A Status on Components Development for Folded Micro NMR Gyro

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***Abstract*—This paper reports on status of components development for miniaturized nuclear magnetic resonance gyroscopes (micro-NMRG). The reported components are (1) coils to generate and control the magnetic field, demonstrating experimental magnetic field to current ratio of B/I=214.1 uT/A and resulting in an estimated magnetic field homogeneity of H=354ppm, (2) a micro-fabricated spherical cells demonstrating confined alkali metal and noble gas, (3) a heater to keep the alkali metal in the vapor state, showing the capability of heating the micro-cell up to 160 degrees C with 1.44W of power, (4) backbone structure with integrated reflectors, demonstrating the ability to preserve 90.9% of initial light polarization. The introduced design utilized glassblowing process on a wafer-level for fabricating miniaturized NMR cell and 3D-folded-MEMS approach for fabricating the coils, heaters, and reflectors. The field homogeneity of the introduced coil design is capable of achieving the transverse-relaxation time of T_2=7.5s. The projected ARW of the current design of micro-NMRG is 0.1 deg/rt-hr**

Keywords*—*NMRG, glassblowing, folded-MEMS, 3D-MEMS, Helmholtz coil, parylene.

I. INTRODUCTION

A nuclear magnetic resonance gyroscope (NMRG) detects the rotation rate via observing the rotation induced shift in Larmor precession frequency of nuclear spins in a precisely controlled magnetic field. Various publications demonstrated that NMRG is a potential candidate for high performance navigation. The angle random walk (ARW) of $0.002°/\sqrt{h}$ and $0.001°/\sqrt{h}$ were reported in [1] and [2], respectively. Those implementations were reported, however, on table-top setups. Our design employs a glass-blowing technology for wafer-level fabrication of NMR cells, introduced in [3], and a 3-D folded MEMS approach, reported in [4], for fabrication of magnetic coils, interconnects, silicon backbone, and light reflectors.

This paper reports on our status of components development for miniaturized nuclear magnetic resonance gyroscopes (micro-NMRG). The basic components for micro-NMRG are (1) coils to generate and control the magnetic field, (2) an optically transparent cell containing alkali metal and noble gas, (3) a heater to keep the alkali metal in the vapor state, (4) laser sources and photo-detectors to polarize and detect nuclear spins, (5) magnetic shields to reduce ambient magnetic field, and (6) control electronics for magnetic field feedback and rate readout.

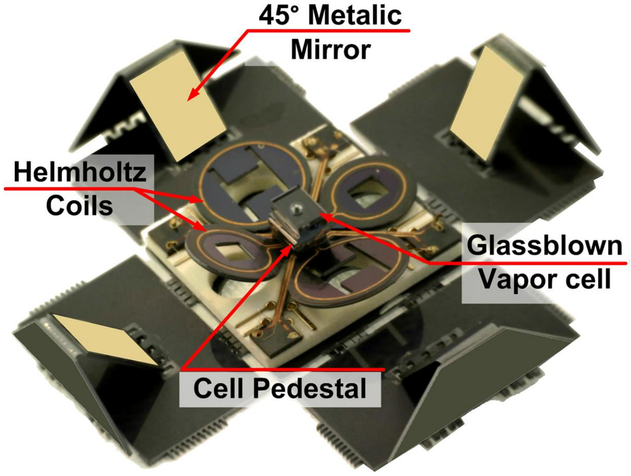

Fig. 1. A prototype of partially folded NMRG prototype

A prototype of micro-NMRG is shown in figure 1. Our approach starts with fabrication of a backbone, which is a double-folded structure with integrated reflectors and Helmholtz coils on a flat silicon wafer, figure 2-(a). Then, the metallic reflectors are folded, and subsequently the coils are assembled, in the middle of the backbone structure, figure 2-(b). Next, the atomic cell is assembled in the middle of the folded Helmholtz coils, figure 2-(c). After folding the coils, two Vertical Cavity Surface Emitting Lasers (VCSEL) and two photo-detectors are assembled, figure 2-(d, e). The backbone structure is finally folded and placed inside multi-layer magnetic shields, figure 2-(f, g). The key advantage of this approach is utilization of the micro-fabrication techniques to batch fabricate the micro-NMRG components, which will subsequently require some very minimum assembly efforts.

II. DESIGN AND FABRICATION OF COMPONENTS

The components of a simplified version of the proposed micro-NMRG were built and characterized. Results are presented in the following subsections. To minimize the magnetic field interference from VCSELs' drive current and the photo-detectors' bias current, VCSELs and photo-detectors were placed outside the backbone structure far away from the cell. A printed circuit board (PCB) was introduced underneath the folded coils to simplify soldering of electrical interconnects. Figure 1 shows the simplified version of the folded NMRG prototype in a partially folded state.

A. *Folded Helmholtz Coils and Integrated Cell Heater*

Helmholtz coils were chosen because of their ability to generate a highly uniform magnetic field. Field homogeneity

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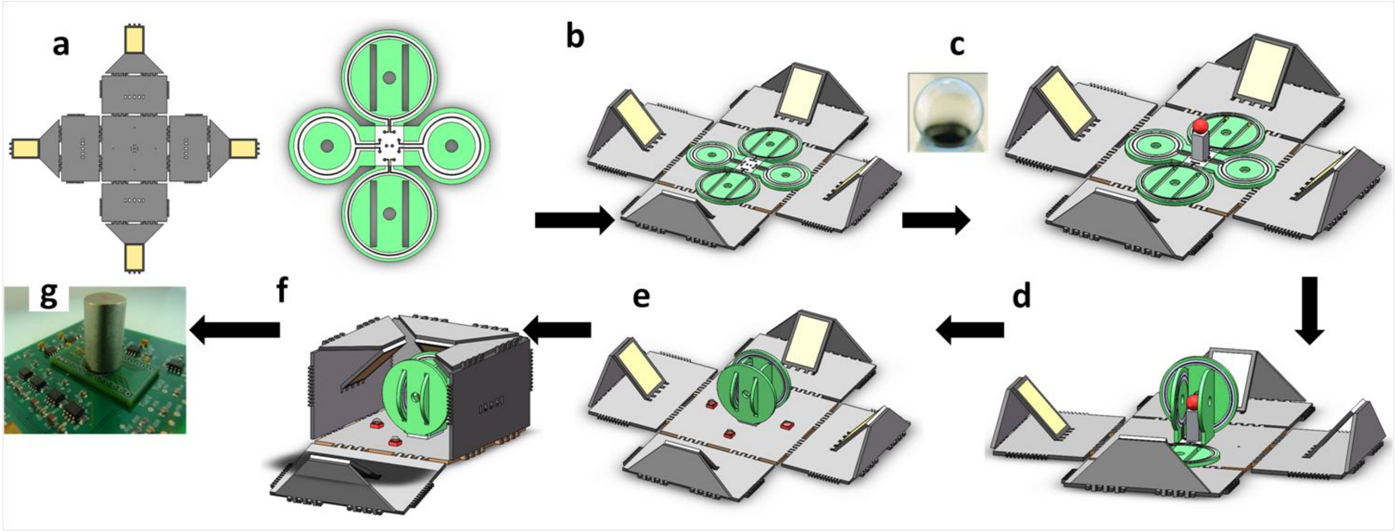

Fig. 2. Conceptual drawing of the folded micro-NMRG. (a) Double-folded structure and coils fabricated on a flat wafer, (b) Initial folding of backbone structure with co-fabricated mirrors, (c) Assembly of glassblown micro cell, (d) Coils are folded, (e) VCSELs and photo-detectors are assembled, (f) Backbone structure is fully folded, (g) The sensor is placed inside magnetic shields

improves as the coil size increases. For 1mm cell diameter a coil on the order of 5mm radius is required to achieve the required homogeneity, [5]. The developed analytical model estimates the spatial variation of the magnetic field across a 1mm cell at the center of the coils and takes into account the magnetic field generated by the circular metal traces, as well as the coil leads, figure 6 insert. The large coil set is designed with the radius of 4.2mm to generate the 10μT nominal magnetic field B_0, with the magnetic field B to current I ratio of B/I=202.5μT/A. The homogeneity across 1mm cell was estimated analytically to be H=354ppm.

A cell heater with suppressed magnetic field generation was designed and integrated on the base of the coil sample. The heater design utilized multipole current carrying conductors with (+–+-++-) configuration; this created a 2^3 poles magnetic moment that resulted in suppressed magnetic field from the heating current, [6]. In addition to using a magnetic field suppressing heater layout, a modulated heater current with a frequency of 100kHz was utilized (the frequency was intentionally selected far away from the Xe resonance frequencies). The heater was placed 4.2mm below the cell and a thermally conductive micro-pedestal made from silicon was used to interface the cell to the heater.

Fabrication process of the folded coils with integrated cell heater starts with a 500μm silicon wafer coated with 3000Å of LPCVD silicon nitride, figure 3-(a). The first metal layer of the cell heater was defined by evaporating 500/5000Å Cr/Au, followed by photo-lithography and wet metal etching, figure 3-(b). Next, a 14μm parylene film is deposited on top of metal-1, then etched using reactive ion etching (RIE) with a Ti film as a hard mask, forming the flexible hinges, figure 3-(c). Metal-2 is subsequently deposited and pattered [7], to form the Helmholtz coil traces, as shown in figure 3-(d). Finally, the coils and hinges were defined using photo-lithography, followed by RIE-DRIE-RIE etching of the Si_3N_4-Si-Si_3N_4 layers, respectively, starting from the backside of the wafer, figure 3-(e).

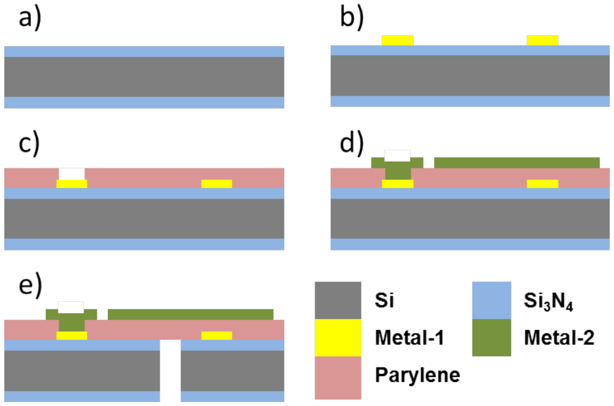

Fig. 3. Fabrication process of the folded Helmholtz coils

B. Glassblown Atomic Vapor Cell

Our approach utilizes glassblowing process for manufacturing of spherical micro-cells, [3]. A possible advantage of spherical cells over the commonly used rectangular cells is their 3-axes symmetry, which is expected to minimize the self-magnetization produced by trapped Rb atoms in corners of non-spherical cells. The presented process allows filling of multiple cells at the same time and gives a control over the Rb gas pressure inside the cell regardless of the cell size.
The process starts with the DRIE etching of 750μm-deep cavities in a 1mm-thick Si-wafer, figure 4-(a). The first anodic bonding of a 500μm-thick Pyrex-wafer to the Si-wafer sealed the cavities at atmospheric pressure. After placing the wafer-stack in a furnace at 850°C for 5-7 minutes, spherically shaped glass shells were formed [3], figure 4-(b). The next step in the process was to open the backside of Si and to define by DRIE $\sim 250\mu$m-deep micro-channels; the micro-channels after this step are shown in figure 4-(c). The second anodic bonding took place after alkali pills were placed in the central cell, and subsequently transferred and anodically bonded in a

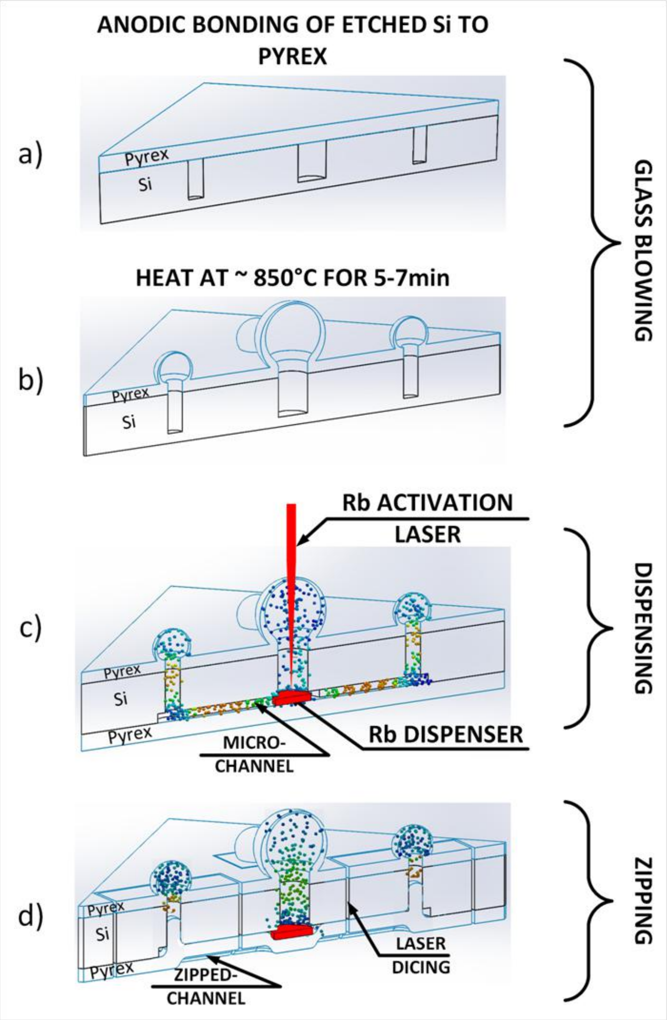

Fig. 4. Description of the process flow: (a) glassblowing of cells, (b) Filling with alkali, noble gas, and buffer gas, (c) Closing channels between dispensing and satellite cells, and then dicing

chamber with a noble gas and a buffer gas at a pressure of 10-15 Torr. After the bonding process was complete, each pill was activated by focusing a 1-1.5W laser for 2 minutes, which released the alkali vapor to the satellite cells, [8], figure 4-(c). After dispensing, the channels and the cells would be sealed, figure 4-(d). This would be accomplished by localized heating of the glass layer with a laser, which would suck-in the softened glass in the below-atmospheric-pressure channels and cells. The glass cooling would permanently seal channels and plug the cells' post, isolating each one of the cells and assuring the necessary level of cell sphericity. Finally, a pulsed laser would be used to dice out cells across the sealed channels.

C. Folded Structure

The backbone of the folded NMRG was fabricated using a process similar to the one used for coils, however it only uses one metal layer. The process starts with a 4-inch silicon wafer. On one side of the wafer the flexible parylene hinges are defined then on the other side a metal layer of 500/5000Å Cr/Au is evaporated and patterned to form the 45° metal reflectors. The fabricated prototype of the double folded structure is shown in figure 5 and one of the two optical paths is illustrated.

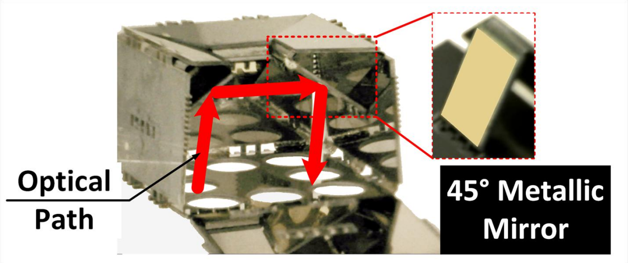

Fig. 5. Fabricated folded structure with 45° metallic reflectors, one optical path is shown

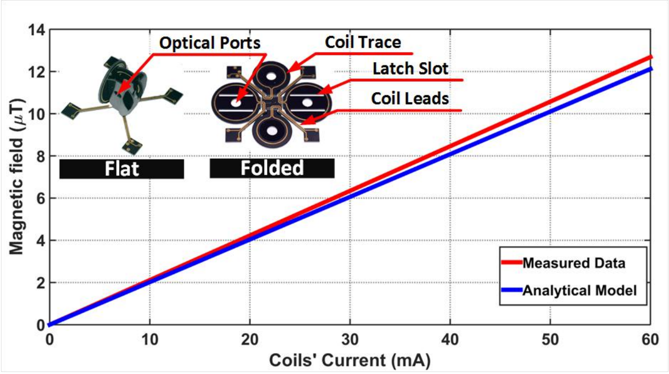

Fig. 6. Magnetic field vs. coils' current, showing a close match between modeling and experimental results; insert on the top left corner shows a fabricated Helmholtz coil sample in flat and folded states

III. EXPERIMENTAL RESULTS

A. Folded Helmholtz Coils

The fabricated sample in figure 6 insert was folded and tested inside a 4-layer magnetic shield to eliminate the surrounding magnetic noise. Using a reference magnetic coil with known B/I ratio and an alkali reference cell, a micro-fabricated prototype measured B/I=214.1μT/A, which showed a close match with our analytical model, figure 6.

B. Integrated Cell Heater

To characterize the heater with the cell pedestal, a sample heater with the pedestal were connected to a DC power supply and placed under an IR camera. The heating current was swept from 60mA to 300mA and the corresponding temperature readings from the IR camera were used to generate the plot in figure 7.

C. Atomic Vapor Cell

To validate experimentally our process of fabrication and cell filling, the fabricated prototypes were placed in a micro-oven which was set at 85°C to maximize the Rb vapor density. Then, a vertical-cavity surface-emitting laser (VCSEL) at 795nm was used to detect the presence of Rb inside the cells. To observe the light absorbed by Rb, the VCSEL wavelength was swept from 794.32nm to 795.12nm by changing the VCSEL's current which resulted in a typical Rb absorption

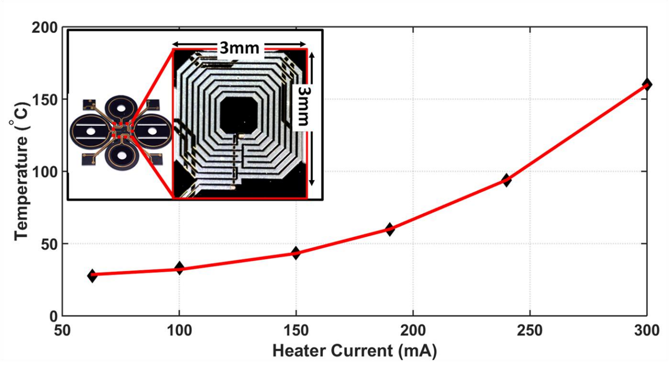

Fig. 7. Temperature (measured) vs. heater current; insert on the top left is showing the fabricated coils sample with integrated cell heater

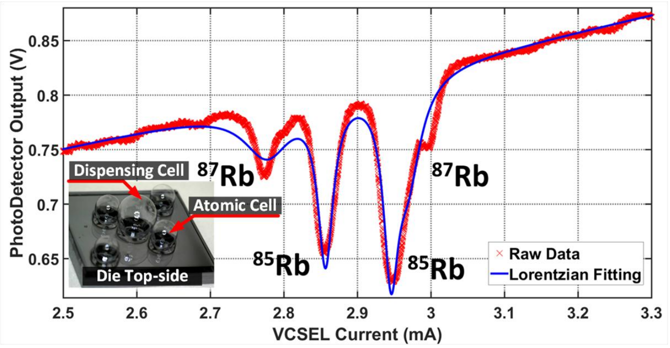

Fig. 8. Absorption Curve of the Rb inside the micro-cell, showing both ^{87}Rb and ^{85}Rb D1 energy lines. Insert on the bottom left corner shows the topside of a fabricated sample

curve, shown in figure 8. The experimental validation of isolation and dicing of cells (step d in figure 4) are still in progress.

D. Folded Structure

The fabricated prototype of the double folded structure, shown previously in figure 5, was tested to determine the power loss and the level of change in light polarization after double reflection from the folded metal mirrors.

It is shown in table I that the measured reflectivity was 74.3% and the laser beam retained 90.9% of its original polarization after reflecting twice from metal mirrors, while tracing the optical path from the source through the cell and to the photo-detector.

TABLE I. MODELING AND EXPERIMENTAL RESULTS ON DESIGN OF METALLIC REFLECTORS

	Analytical Model	**Prototype**
Reflectivity	90%	74.3%
Polarization	100%	90.9%
Material	500Å/5000Å Cr/Au	

IV. DISCUSSION

The achieved coils homogeneity of 354 ppm can be translated to transverse-relaxation time of T_2=7.5s. Assuming Rb-magnetometer is limited by photon shot-noise, the magnetometer sensitivity of the current design is estimated to be on the order of 35pT/Hz. A 1mm cell filled with 100 Torr ^{129}Xe, which is held at 110°C, produces 2% polarized Xe, resulting in the Xe field of 120nT. Assuming the coils and the cell are kept inside a 4-layer μ-metal shield with a shielding factor of 10^6. A predicted SNR for these conditions is on the level of 3400, [9]. Assuming the closed-loop operation and the white noise from the detectors, ARW $\sim 0.1°/\sqrt{h}$ is projected to be achieved with the current design of components, [10].

V. CONCLUSION

We reported in this paper our status on development of the micro components for folded micro-NMRG. We presented the fabrication process and experimental characterization of double-folded backbone structure with integrated reflectors, folded micro Helmholtz coils, micro glass-blown atomic cells, and non-magnetic cell heaters. The discussed approach of component development is believed to have an advantage of minimum assembly requirements. The analysis suggested that the presented folded MEMS approach is a strong candidate for implementation of a tactical-grade micro-NMRG.

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