A solution to high frequency oscillation in the driving loop of silicon microgyroscope

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Abstract. Parasitic capacitances are unavoidable in silicon microgyroscope because of the limitation of MEMS technology and packaging. Due to the existence of parasitic capacitance between the driving electrodes and driving detection electrodes in the gyroscope, another possible oscillation loop is formed, which leads to unwanted high frequency oscillation in the driving loop. In order to solve the problem caused by the parasitic capacitances, a new type of interface circuit based on two-stage integrators is presented in this paper. Firstly, a theoretical analysis model of the proposed circuit is established, then it was simulated in Cadence/PSPice with the established electrical equivalent model of the driving module. Experimental results indicate that the proposed interface circuit can effectively eliminate high frequency oscillation in the drive loop, and it has an equivalent input current noise of 24.7fA/√Hz, corresponding to a capacitance resolution of 0.061aF/√Hz.

Keywords: silicon microgyroscope; driving loop; oscillation; interface.

1 Introduction

Silicon microgyroscope is a typical MEMS device, which has a well application prospect and has promise to completely replace the quartz gyroscope in current market in the middle and lower end applications. Silicon microgyroscope has the advantages of small volume, low power consumption, high reliability, bulk production, etc [1]. Capacitance detection operation mode is commonly adopted by silicon microgyroscope, the actual detected capacitance change is in the range of 10^{-18}~10^{-15}F, so high performance interface circuits are required.

At present, there are a lot of research on the interface circuit, such as trans-impedance amplifier (TIA) [2], charge sensitive amplifier (CSA) [3], switched capacitor charge integration circuit [2,3] and so on. The TIA topology consists of a voltage amplifier and a feedback resistor sets the gain, when larger than MΩ feedback resistor is adopted, TIA's bandwidth is sensitive to compensation capacitor, so that its phase shift error is usually large and the gain bandwidth product is limited. The CSA topology use a capacitance as feedback to set the gain, while it need additional phase shifter to ensure the phase conditions required for close-loop oscillation. Switched capacitor amplifier is convenient to realize in integrated circuit technology, but its noise floor is usually high, because of inevitable noise folding. By using the correlated double sampling technique and chopper stabilization technique [4], the 1/f noise can be reduced, but the white noise performance can't be improved.

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At present, there is few articles focus on problem caused by parasitic capacitance in the driving loop. Giacomo Langfelder published an article introduced that there are two resonant points in the driving loop of silicon resonant accelerometer arisen from parasitic capacitance[5]. In the actual test we found that there are also two resonant points in silicon microgyroscope with TIA interface circuit. Through analysis, we find that the second resonant point at high frequency is motivated by the parasitic capacitance between driving electrode and driving detection electrode in the gyroscope. Because the silicon microgyroscope is small in size, the parasitic capacitance is obvious, so the problem is widespread.

With the electrical model of the driving loop of silicon microgyroscope [6], the conventional interface circuits introduced above are simulated in Cadence/PSPice. Results show that none of them can solve the problem of high frequency resonant. This paper presents a new type of interface circuit based on two-stage integrators, which can suppress the high frequency gain. Test results show that the problem of high frequency oscillation is solved by adopting the proposed interface circuit, without the penalty of extra phase shift and noise.

2 Silicon microgyroscope and its measurement and control circuit

2.1 Schematic and structure of silicon microgyroscope

In this paper, we focus on z-axis tuning fork gyroscope based on Coriolis effect. Figure 1 gives the schematic and SEM of the silicon microgyroscope, it consists of two proof masses supported by a suspension structure [7]. AC drive signal with DC bias are applied to the drive elements, then the electrostatic force drives the proof masses antiparallel in the drive axis (x-axis).When the device is rotated about the out-of-plane z-axis, the Coriolis acceleration will deflects the proof masses in the sense axis (y-axis) by an amount proportional to the product of the input rotational rate and the drive velocity. Differential proof mass motion induces differential capacitance change in sense elements, which is detected by the readout circuit.

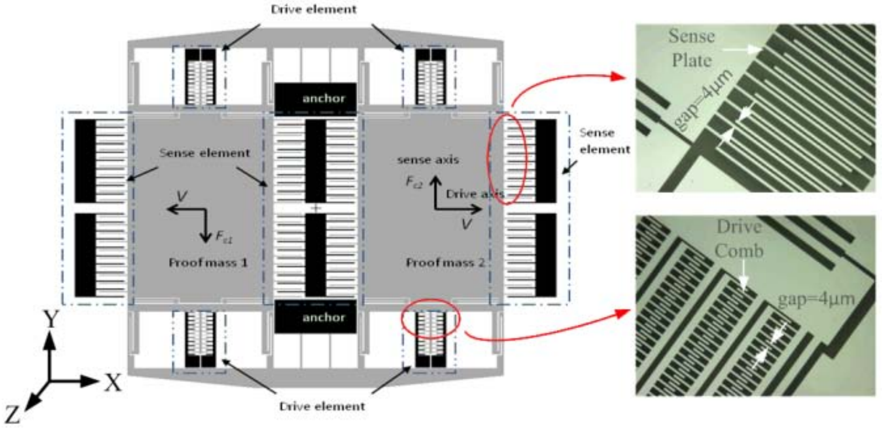

Figure 1. Schematic and SEM of the silicon microgyroscope

2.2 Driving circuit

The measurement and control circuit of gyroscope mainly comprises a closed loop drive module and an open loop detection module. In this paper, we mainly study the interface circuit in the drive module. The driving loop adopts the way of self excitation oscillation, using the frequency-selection characteristic of high quality factor gyroscope to make the gyroscope operate in its driving mode. Figure 2 is the block diagram of driving loop of silicon microgyroscope. When the circuit is powered on, the noise is constantly amplified until the amplitude and phase meet the oscillation condition, then it can realize self excitation oscillation. An automatic gain control(AGC) module is adopted to make the amplitude of driving detection voltage V_{ds} constant and then the gyroscope can work steadily.

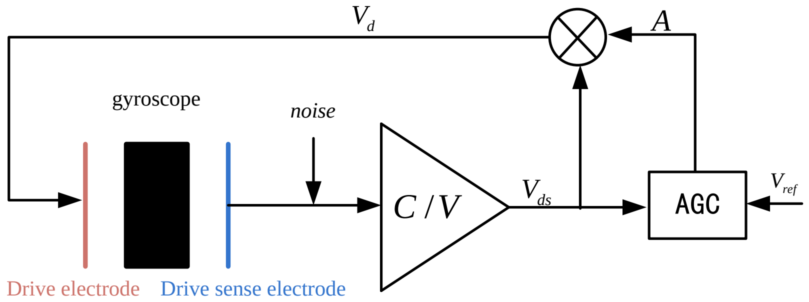

Figure 2. Block diagram of driving loop of silicon microgyroscope

For the C/V conversion section, Comb capacitance structure is used both in the drive elements and the drive detection elements, whose nominal capacitance is $C = N\varepsilon\frac{bx}{d}$. The variation of drive displacement x produces the current in the drive detection electrode due to the change of capacitance, and the current i can be written as:

$$i = \frac{dQ}{dt} = V_{dc}\frac{dC}{dt} = V_{dc}\frac{dC}{dx}\frac{dx}{dt} = V_{dc}N\varepsilon\frac{b}{d}\frac{dx}{dt} \quad (1)$$

where V_{dc} is the DC bias of drive signal, N is the number of driving detection comb, ε is the dielectric constant, b is the width of the comb, d is the gap between two combs, x is the displacement of proof mass.

According to (1), we can find that the detection of capacitance can eventually be converted to the detection of the current, which can be easily detected by interface circuit.

3 Analysis of high frequency oscillation

3.1 Problem description

In the test process of silicon micro gyroscope, it is found that there is a high frequency oscillation which is caused by the parasitic capacitance between the driving electrode and the driving detection electrode.

As shown in the Figure 3. Ideally, there is only one oscillation-loop in the driving system, only the gyroscope's drive mode is motivated. But due to the existence of parasitic capacitance C_p, there is another oscillation-loop in the driving circuit. Current I_p is directly generated by the driving voltage V_d through the parasitic capacitance C_p. There is a certain frequency outside the bandwidth of interface circuit, at which the self excited oscillation conditions are met, then the high frequency oscillation will be generated.

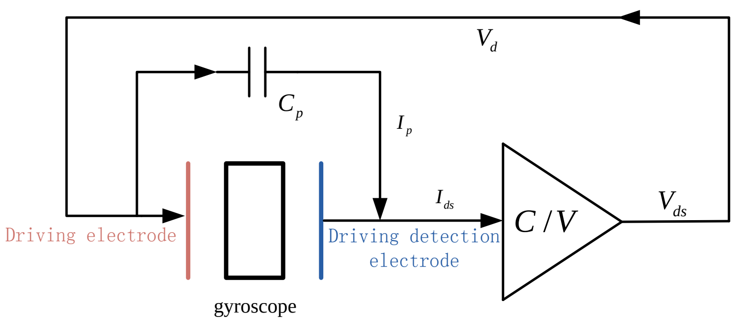

Figure 3. Schematic diagram of driving loop with parasitic capacitance

Using TekMDO3014 oscilloscope to observe the phenomenon of high frequency oscillation, Figure 4 is the oscilloscope screenshot. As shown in the figure, there are two resonant frequencies. One is the driving mode of gyroscope (6kHz) and the other is the high frequency oscillation.

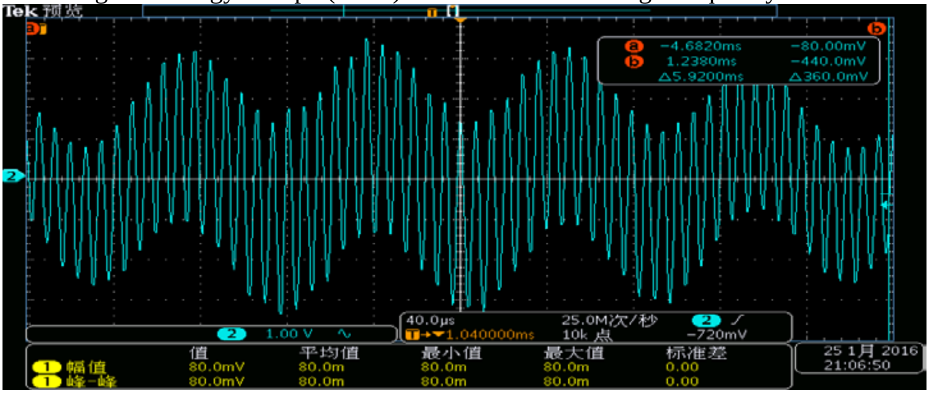

Figure 4. High frequency oscillation observed by oscilloscope

3.2 Theoretical analysis

Taking the parasitic capacitance C_p in Figure 3 into account, the transfer function of the driving voltage V_d to the drive detection current Ids can be written as:

$$\frac{I_{ds}(s)}{V_d(s)} = k\frac{s}{\frac{s^2}{\omega_x^2}+\frac{s}{Q\omega_x}+1}+C_p s \tag{2}$$

where Q is the quality factor, ω_x is the natural frequency of driving mode, k is a constant gain term.

According to the test, C_p is generally on the order of pF, so the detection current generated through C_p can be ignored at low frequency. While the parasitic current increases with the growth of frequency. If the loop gain at high frequency is still greater than 1, then the high frequency oscillation is generated at a frequency where the phase condition is satisfied. We do the simulation in Cadence/PSPice, using TIA as the interface circuit. In the simulation result shown in the Figure 7, we can see the frequency described above is about 30kHz.

Because the silicon microgyroscope is small in size, the parasitic effect is obvious, therefore the interface circuit should be carefully designed to suppress the loop gain at high frequency, avoiding the occurrence of high frequency oscillation.

4 Interface circuit based on two-stage integrators

In this paper we propose a new type of interface circuit based on two-stage integrators to solve the problem of high frequency oscillation. The circuit is shown in Figure 5, its transfer function can be written as :

$$\frac{v_o}{i_s} = A_1A_2A_3 = (-\frac{R_1}{C_1R_1s+1}) \times \frac{\left(\frac{R_2R_4}{R_2+R_4}\right)C_2s}{\left(\frac{R_2R_4}{R_2+R_4}\right)C_2s+1} \times (-\frac{R_3}{R_4\left(C_3R_3s+1\right)}) \tag{3}$$

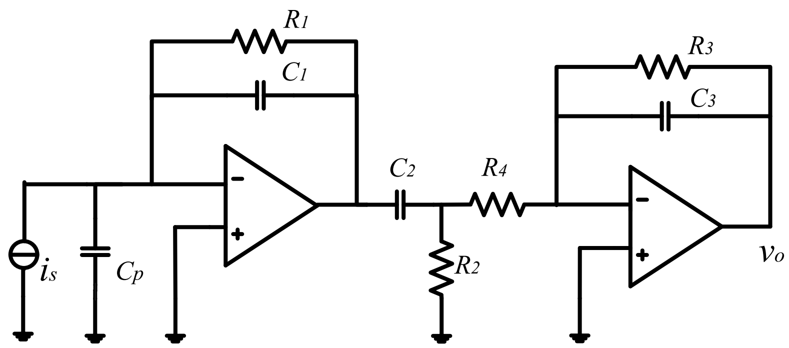

Figure 5. Schematic of two-stage integrator circuit

A_1, A_2, A_3 are the gain of first-stage integrater, passive high pass RC filter, second-stage integrater respectively. The first-stage integrater has the same topology with TIA interface circuit, while the role of resistance and capacitance is different. The gain is generated by resistance and capacitance is used as a compensation for amplifier in the TIA topology, and the phase difference between output voltage and input current is 180 degrees. In this circuit, the gain of first stage is generated by C_1 and R_1 is used to offer DC feedback for amplifier in the first-stage integrater, and Phase difference between output voltage and input current is 90 degrees. Since the capacitor is used as feedback, the input stray capacitance Cp will not cause the stability problem in first stage.

In order to guarantee the self excitation oscillation conditions of the driving loop, the interface circuit should provide a gain larger than 20MΩ near the working frequency, meanwhile the cut-off frequency should be low enough to ensure the 90 degrees phase shift, therefore R_1, C_1 shall meet the following formulas:

$$\frac{1}{2\pi C_1 f} = 20M\Big|_{f=6k} \tag{4}$$

$$\frac{1}{2\pi R_1C_1} < \frac{f}{10}\Big|_{f=6k} \tag{5}$$

The resistance calculated by the above formula is generally quite large, whose magnitude is GΩ order. The low frequency noise of the first stage amplifier would be amplified by R_1. In order to filter noise and avoid phase shift, a passive high pass RC filter is used between the two integrators. Making R_2 and C_2 meet the following formula:

$$200 < \frac{1}{2\pi\left(\frac{R_2R_4}{R_2+R_4}\right)C_2} < \frac{f}{10}\Big|_{f=6k} \tag{6}$$

The same parameters as the first-stage integrator are used for second-stage integrator, the loop gain at high frequency can be further suppressed, and 90 degrees phase shift is provided for the circuit to meet the phase conditions of the self excitation oscillation.

According to the above relationship, and combined with PSPice simulation, the final determinations of parameters are shown in Tab.1.

Table 1. Parameters of the circuit

parameter	value	parameter	value
R_1	$5G\Omega$	C_1	$1pF$
R_2	$2M\Omega$	C_2	$2.7nF$
R_3	$5G\Omega$	C_3	$1pF$
R_4	$20M\Omega$		

Compared with the TIA interface circuit, the newly designed circuit mainly consists of the following advantages:

1) The circuit is not sensitive to the input stray capacitance of amplifier, then larger bandwidth and smaller phase error could be achieved.

2) The gain at high frequency is suppressed, and the high frequency oscillation caused by the parasitic capacitance between the driving electrode and the driving detection electrode is avoided.

3) The equivalent input current noise is lower, since current noise of feedback resistors could be ignored when larger than GΩ is adopted, and feedback capacitances are noise free components.

5 Simulation and test

5.1 Noise test

The noise performance of the proposed circuit is evaluated firstly, and is compared with TIA topology. Ni 6366 data acquisition card is used to collect the drive loop output signal Vds at a sampling rate of 300kHz with10s sample time. The noise power spectrum of the collected data is analyzed and is compared with the PSPice simulation results, as shown in Figure 6:

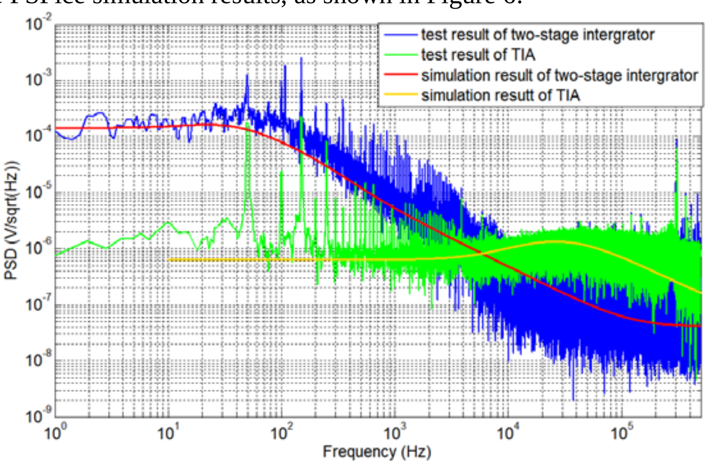

Figure 6. Output voltage noise power spectrum and PSPice software simulation results

The simulation results are measured in PSPice, and the performances are compared in the following Tab.2

Table 2. Circuit performance comparison

	Equivalent input current noise (fA/√Hz)	Capacitance resolution (aF/√Hz)
TIA	37.7	0.094
Two-stage integrators	24.7	0.061

5.2 Test of loop response

In accordance with the designed parameters, the improved circuit board with gyroscope was tested, the open loop Bode diagram is drawed using analog discovery development kit network analyzer function, and it's compared with simulation results in Figure 7.

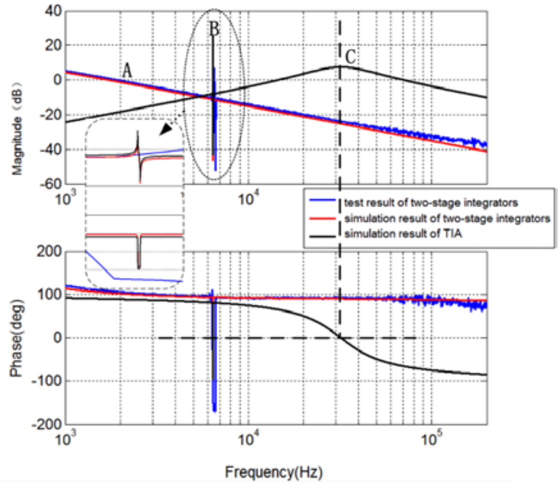

Figure 7. Open loop Bode diagram of driving closed-loop

We focus on the A B C three points in the figure. At point A, the loop gain is above 0dB and its phase is 100 degrees, that is, the phase margin of about 100 degrees; The B point is the gyroscope working frequency, its gain is more than 0dB and the convex is sharp, the phase is 0 degrees, which satisfies the condition of self excitation oscillation and the design of high Q factor; At point C, the loop gain using TIA is above 0dB and the phase is 0 degrees, so self excitation oscillation is generated,casusing the drive circuit does not work. While the gain of the newly designed circuit is suppressed and the phase doesn't meet self excitation oscillation conditions. It can be concluded that the newly designed circuit effectively solves the problem of high frequency oscillation in driving closed-loop.

6 Conclusion

In this paper,we proposed a novel interface circuit based on two-stage integrators to solve the high frequency oscillation in the driving loop which is motivated by the parasitic capacitance between the driving electrodes and driving detection electrodes in the gyroscope.Tested and found that the gain of high frequency is effectively suppressed and the problem of high frequency oscillation is solved. At the same time, the noise performance of the interface circuit is improved too. Its equivalent input current noise is 24.7fA/√Hz, corresponding capacitance resolution is 0.061aF/√Hz. Compared to the previous 0.094aF/ √Hz, the accuracy of interface circuit is improved by 35%.

References

1. LI J M. *Design of capacitive MEMS gyroscope* (National Defence Industry Press,2006)
2. Sun H, Jia K, Liu X, et al. Sensors Journal IEEE, **11(11)**:2740-2748(2011)
3. Fang R, Lu W, Liu C, et al. Solid-State and Integrated Circuit Technology (ICSICT), 2010:1456-1458.(2010)
4. Enz C C, Temes G C. Proceedings of the IEEE, **84(11)**:1584-1614.(1996)
5. Langfelder G, Caspani A, Tocchio A. IEEE Transactions on Industrial Electronics, **61(1)**:567 - 574.(2014)
6. *Modeling of silicon microgyroscope interface distributed parameter and designing of measurement and control circuit.* Graduate Nanjing University of Science and Technology,(2015)(in Chinese)
7. JIA F X, QIU A P, SHI Q, et al. Opt. Precision Eng.**21(5)**:1272-1281.(2013) (in Chinese)