a DC source (Input conditions: 7.1 V, 0.2 A for 110 degree Celsius) where the temperature was set and controlled using a PID feedback loop. The optical power was detected using a standard broadband silicon photodiode and a photodiode amplifier. The observed result in Fig. 6 shows the capacity of the LTCC module to enable highly stable and long-term reliable optical pumping in miniature atomic clocks and other applications. The Rb DBD light source has also been observed to be very robust being ignited thousands of times and run continuously for several months without showing any degradation in the output power level.

IV. CONCLUSIONS AND FUTURE WORK

A novel LTCC integrated Rb mini-lamp module was developed for stable optical pumping in miniature applications. A suitable LC drive stage was developed for the Rb DBD lamp for impedance matching and voltage amplification which can be conceptually adapted for powering other DBD lamps. All the drive electronics and the test setup externally used for measurements can be integrated into a single module with only one external power supply connector. The L-C component values have to be carefully chosen for highest power efficiency and hence have to be standardized for consistency and best results. The combination of ITO and Al electrodes allows for a high photon output from the light source for a given input power. The ideal operating frequency range of the DBD lamp has to be identified based on the discharge gap conditions where the electron oscillation amplitude is just below the discharge gap length. While changing the buffer gas in the DBD lamp has almost no effect on the stability of the discharges, the power required for breakdown can be reduced by changing to other inert gases like Neon or a mixture of buffer gases. Adding a rubidium-compatible high secondary electron emissive layer to the inner dielectric walls would highly reduce the power consumption by increasing the discharge gap space-charge for a given input rf voltage.

The components can be batch fabricated and the module can be independently used for optical pumping in other applications including magnetometers and gyroscopes. The LTCC heater platform can be easily further reduced or customized according to future rubidium lamp design requirements. It is also possible to individually temperature control the L-C components by having dedicated heaters and temperature controllers for each L-C component to achieve a high LC series resonant quality factor and minimize the rf reflected power.

Currently the total power consumption of this module needs to be reduced for it to be operable in completely portable conditions (without the need for a wired power supply). The main focus of future work is towards achieving this goal by working on the points discussed previously in this section and integrating all electronics to arrive at a completely packaged module with only an external power supply connector.

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