A 131 dBΩ 146 MHz Transimpedance Amplifier for 20 MHz Capacitive MEMS Beam Resonator[1]

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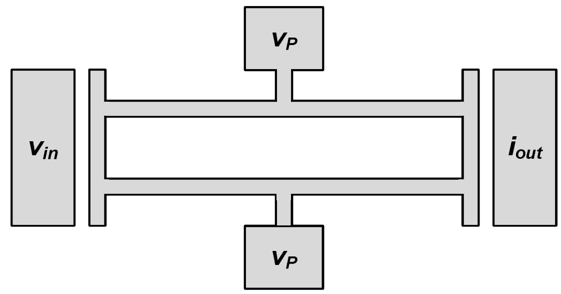
***Abstract*—This paper proposes an ultra-high-gain wideband transimpedance amplifier (TIA) for a 20 MHz capacitive MEMS beam resonator. The TIA consists of a common-gate amplifier, a wideband Cherry-Hooper amplifier, and buffers. The common-gate amplifier uses a self-biased inverter to expand the bandwidth. The output transistors in the Cherry-Hooper amplifier are tunable to combat the process variation. The output buffer employs a small load resistor to guarantee wideband and sets switches to cut off the parasitic from the test buffer. Implemented in the 0.35 µm CMOS process, the TIA shows a simulated gain of 131 dBΩ, a bandwidth of 146 MHz, and an input-referred current noise of 16.3 pA/√Hz. The proposed TIA works well with the resonator, and oscillation builds up within 50 µs with a swing of 2.9 Vp-p. The simulated phase noise is -108.6 dBc/Hz at 10 kHz offset and -112.4 dBc/Hz at 100 kHz. The power consumption is 15 mW under 3.3 V supply. This work provides a reference for V/UHF resonator driving and voltage-controlled MEMS oscillators.**

Keywords—MEMS oscillator; transimpedance amplifier (TIA); wideband; high gain; common-gate amplifier

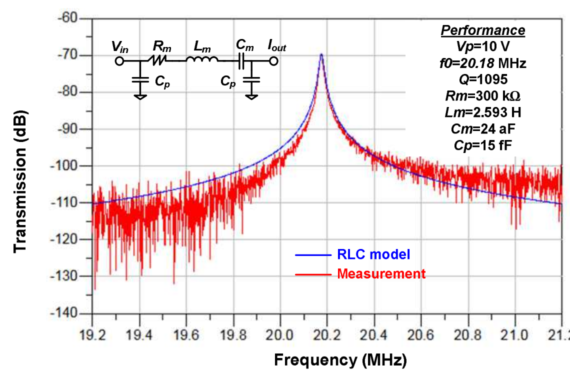
I. Introduction

MEMS oscillators have become a strong competitor of quartz by the high frequency, integrable, and low-cost advantages. Due to the high frequency and high Q merits, capacitive MEMS resonators draw a lot of research attention. However, the ultrahigh motional resistance prevents them from practical use. Recently, many works have made outstanding achievements on array design [1], process optimization [2], and new mechanism [3], and reduced the motional resistance to a level comparable to piezoelectric resonators and even the quartz. This work endeavors to explore how to design an ultrahigh gain wideband transimpedance amplifier (TIA) from the perspective of the circuit.

Fig. 1(a) shows the brief schematic of the capacitive MEMS beam resonator used in our work, and Fig. 1(b) gives the ADS-fitted electrical-model parameters based on the measurement results. The resonator works in flexural mode. At resonance, the resonator is modeled as an R-L-C series circuit. The resonant frequency is 20.18 MHz with a motional resistance of up to 300 kΩ. To successfully actuate the resonator, the peripheral TIA needs a gain of larger than 117.5 dBΩ and a bandwidth of 202 MHz. Considering the interface parasitic of the TIA and the resonator, we set 0.5 pF capacitor both at the input and output



(a)



(b)

Fig. 1. (a) The brief schematic of the 20 MHz capacitive MEMS flexual beam resonator; (b) The ADS-fitted electrical-model parameters of the resonator.

of the TIA. The regulated-cascode (RGC) style is commonly used in the first stage of the TIA to combat the large input capacitance [4, 5]. The popular Cherry-Hooper amplifier [6, 7] is employed to simultaneously obtain high gain and wideband. Based on the previous works, this paper proposes an ultrahigh gain wideband TIA by simply using a common-gate amplifier but with a self-biased inverter to extend bandwidth. Besides, two identical resistors are used to set a stable input bias for the Cherry-Hooper amplifier and tunable transistors are designed to combat the process deviation. Based on the 0.35 µm CMOS process, the TIA shows a simulated gain of 131 dBΩ with a bandwidth of 146 MHz. Compared with [8], this work increases the gain by 50 dB when their bandwidth is similar; compared to [9], this paper extends the bandwidth by 100 times while their

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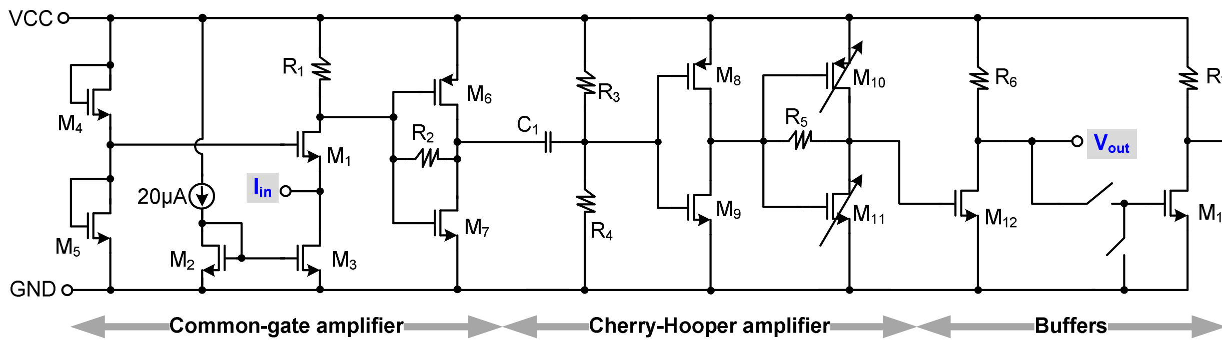

Fig. 2. The proposed TIA with a gain of 131 dBΩ and a bandwidth of 146 MHz for the 20 MHz capacitive MEMS beam resonator.

gain is close. The proposed TIA works well with the resonator, and oscillation builds up within 50 µs with a swing of 2.9 Vp-p. The simulated phase noise of the MEMS oscillator is -108.6 dBc/Hz at 10 kHz offset and -112.4 dBc/Hz at 100 kHz offset.

II. Transimpedance Amplifier Design

The complete schematic of the TIA is shown in Fig. 2. It mainly consists of three stages: a common-gate amplifier with a self-biased inverter, an inverter-based Cherry-Hooper amplifier with a stable input bias, and buffers with two switches.

For the common-gate amplifier, the gate voltage is biased by two diode-connected transistors due to the low thermal noise at the resonant frequency. The drain terminal of M1 is connected to a self-biased inverter to lower the load resistance and extend the bandwidth. The load resistance (transimpedance gain) is:

$$R_{out} = R_1 \parallel \left(R_2 + r_{o6} \parallel r_{o7}\right) \quad (1)$$

Herein, the r_{o6} and r_{o7} are small-signal output resistance of the M6 and M7, respectively. The self-biased inverter also serves as an isolation and amplification function.

For the Cherry-Hooper amplifier, the current reuse scheme is used to enhance the gain and save power. The voltage gain is:

$$A_{V,CH} = \left(g_{m8} + g_{m9}\right) * R_5 \quad (2)$$

Herein, the g_{m8} and g_{m9} are transconductances of the M8 and M9, respectively. The sizes of M8 and M9 are made larger to obtain a larger transconductance and thus a larger gain. Besides, two identical resistors instead of a MOS transistor [6] are used to set the input bias voltage because this scheme is more stable and practical. The resistors are set a large value to reduce the power consumption and the decoupling capacitor that occupies a small silicon area. The capacitance should not be too small, and the lower cutoff frequency should be at least 10 times less than the resonance frequency. The sizes of M10 and M11 are adjustable to accommodate the process deviation.

For the buffers, the output buffer made by M12 and R7 serves as an isolation and drivability function. The output terminal connects to the input of the MEMS resonator. R7 is 1.5 kΩ to achieve a 212 MHz bandwidth with a 0.5 pF load. The test

TABLE I. The Component Sizing of the Proposed TIA.

Common-gate amplifier		Cherry-Hooper amplifier	
M1	w=28µm, l=0.35µm	C1	c=0.6pF
M2	w=5µm, l=0.35µm	R3=R4	r=84kΩ
M3	w=30µm, l=0.35µm	M8	w=37.2µm, l=0.35µm
M4	w=2µm, l=0.35µm	M9	w=18µm, l=0.35µm
M5	w=10µm, l=0.35µm	R5	r=147kΩ
M6	w=10µm, l=0.35µm	M10	w=7µm, l=0.35µm
M7	w=9µm, l=0.35µm	M11	w=4µm, l=0.35µm
R1	r=52.6kΩ		
R2	r=5.2kΩ		
Buffers			
M12	w=10µm, l=0.35µm	M13	w=100µm, l=0.35µm
R6	r=1.5kΩ	R7	r=100.6Ω

buffer made by M13 and R8 is for interfacing the external measurement instrument and can be switched off to reduce the total load capacitance seen by the previous output buffer. The sizing of the TIA is shown in Table I.

III. Simulation Results

Based on the 0.35 µm CMOS process, the proposed TIA layout is shown in Fig. 3. The occupied silicon area is 105 µm *45 µm. The simulated frequency response of the TIA is also shown in Fig. 3. The TIA shows an ultrahigh gain of 131.2 dBΩ and a wideband of 146 MHz. The TIA gain is enough to compensate for the motional resistance of the resonator. The frequency-related phase shift at 20.18 MHz is only -3.1°, which

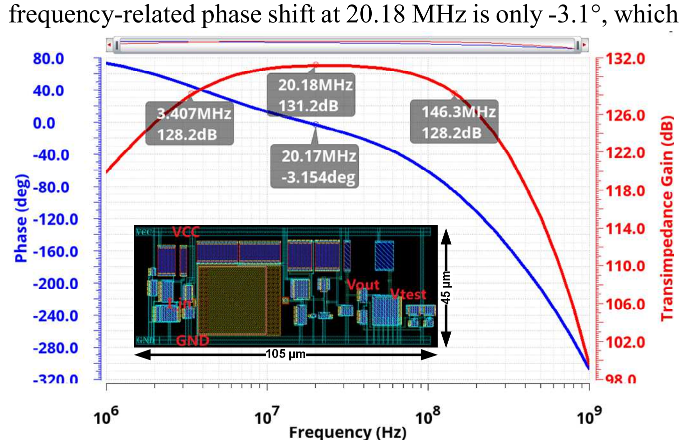

Fig. 3. The simulated gain and phase response of the proposed TIA. The inset is the TIA layout.

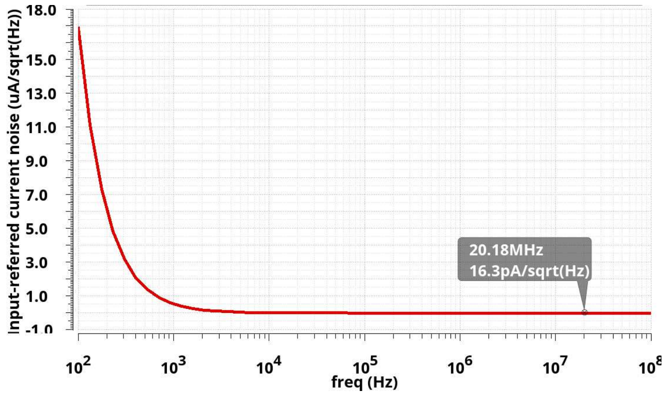

Fig. 4. The simulated input-referred noise current spectrum of the TIA.

guarantees the closed-loop positive feedback. In addition, the noise characteristics of the TIA were also simulated, as shown in Fig. 4. The input-referred noise current at the resonant frequency is 16.3 pA/√Hz.

Connect the proposed TIA and the MEMS resonator in a closed loop to simulate the oscillation behavior. The transient start-up of the MEMS oscillator is shown in Fig. 5. The TIA works well with the resonator, and oscillation sets up within 50 µs with a swing of 2.9 Vp-p. The highest voltage is about 3.3 V, near the supply rail, and the lowest is about 0.38 V. Next, do the phase noise simulation, and the result is shown in Fig. 6. The simulated phase noise at 1 kHz offset (in-band noise) is

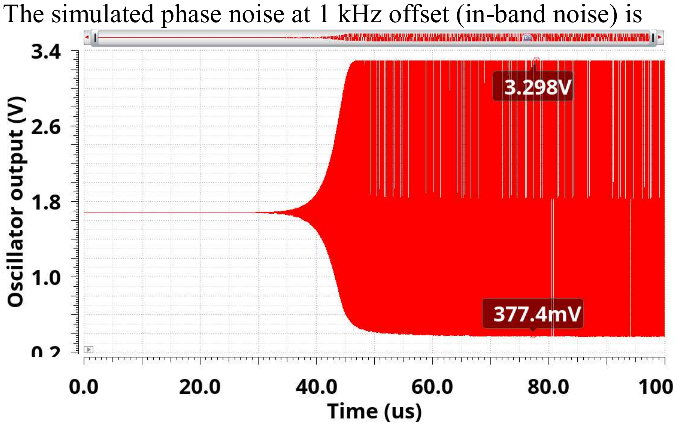

Fig. 5. The simulated oscillation start-up process when connecting the TIA and the resonator to form a closed-loop oscillator.

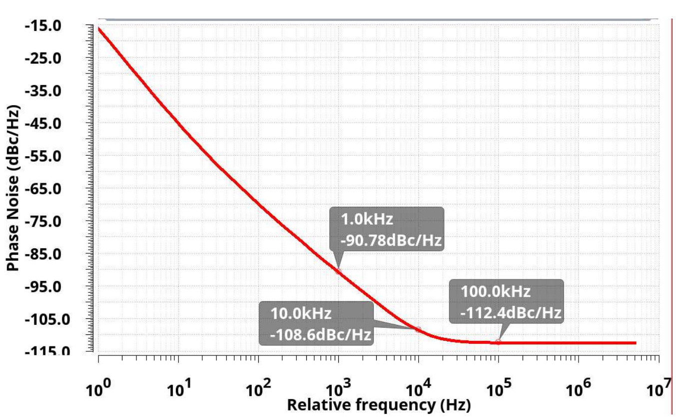

Fig. 6. The simulated phase noise of the proposed MEMS oscillator.

TABLE II. SIMULATED RESULTS OF THE PROPOSED TIA AND THE COMPARISON WITH OTHER SIMILAR WORKS

References	Gain, dBΩ	Bandwidth, MHz	Power, mW
[6][a]	99	280	1.5
[7]	76	2500	7.2
[8]	80	214	1.4
[9]	138	1.2	0.15
[10]	100	110	8
[11]	102	190	37
[12]	86	281	200
This work[a]	131	146	15

a. Simulation results

-90.78 dBc/Hz, and the one at 100 kHz offset (out-band noise, also noise floor) is -112.4 dBc/Hz. The summary of the TIA performance and the comparison with other related works are shown in Table II. We can see the proposed TIA simultaneously achieves higher gain and larger bandwidth. The presented TIA meets the driving requirement of the MEMS beam resonator.

IV. CONCLUSIONS

This paper proposes a 131 dBΩ 146 MHz transimpedance amplifier implemented in the 0.35 µm CMOS process for the 20 MHz MEMS beam resonator. High-gain and large bandwidth can be simultaneously achieved by using a common-gate amplifier with a self-biased inverter and an inverted-based Cherry-Hooper amplifier with an stable bias scheme. The presented TIA works well with the MEMS resonator, and oscillation builds up within 50 µs with a swing of 2.9 Vp-p. The simulated phase noise at 1 kHz offset is -90.78 dBc/Hz, and the one at 100 kHz offset is -112.4 dBc/Hz. The subsequent research will focus on the driving circuit of V/UHF resonators. This technology provides a design reference for other applications that require an ultrahigh gain wideband transimpedance amplifier.

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