LETTER
IEICE Electronics Express, Vol.13, No.19, 1–6

# A quartz vibrating gyroscope interface circuit driven by sine-wave based on nonlinear multiplier

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**Abstract:** A new simple interface circuit for quartz vibrating gyroscope (QVG) driven by sine-wave is presented in this paper. The interface circuit is composed of self-excited loop of driving circuit and detecting circuit. A new multiplier is designed to achieve the controlling to drive signal. The usage of new multiplier realizes the nonlinear adjustment to the amplitude of feedback drive signal. Consequently, the requirement of rapid oscillation, low harmonic and high stability is also achieved. The interface circuit is fabricated in a 0.5 µm CMOS process and the test results show that the start time of drive signal is less than 2 ms. The drive signal frequency stability can reach to 0.084% (1-sigma) and the harmonic distortion is about 1.056%. The output noise of Quartz Vibrating Gyroscope is $0.00023°/s/\sqrt{Hz}$ at 3 Hz and nonlinearity is about 107 ppm. The bandwidth is more than 60 Hz. Meanwhile, the short stability (1-sigma) is 2.1°/hr, the angular random walk (ARW) and bias drift are $0.01388°/\sqrt{hr}$ and 0.16°/hr respectively.

**Keywords:** quartz vibrating gyroscope, interface circuit, multiplier, high performance

**Classification:** Integrated circuits

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DOI: 10.1587/elex.13.20160565
Received June 7, 2016
Accepted August 25, 2016
Publicized September 9, 2016
Copyedited October 10, 2016

IEICE Electronics Express, Vol.13, No.19, 1–6

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## 1 Introduction

Quartz vibrating gyroscopes are acknowledged inertial sensors that have been used in various civil and military applications due to the low power consumption, batch fabrication, adequate stability and reliability. Also it is favored by automobile industry, medication and electronics owing to its low costs in mass production [1, 2]. These characteristics have attracted many leading corporations in areas of navigation guided weapons and exploration throughout the world, such as BEI, ADI, ROCKWELL, Nihon Dempa Kogyo and Atlantic Inertial Systems [3, 4, 5, 6, 7]. The quartz element consists of three parts: a driving fork, a detection fork and a sporting beam. The driving fork is driven by driving signal to vibrate in simple harmonic state which is generated by piezoelectric effect of quartz crystal. When there is an angular rate along the driving fork presents a vibration as a result of Coriolis force. The vibration is at the frequency of drive signal and its magnitude is proportional to the input angular rate. The vibration can be transferred to the detection fork by mechanical coupling. There are charges on the electrode produced by anti-piezoelectric effect which are then collected by the detection fork. The input angular rate can be detected by this process [8].

## 2 Proposed architecture of interface circuit

Most interface circuit of quartz vibrating gyroscopes is driven by square-wave. However, the phase noise which is caused by current injection in drive signal will greatly reduce the stability of quartz vibrating gyroscope. From the linearity time varying model of oscillator phase noise proposed by Ali Hajimiri [9], the phase noise of square-wave drive signal caused by the harmonics of drive signal and the component nearby $\Delta\omega$ to the harmonics frequency can be expressed as:

$$\varphi(t) = \frac{I_n c_n \sin\Delta\omega t}{C_d V_{d0} \Delta\omega} + \frac{I_n c_n \sin(2n\omega_d + \Delta\omega)t}{2C_d V_{d0} \Delta\omega}, \tag{1}$$

Which $I_n$ is the injection current, $C_d$ is the equivalent capacitance of driven state, $V_{d0}$ is the maximum voltage of $C_d$, $c_n$ is the coefficient of the current impact sensitivity function in the driven circuit at driven frequency. The method that is driven by sine-wave which generates lower harmonic is a solution to decrease the influence of phase noise, but the slow oscillation limits the usage of this project. This paper proposes a new interface circuit based on a new model nonlinear multiplier. It ensures the low harmonic as well as the rapid oscillation. Fig. 1 shows the new interface circuit architecture proposed by this research of QVG self-excited drive loop used nonlinear multiplier and detecting circuit. The driven loop is composed of trans-impedance amplifier (E1), peak value detector (E2), PI controller (E3) and nonlinear multiplier (E4). When the circuit is powered on, the output of driving fork is small and the output of E3 which is related to $V_{ref}$ is at


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Received June 7, 2016
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ELectronics EXpress
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negative low voltage. The multiplier operated in nonlinear region this moment. A square-wave drive signal that is controlled by PI and multiplier is generated to maximize driven feedback force. With the amplitude of driving fork output signal increased, the output of driving fork is enlarged and the output of E3 decreased. The multiplier works in linear region, and loop circuit finally reaches to dynamic stability. And the drive signal is sine-wave now. The principle of nonlinear multiplier will be introduced in Part 3.

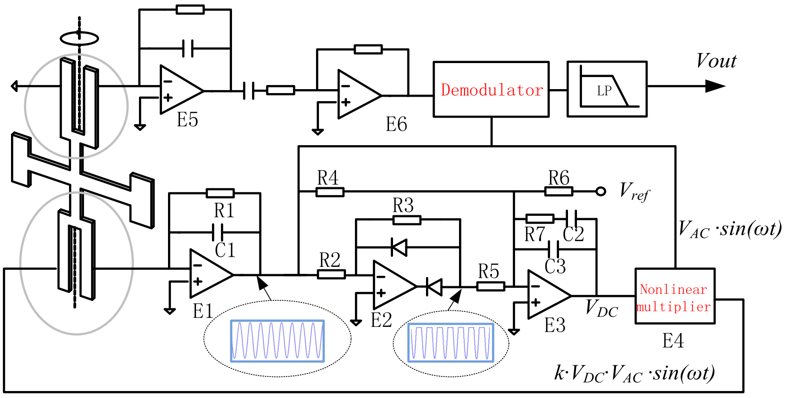


**Fig. 1.** The interface circuit architecture of QVG

The detecting signal flowed from detection fork is sampled and amplified by charge sensing amplifier (E5) and proportion amplifier (E6). Afterwards, the signal is synchronous demodulated by the signal output from driving circuit and filtered by a low pass filter.

## 3 Technology realization

The new multiplier is shown in Fig. 2. 'Control' is settled according to output dc voltage, '$V_{out1}$' is connected to the dc output of PI controller (E3), '$V_{out8}$' is connected to the ac output of trans-impedance amplifier, '$V_{out12}$' is inverted to '$V_{out8}$'. The working stage of it can be described as two states. The first state is nonlinear state, and in this state, '$V_{out1}$' is so large that the branch composed by M2 and M9 can be considered as open circuit. The OPA A1 is operated in the open loop state and the output of multiplier $V_{f-}$ will be saturation.

The output $V_{f-}$ can be expressed as:

$$V_{f-} = AV_{out1-} = AI_{d1}R_5, \tag{2}$$

And $I_{d1}$ can be written as follow:

$$I_{d1} = 1/2g_m(V_{GS8} - V_{TH}), \tag{3}$$

So the output $V_{f-}$ can be rewritten as:

$$V_{f-} = 1/2Ag_m(V_{GS8} - V_{TH}), \tag{4}$$

Which A is the open-loop gain of OPA A1.

The waveform of output $V_{f-}$ is similar to a square-wave. Feedback square-wave drive signal is large enough to achieve the destination of rapid oscillation. With the decrease of '$V_{out1}$', the branch that consists of M2 and M9 will be under conducting state. At this point the multiplier is in the linear state.


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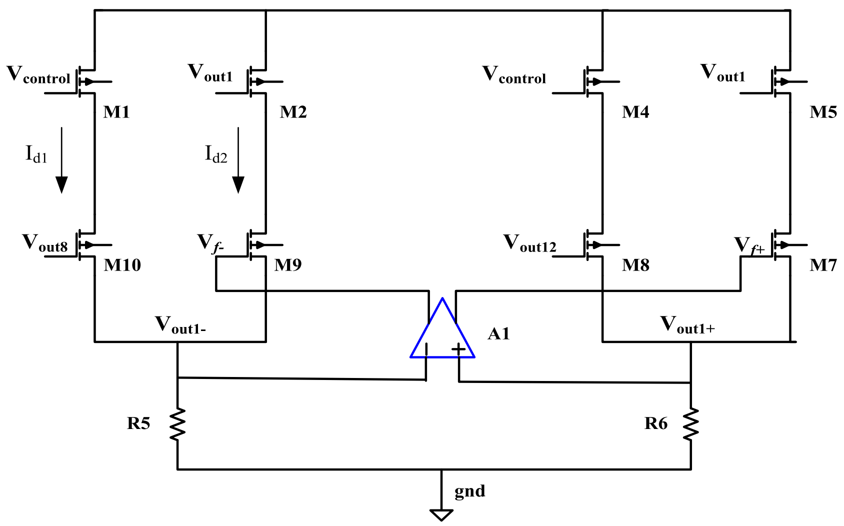


**Fig. 2.** The circuit of new multiplier

The second state that the QVG has been oscillated can be explained as follow: M1 is set to work on the linearity region. The trans-conductance $g_{m10}$ of M10 which can be written as $g_{m10} = B/R$ is related to the resistance of M1, B is the proportionality factor and the resistance of M1 can be written as:

$$R_{M1} = \frac{1}{\mu C_{ox}\frac{W}{L}(V_{GS} - V_{TH})} = \frac{1}{\mu C_{ox}\frac{W}{L}(V_{DD} - V_{control})}, \tag{5}$$

From equation (5), we can find that the resistance of M1 can be expressed by $V_{control}$. So the trans-conductance of M10 $g_{m10}$ can be controlled by $V_{control}$. The W/L of M1, M2 and the W/L of M10, M9 are the same, so $I_{d1}$ is equal to $I_{d2}$. And $I_{d1}$ can be represented as:

$$I_{d1} = V_{out8}g_{m10} \tag{6}$$

$I_{d2}$ can be described as:

$$I_{d2} = V_{f-}g_{m9} \tag{7}$$

From (6) and (7):

$$V_{out8}g_{m10} = V_{f-}g_{m9} \tag{8}$$

Equation (8) can be rewritten as:

$$V_{f-} = \frac{V_{out8}g_{m10}}{g_{m9}} = \frac{V_{out8}B1/R_{m10}}{g_{m9}B1/R_{m9}} \tag{9}$$

Replacing the $R_{m10}$ and $R_{m9}$ in (9) with (5), the $V_{out-}$ is changed to:

$$V_{f-} = \frac{V_{out8}(V_{DD} - V_{out1-} - V_{TH})}{(V_{DD} - V_{control} - V_{TH})} \tag{10}$$

From equation (10), the $V_{f-}$ equals to the product of $V_{out8}$ and $V_{out1}$, and the multiplier is achieved by the circuit. A sine-wave will be observed in the output of multiplier at this state.

Moreover, the right side circuit composed of M4, M5, M7, M8 is symmetrical to the left side circuit composed of M1, M2, M9, M10. Only the input $V_{out12}$ is


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© IEICE 2016
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inverted to the input $V_{out8}$ of the left branch. Because the input is reversed, the coefficient of even order harmonics is reversed too. The even harmonics are further cancelled by making subtraction between $V_{f-}$ and $V_{f+}$. A high linearity and stable oscillation is established in the second state and a sine-waveform will be observed in the output of multiplier that is the subtraction between $V_{f-}$ and $V_{f+}$.

## 4 Experimental results

The chip has been fabricated in a standard 0.5 m two-metal two-poly n-well CMOS process. The chip micrograph of the complete interface IC is shown in Fig. 3(a). The interface combined with the sensor element is powered by ±5 V power supply. The nonlinearity is about 107 ppm as is shown in Fig. 3(b) and the scale factor is 20 mV/°/s. The noise curve is shown in Fig. 3(c), the output noise is 4.7 μV/$\sqrt{\text{Hz}}$ which is about 0.00023°/s/$\sqrt{\text{Hz}}$ at 3 Hz. The bandwidth is more than 60 Hz. Meanwhile, from the Allen Variance stability curve as shown in Fig. 3(d), the angular random walk (ARW) and bias drift are 0.01388°/$\sqrt{\text{hr}}$ and 0.16°/hr respectively. The test result of output waveform from driving fork is shown in Fig. 4. Fig. 4(a) describes the process from the starting of oscillation driven by square-wave to the stable state driven by sine-wave, and the Fig. 4(b) and (c) exhibit the square-wave drive signal in the initial stage and sine-wave drive signal in the stable stage. From Fig. 4, we can observe that the starting time of oscillation can be less than 2 s. The frequency stability can reach to 0.084% and the harmonic distortion is about 1.056%. The comparison of this work with QRS11 and QRS116 produced by BEI which is a world's leading cooperation in the QVG interface circuit filed is listed in Table I. Also comparison with Si gyroscope [10] which is published in 2015 with high performance is listed in Table I too.

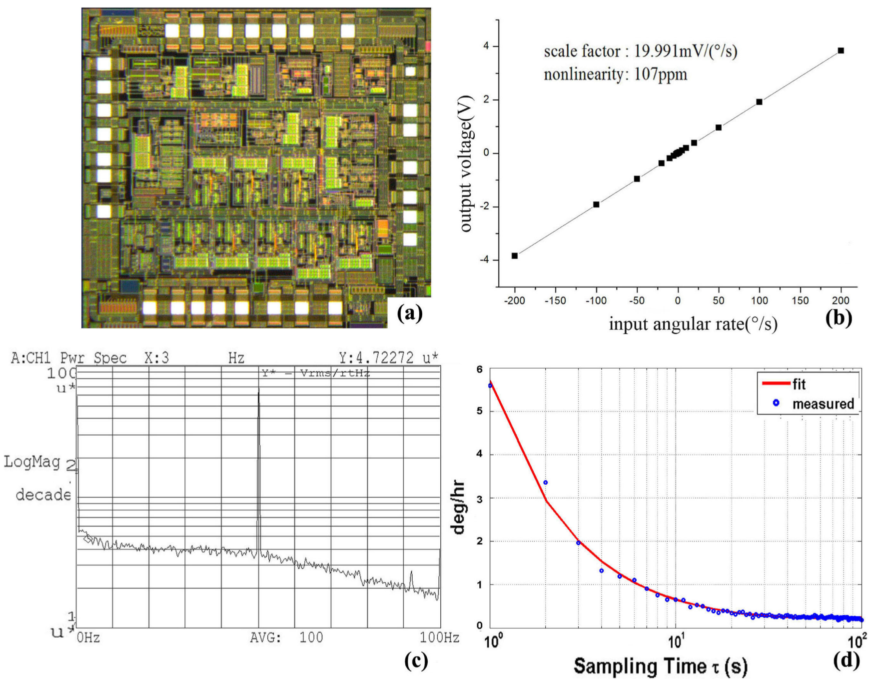


Fig. 3. (a) The chip micrograph of the complete interface IC. (b) The linearity curve of QVR. (c) The output noise curve. (d) The Allen Variance stability curve.

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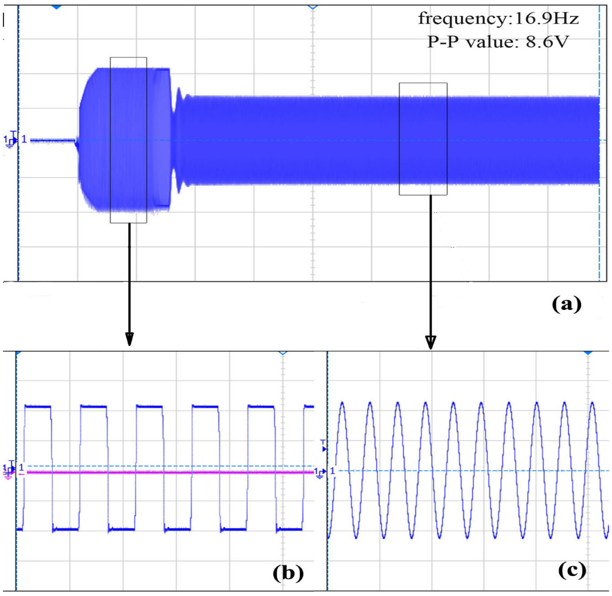


**Fig. 4.** The output waveform from detecting fork

**Table I.** Comparison of the this work with reported sensors

| Parameter | QRS11 | QRS116 | [10] | This work |
|---|---|---|---|---|
| ARW | / | / | 0.067°/$\sqrt{}$hr | 0.01388°/$\sqrt{}$hr |
| Bias Instability | / | / | 0.5°/hr | 0.16°/hr |
| Nonlinearity | 0.05% | 0.05% | / | 0.0107% |
| Short Stability(1-sigma) | 36°/hr | 3°/hr | 4.9°/hr | 2.1°/hr |
| Output noise | ⩽0.01°/s/$\sqrt{}$Hz | ⩽0.002°/s/$\sqrt{}$Hz | / | 0.00023°/s/$\sqrt{}$Hz |

## 5 Conclusions

A new high performance interface circuit which includes a new nonlinear multiplier for QVR is proposed in this paper. The multiplier achieves the nonlinear control to the drive signal and the overall system fulfills the requirement of rapid oscillation, low harmonic and high stability. The test results show the start time of drive signal is less than 2 ms. The drive signal frequency stability can reach to 0.084% (1-sigma) and the harmonic distortion is about 1.056%. The output noise of Quartz Vibrating Gyroscope is 0.00023°/s/$\sqrt{}$Hz at 3 Hz and nonlinearity is about 107 ppm. The bandwidth is more than 60 Hz. Meanwhile, the short stability (1-sigma) is 2.1°/hr, the angular random walk (ARW) and bias drift are 0.01388°/$\sqrt{}$hr and 0.16°/hr respectively.

## Acknowledgments

This work was supported by National Natural Science Foundation of China (Project 61204121), National Hi-Tech Research and Development Program of China (863 Program) (Grant No. 2013AA041107) and the Fundamental Research Funds for the Central Universities (Grant No. HIT.NSRIF.2013040).


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