Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2026

Design of a Robust Frequency Stabilization Circuit using Ring Oscillator for Therapeutic Ultrasound Systems

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***Keywords : Ring Oscillator, HIFU, Frequency Tuning, Coarse-Fine Control, Process Variation**

1. Introduction

High-Intensity Focused Ultrasound (HIFU) technology has gained significant attention for its applications in non-invasive dermatological treatments, including pigmentation disorder corrections and tattoo removal [3]. A critical challenge in HIFU systems is maintaining a stable resonant frequency, typically around 20 MHz, over prolonged usage, as environmental factors and aging effects alter the transducer's performance. Traditional ring oscillators often suffer from frequency drift due to Process, Voltage, and Temperature (PVT) variations, which degrade the efficiency of ultrasonic wave transmission [4, 5].

To address this, we propose a robust ring oscillator-based frequency control circuit featuring a novel coarse-fine tuning architecture. This design allows for precise manual control of the oscillation frequency to compensate for resonance drift, ensuring sustained and precise ultrasonic wave generation [1]. The proposed circuit integrates an additional NMOS transistor control mechanism to modulate the effective delay within the inverter chain, thereby fine-tuning the oscillation frequency [2].

2. Circuit Design and Layout

2.1. Coarse and Fine Tuning Architecture

The proposed ring oscillator employs a multi-stage inverter chain designed to drive the ultrasound transducer. Unlike conventional fixed-frequency drivers, our design incorporates a dual-control mechanism: a 'Coarse' tuning stage for broad frequency adjustments and a 'Fine' tuning stage for precise calibration [1]. This is achieved by adjusting the gate voltages (Vctrl) of the NMOS transistors connected to the delay cells. By modulating the current drive capability, the delay of each stage is controlled, resulting in a tunable oscillation frequency [2].

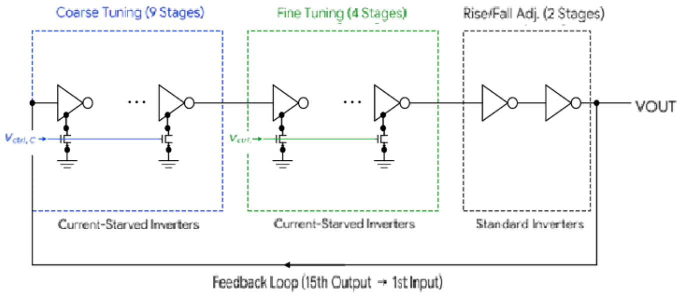

Fig.1. Schematic of Proposed 15-stage Hybrid Ring Oscillator Architecture

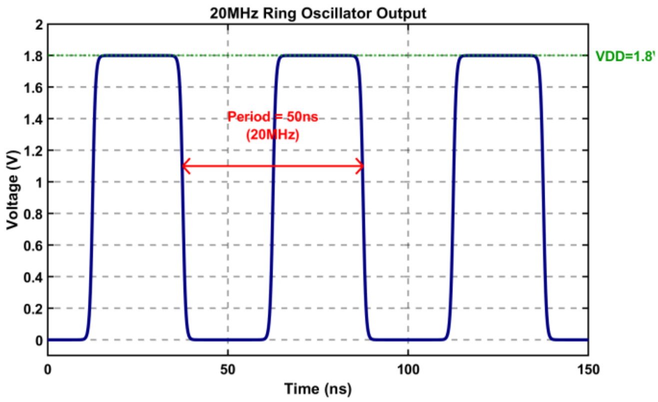

Fig.2. Output of Proposed 15-stage Hybrid Ring Oscillator

2.2. Layout Implementation

The physical design of the proposed ring oscillator was implemented using a standard CMOS process. To optimize area efficiency and minimize parasitic capacitance, the layout adopts a block-based architecture rather than a fully symmetric structure. The layout is logically partitioned into two distinct blocks: a 9-stage Coarse tuning block and a 4-stage Fine tuning block. This hierarchical placement allows for simplified signal routing and ensures that the coarse and fine control voltages (Vctrl) are applied independently without interference. The connection lines between the inverters were designed with minimal length to reduce interconnection delays, ensuring the target oscillation frequency of 20 MHz. The complete layout is shown in Fig. 2.

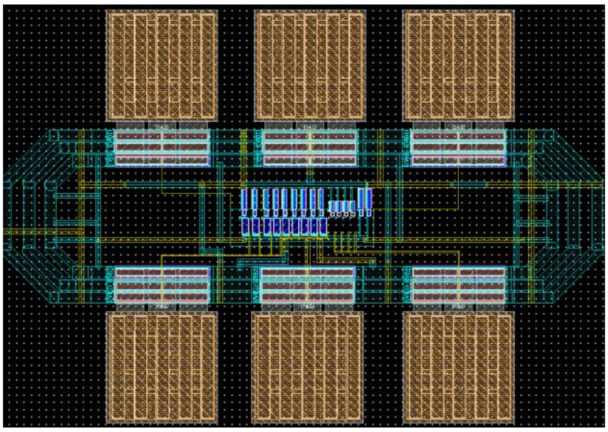

Fig 3. Layout of Ring Oscillator

3. Simulation Results

3.1. Linearity and Tuning Range

The oscillation frequency was simulated by sweeping the fine control voltage (Vctrl fine) while holding the coarse voltage fixed. As shown in Fig. 3, the circuit exhibits highly linear frequency tuning characteristics around the target frequency of 20 MHz. The result demonstrates that the oscillation frequency can linearly adjusted, providing a seamless tuning range to compensate for any resonant frequency deviations.

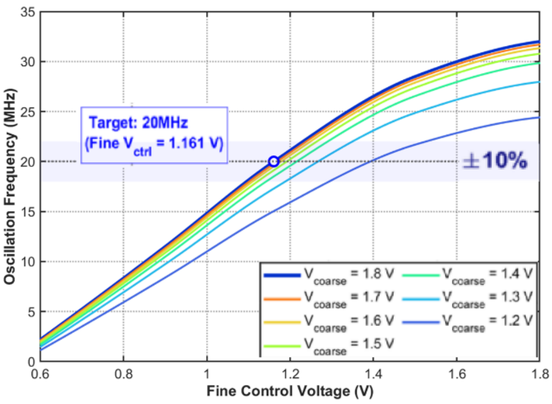

Fig. 4. Simulated oscillation frequency versus control voltage (Vctrl), showing linear tuning capability around 20 MHz.

3.2. Corner Simulation Analysis

To verify the robustness of the design against process variations, corner simulations were performed for Typical (TT), Fast-Fast (FF), Fast-Slow (FS), Slow-Fast (SF), and Slow-Slow (SS) conditions [4]. The results are summarized in Table I. The simulation confirmed that even under extreme process corners, the oscillation frequency remains within a controllable range. Specifically, the deviation in the TT corner was negligible (-0.03%), and even in the worst-case corners (FF and SS), the frequency shifts were within ±8%, which can be fully compensated by the proposed coarse-fine tuning mechanism.

Corner	Frequency (MHz)	Error (%)
TT	19.99	-0.03
FF	21.6	+8
FS	20.39	+1.985
SF	19.598	-2.01
SS	18.43	-7.85

Table I. Results of Corner Simulation

4. Conclusion

In this paper, we presented a 20 MHz adaptive ring oscillator with a coarse-fine tuning capability for HIFU applications. The simulation results demonstrated excellent linearity in frequency control and robust performance across process corners. The physical layout was successfully implemented, validating the feasibility of the design. This architecture ensures that the HIFU transducer operates consistently at 20 MHz, enhancing the reliability and lifespan of next-generation HIFU devices [3]. Finally, we will present post-layout simulation results to further validate the practical reliability of the proposed circuit.

5. Acknowledgement

This work was supported by multiple grants from the Korea government, including the Ministry of Trade, Industry & Energy (MOTIE, KETEP No. 20214000000070), the Ministry of SMEs and Startups (MSS, RS-2023-00322102), the Ministry of Science and ICT (MSIT, NST No. GTL25051-000), and the Ministry of Education (MOE) and Gangwon State through the RISE program (2025-RISE-10-006).

6. References

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