An Integrated Microheater Array with Closed-Loop Temperature Regulation Based on Ferromagnetic Resonance of Magnetic Nanoparticles

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***Abstract*—This report presents a first-of-its-kind fully integrated magnetic microheater array based on the ferromagnetic resonance of MNP at Gigahertz (GHz) microwave frequencies. Each microheater pixel consists of a stacked oscillator to actuate MNP with a high magnetic field intensity and an electro-thermal feedback loop for precise temperature regulation. The four-stacked/five-stacked oscillator achieves >19.5/26.5 V_{pp} measured RF output swing from 1.18 to 2.62 GHz while only occupying a single inductor footprint, which eliminates the need for additional RF power amplifiers for compact pixel size (0.6 mm × 0.7 mm) and high dc-to-RF energy efficiency (45%). The electro-thermal feedback loop senses the local temperature and enables closed-loop temperature regulation by controlling the biasing voltage of the stacked oscillator, achieving a measured maximum/RMS temperature error of 0.53/0.29 °C.**

***Index Terms*—Biosensor, CMOS SOI, electro-thermal feedback, integrated circuits, magnetic nanoparticle, microheater, multiphysics modeling, permeability, stacked oscillator, temperature regulation**

I. Introduction

TEMPERATURE plays an important role in determining the physiological behavior of biological systems, and therefore, enabling localized yet accurate temperature manipulation in cells and tissues finds a wide range of biomedical applications.

There are three mechanisms that can generate heat loss electrically, namely ohmic loss, dielectric loss, and magnetic loss. Compared to dielectric heating and ohmic heating, MNP-based magnetic heating offers superior specificity and minimal damage to the surrounding tissues since most biological systems are non-magnetic. However, existing magnetic thermal applicators face two challenges, namely, low heating efficiency and limited spatial resolution.

To address these challenges, we present a fully integrated magnetic microheater array with closed-loop temperature regulation as shown in Fig. 1 [1][2]. Its heating principle is based on the ferromagnetic resonance of MNP at GHz microwave frequencies, bringing two unique advantages. First, the required magnetic field strength is significantly reduced at GHz, leading to a fully integrated solution as opposed to conventional bulky benchtop magnetic field generators. Second, we can now manipulate the local magnetic field and heating profiles using on-chip inductors due to the high operating frequency, resulting in substantially improved spatial resolution at the sub-millimeter scale. The high spatial resolution also releases the burden of precise delivery of MNP to the target.

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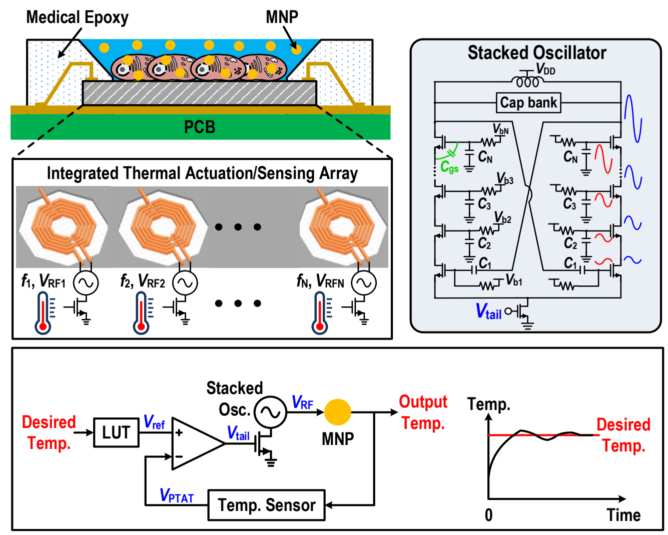

Fig. 1. The proposed microheater array with closed-loop temperature regulation. Each pixel consists of a stacked oscillator and an electro-thermal feedback loop.

II. Integrated Microheater Array with Closed-Loop Temperature Regulation

The proof-of-concept microheater array chip as shown in Fig. 2 has 12 pixels with a pixel size of 0.6 × 0.7 mm^2. The stacked oscillators in the first three rows of the array are designed with three different frequency tuning ranges (1.2 – 1.6 GHz, 1.5 – 2.1 GHz, and 2.0 – 2.6 GHz, respectively), allowing for efficient heating of a wide range of MNP with different ferromagnetic resonant frequencies due to their diverse sizes, material compositions, and nanostructures.

A high rf swing is desired for strong magnetic field strength. One possible solution to boost the RF swing is to amplify the oscillator output using RF amplifiers. However, additional inductors are needed in the design of RF amplifiers to serve as

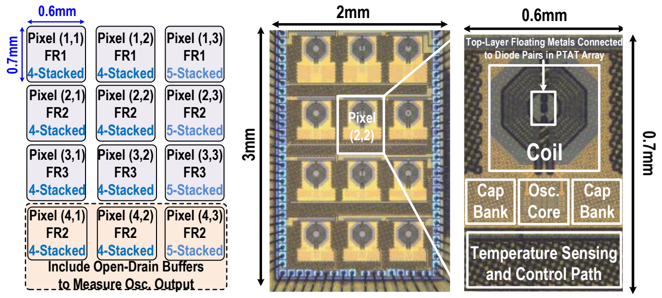

Fig. 2. Floorplan of the integrated microheater array and the microphotograph of the integrated microheater array chip.

the resonating tank or the impedance matching network, which sacrifices the spatial resolution of the microheater.

We propose a stacked oscillator topology (Fig. 1), in which multiple transistors are connected in series to distribute the voltage stress and, in turn, to achieve a large RF output swing using a single inductor footprint. The gate and drain voltage swings gradually build up from the bottom transistor to the top, and only V_{g1} is out of phase due to the positive feedback. The simulation results also verify that V_{ds} and V_{dg} for different transistors are close to one another and within the breakdown limit of 3 V. The temperature sensing and control path (Fig. 1) in each pixel senses the local temperature and generates the biasing voltage for the tail transistor of the stacked oscillator for closed-loop temperature control. To verify the thermal regulation behavior, we perform a transient closed-loop electro-thermal simulation using Cadence Virtuoso and COMSOL. The overall loop gain including the T-to-V_{swing} conversion and the V_{swing}-to-T conversion is calculated as approximately 27 dB from Cadence Virtuoso and COMSOL simulations. All the electrical poles are designed and verified to be higher than 100 kHz. Thus, the electro-thermal feedback loop behaves as a first-order system without stability concerns.

III. Measurement

Two PDMS membranes mixed with and without MNPs are used to validate the localized heating performance of the magnetic microheater array. In the open-loop demonstration (Fig. 3), V_{tail} is biased off-chip through V_{IO}. We use the three stacked oscillators in the second column to measure the local temperature rise in the three different frequency ranges. For the PDMS membrane mixed with MNP, the local temperature is between 41.93 and 47.05 °C. On the other hand, for the PDMS membrane without MNP, the local temperature stays below 37.8 °C under the same biasing condition.

In the closed-loop demonstration, we first program the DAC setting of V_{ref2} based on the targeted temperature. V_{tail} is then automatically generated through the electro-thermal feedback loop. Fig. 3 summarizes the settled temperature $T_{settled}$ against the desired temperature $T_{desired}$. $T_{settled}$ is the average IR camera reading over 5 minutes at 1 frame/s frame rate. Extra calibration steps, e.g., correlating the camera reading with on-chip PTAT voltage and comparing the camera reading of the PCB with the known ambient temperature, were performed to guarantee the accuracy of the temperature measurement. The maximum/RMS temperature error is 0.53/0.29 °C from 37 to 49 °C. A smaller

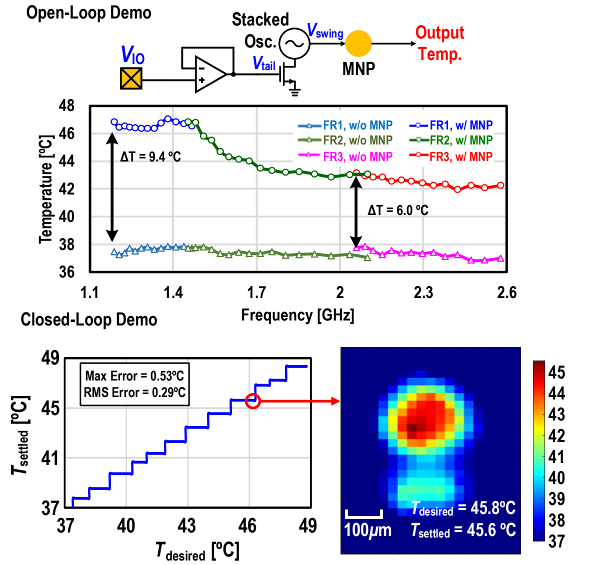

Fig. 3. **Open-loop demonstration:** measured surface temperatures of PDMS membranes with and without MNP against oscillation frequency. **Closed-loop demonstration:** settled temperature versus the desired temperature and a zoom-in view of the surface temperature distribution.

temperature error can be potentially achieved by increasing the number of bits of the DAC.

This paper presents a first-of-its-kind fully integrated magnetic microheater array based on the ferromagnetic resonance of MNP at GHz microwave frequencies. Powered by the proposed stacked oscillator, this work offers the highest spatial resolution, the lowest dc power consumption, and the best dc-to-RF energy efficiency. In addition, precise closed-loop temperature regulation is achieved by the proposed electro-thermal feedback loop. With these features, the presented high-resolution magnetic microheater array would be applicable in a wide range of biomedical applications requiring localized heating.

IV. Career Plan and Impact Statement

I am truly honored and grateful to receive the fellowship at the early stage (2nd year) of my PhD journey. It offered me the chance to attend my first IMS in person and got recognized at the Awards Banquet which was unique due to the COVID pandemic. At the conference, I was able to learn from the presentations and the showcase of companies about cutting-edge microwave technologies. This experience helps me to gain more confidence to tackle challenges in my ongoing projects and my future career.

Reference

[1] Y. Fan, L. Zhang, Q. Zhang, G. Bao and T. Chi, "18.3 An Integrated Thermal Actuation/Sensing Array with Stacked Oscillators for Efficient and Localized Heating of Magnetic Nanoparticles with Sub-Millimeter Spatial Resolution," *2021 IEEE International Solid- State Circuits Conference (ISSCC)*, 2021, pp. 280-282.

[2] Y. Fan, L. Zhang, Q. Zhang, G. Bao and T. Chi, "An Integrated Microheater Array With Closed-Loop Temperature Regulation Based on Ferromagnetic Resonance of Magnetic Nanoparticles," in *IEEE Transactions on Biomedical Circuits and Systems*, vol. 15, no. 6, pp. 1236-1249, Dec. 2021