Transimpedance Amplifier for MEMS SAW Oscillator in 1.4GHz

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Abstract. This work is to design a transimpedance amplifier for MEMS SAW resonator to achieve low power consumption at desired frequency. A transimpedance amplifier is designed and characterized for MEMS SAW resonator in 0.18μm CMOS process. The transimpedance amplifier achieves gain is 31 dBΩ at 176°.The power consume by oscillator is 0.6mW at V_{DD} 1.8V while phase noise at -133.97dB$_c$/Hz at 10kHz.

1. Introduction

Oscillator is a key component in electronic circuit. They provide "heartbeat" to circuit in processor, digital-to-analog converter, analog-to-digital converter, memory function, communication ports and many others function. Many types of oscillator are available in electronic industrial, such as quartz oscillator, LC Oscillator, RC oscillator and MEMS oscillator. Commonly used is crystal oscillator since it provides higher stability. Although crystal oscillator can provide clean and stable signal, unfortunately it cannot be fabricate in system on chip since quartz crystal resonator has to be fabricate on piezoelectric substrates instead of silicon substrate.

The demand of technology today required miniaturized sizes, low power consume, reliability, system on chip and low cost during fabrication and CMOS-MEMS oscillator offer entire requirement. Previous work indicates that dealing with passive components, extra sources at bias circuit and sizing the transistor are challenging. External sources give a circuit not fully integrated since it has more than one voltage sources. Transimpedance amplifier proposed in this work consists of minimum passive component, single source at higher frequency and low power dissipation. Passives component are reduce and circuit design used only single source, V_{DD} to power up the CMOS MEMS oscillator.

2. Literature Review

2.1. SAW Resonator

Vibrating mechanical tank components, such as crystal and surface acoustic wave (SAW) resonators, are widely used for frequency selection in communication sub-systems because of their high quality factor (Q's in the tens of thousands) and exceptional stability against thermal variations and aging[1]. MEMs SAW resonator was chosen in this work due to following fact that it can provide system integration capabilities, high precision fabrication, low cost and suitable for high volumes[2]. Besides, it also can provide fully integrated oscillator in electronic application.
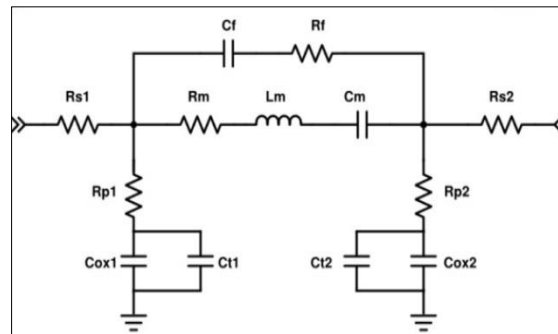
Figure 1. SAW resonator circuit.

Figure 1 shows equivalent circuit model of two port of SAW resonator. It develops by RLC circuit. It consists of resistor, capacitance and inductor in circuit.

Table 1. Parameter in SAW Resonator.

Parameter	Value	Unit
Rm	512	Ω
Lm	2.13	µH
Cm	6.0	fF
Rf	91.8	Ω
Cf	295.8	fF
Rs1	493	Ω
Rs2	412	Ω
Rp1	22.1	Ω
Rp2	19.4	Ω
Cox1+Ct1	0.2365	pF
Cox2+Ct2	0.2725	pF

Table I shows summarize parameter for SAW Resonator. Figure 2 show the S_{21} simulation for SAW resonator with insertion loss is -26.56dB of frequency response 1.396GHz.
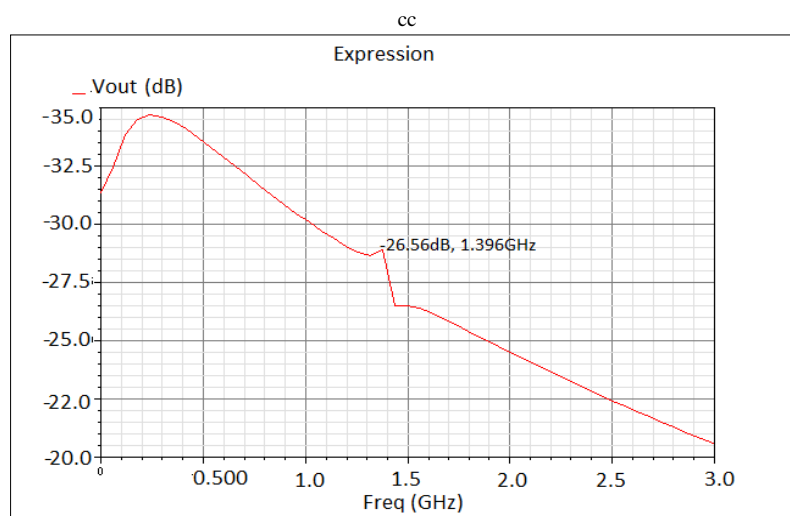

Figure 2. Transmission characteristic SAW Resonator.

3. TIA Amplifier

This work indicates on designing transimpedance amplifier for an oscillator. Transimpedance amplifier was selected to keep low current with sufficient gain-bandwidth in feedback compensation. This simulation performed in Cadence Tools 0.18µm CMOS technology.

There are two major step required in design process. Firstly, conception of design ,and secondly optimization of design[3]. To have accurate parameter during sizing the transistor, g_m/I_D methodology was chosen. g_m/I_D methodology strongly related to performance of analog circuit, give an indication point of device operating region and provide tools for calculating transistor dimension.

$$\frac{gm}{I_D} = \frac{1}{I_D}\frac{\partial I_D}{\partial V_{GS}} = \frac{\partial I_D}{\partial V_{GS}}\log(I_D) \qquad (1)$$

Equation 1 shows derivation at maximum weak inversion region. The transconductance efficiency, g_m/I_D decreases when the operating points move toward strong inversion region. To have low power consume in oscillator, the transconductance efficiency in oscillator should be higher.

$$\text{Tranconductance efficiency} = \frac{g_m}{I_D} \qquad (2)$$

Design specification
- Bandwidth >3GHz
- Amplifier gain <32dB
- Power consume by oscillator <1mW
- L=0.18µm

Since the design circuit is to achieve high frequency amplifier, the minimum length of transistor is selected and all transistor working in minimum current in saturation region
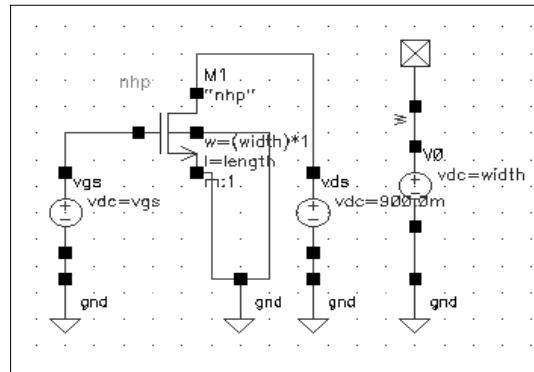

Figure 3. Simulation of NMOS transistor.

Figure 3 shows NMOS transistor circuit. The purpose of this simulation is to obtain characteristic of the transistor. Characterization can be made by plotting curves for NMOS and PMOS transistor based on our requirement.

- g_m/I_D vs V_{OV}
- I_D(W/L) versus g_m/I_D
- F_t vs g_m/I_D

Low current mean higher transconductance efficiency required.   In order to have higher transconductance efficiency, transistor must be biased in lower overdrive voltages, V_{OV}. g_m/I_D is

obtained by using V_{OV}. Then, the width (W) of the mosfet is determined by using the following formula:

$$\frac{I_D}{\left(\frac{W}{L}\right)} = \frac{I_D\, design\, spec}{\left(\frac{Wactual}{L}\right)} \tag{3}$$

Table II show parameter of transimpedance amplifier and the value was obtained from simulation in cadence.

Table II. Parameter Transimpedance Amplifier.

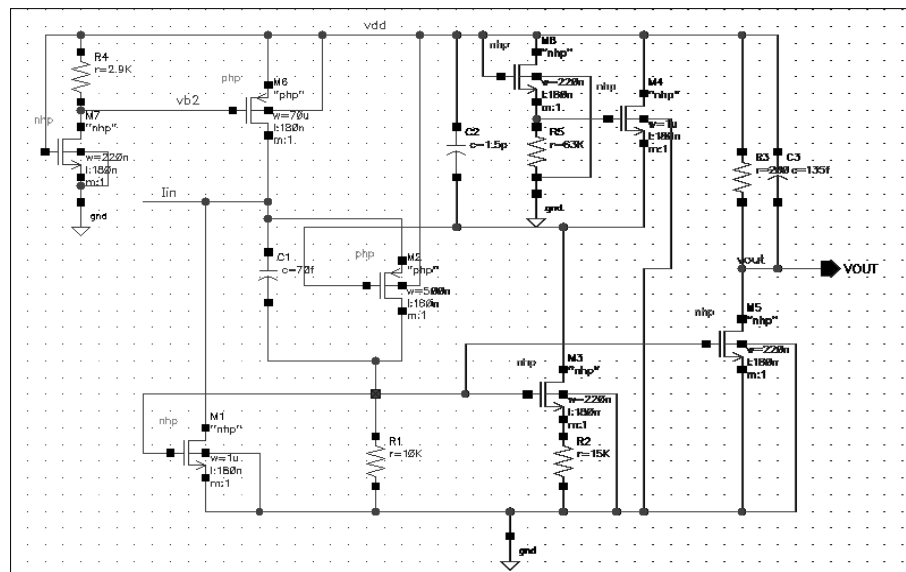| Parameter	g_m/I_D	0.18μm Cadence	
		Value	Unit
R_1	-	500	Ω
R_2	-	10	kΩ
R_3	-	2	kΩ
R_4	-	2.9	kΩ
R_5	-	63	kΩ
W_1/L_1	6.304	1.0/ 0.18	μm/μm
W_2/L_2	1.064	0.5/ 0.18	μm/μm
W_3/L_3	8.704	0.5/ 0.18	μm/μm
W_4/L_4	6.034	1.0/ 0.18	μm/μm
W_5/L_5	12.91	0.22/ 0.18	μm/μm
W_6/L_6	13.37	70.0 /0.18	μm/μm
W_7/L_7	0.965	0.22/0.18	μm/μm
W_8/L_8	6.137	0.22 /0.18	μm/μm
C_1	-	70	fF
C_2	-	1.5	pF
C_3	-	135	fF

Figure 4. Transimpedance amplifier schematic.

Figure 4 shows detail schematic at the designed TIA. Three circuit has been divided into three main block: an input stage, a positive feedback loop, and the final output[4].   The input stages consist of resistor R_1 and transistor M_1 and M_2[4]. Transistor M7 and R4 provide sufficient current to M6 to 'turn on' input stage while M8 and R5 is used to give sufficient current to positive feedback loop. C_1 has be added to the circuit and implements at feedforward compensation to enlarges bandwidth to more than 2GHz. At high frequencies, above singularities introduced by C_1 the feedback loop is closed by capacitance;M1 works in triode configuration and TIA functionality is preserved[5].

This circuit biasing current at very low to keep power consume less than 1mW and all the MOSFET in strong inversion region. Strong inversion region give maximize cut off frequency and give extra advantages for TIA working at high frequency application. The transconductance of transistor in circuit design cannot be increase to keep minimize power dissipated in oscillator. Only one source was used in the design to obtain fully integrated circuit. Besides, second stage is added to keep low input impedance. Second stage which is positive feedback amplifier is chosen to ensure stability in circuit [4]. Without this part, the gate of M_2 were fixed, the input voltage will rise when the input current rises[4].

Fig.5 show transimpedance gain of transimpedance amplifier in 31.3dB with phase shift 176°. The bandwidth of this amplifier extends to 16.531GHz.
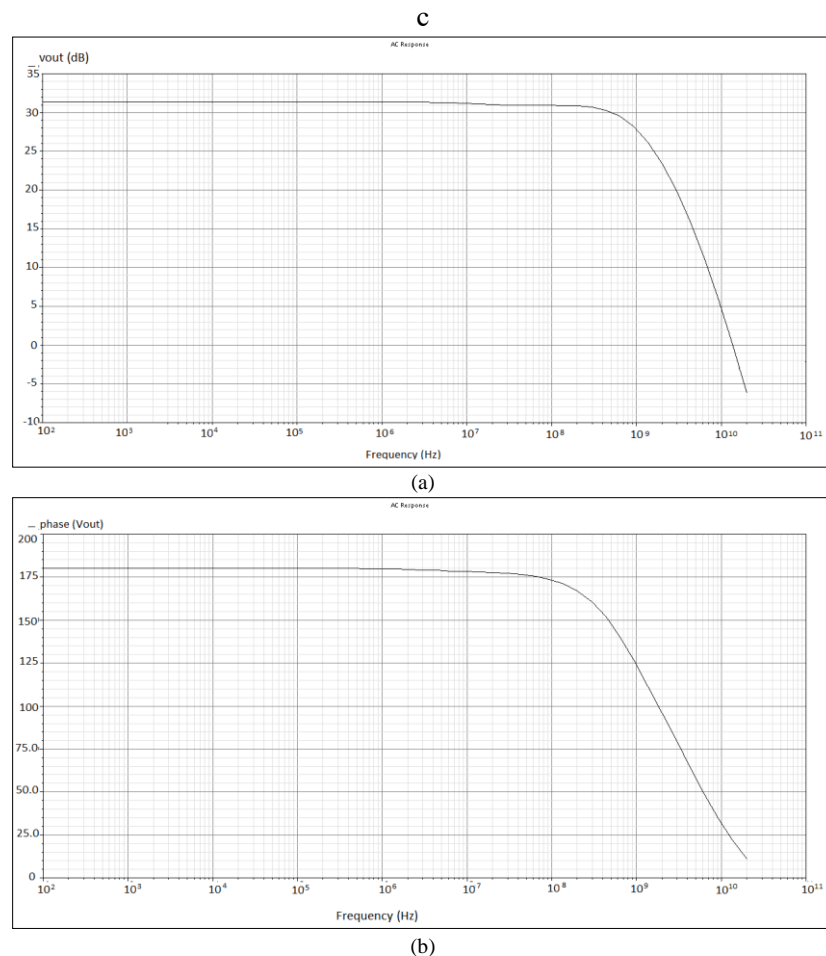

(a)

(b)

Fig 5. Open loop response of transimpedance amplifier. a) Gain plot
b) Phase plot.

4. Simulation Results and Discussion

The simulation of TIA circuit connected with MEMS SAW resonator has been conducted. The bandwidth of transimpedance amplifier extends to 16.531GHz with 31dB gain and phase shift 176°. The gain obtained is able to overcome losses of the resonator. Meanwhile in Figure 6 shows transient analysis of CMOS MEMS oscillator. The oscillation produced after close loop gain at 1.396GHz. The oscillator achieved phase noise at -133.97dB$_c$/Hz of 10kHz in Figure 7. The power consume by oscillator calculate by using equation 3. The power consume by oscillator is 0.6mW.

$$P_{consume} = V_{DD} \times I_D$$
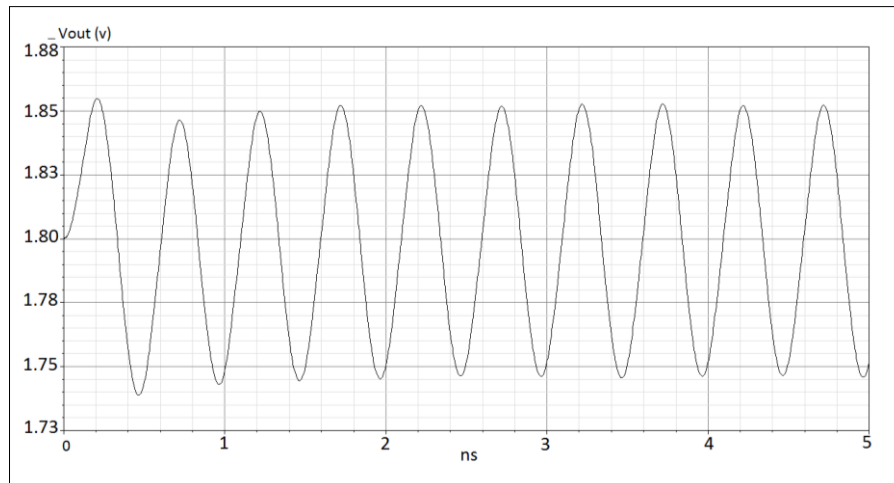$$P_{consume} = 1.8 \times 328.1021\mu$$
$$= 0.6mW$$

(4)

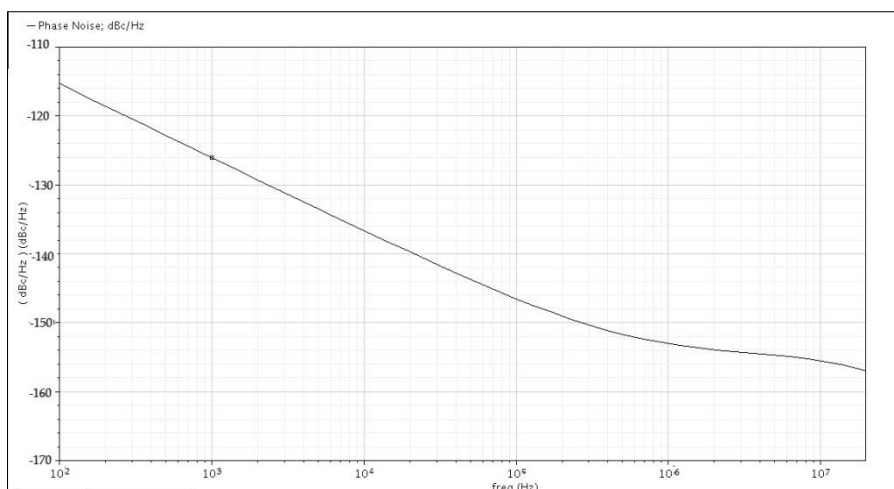Figure 6. Close loop feedback simulation of transimpedance amplifier with SAW resonator.

Figure 7. Simulated phase noise of transimpedance amplifier with SAW resonator.

Table 3. Design performance comparison.

Ref.	Year	Tech. (µm)	Power Consume, (W)	Gain (dB)	Phase Noise	F_t (Hz)
[6]	2011	0.18	7.2m	76	-122dB$_c$/Hz at 10kHz	1.006G
[7]	2012	0.18	1.57m	99	-128dB$_c$/Hz at 1KHz	48M
[5]	2015	0.18	6.4m	120	-102 dB/Hz at 10kHz	17.22M
[8]	2016	0.18	6.24m	122	-97dB/Hz at 10kHz	17.22M
This work		0.18	0.6m	31	-133.97dB$_c$/Hz at 10kHz -124.3dB$_c$/Hz at 1kHz	1.396G

Table 3 demonstrate comparison between previous works and propose design. CMOS MEMS oscillator in this work show lowest power consumes resultant low gain in amplifier. Although it has lowest gain compare to previous work, the frequency response provide by TIA at highest frequency. Therefore, it give an advantages for proposed design to operate at higher frequency with low power consume.

5. Conclusion

The objective of this work is to obtain low power consume for sustaining circuit in oscillator. The transimpedance amplifier was selected as a sustaining circuit for CMOS-MEMS oscillator since it can provide low power consume with desired frequency and gain. The oscillator consumes 0.6mW of frequency response 1.39GHz at phase noise -133.97dB$_c$/Hz at 10kHz. Further improvement is needed for the next work by reducing passive component and transistor in circuit design. Besides, obtain more sustaining amplifier also required to variety application among oscillator.

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