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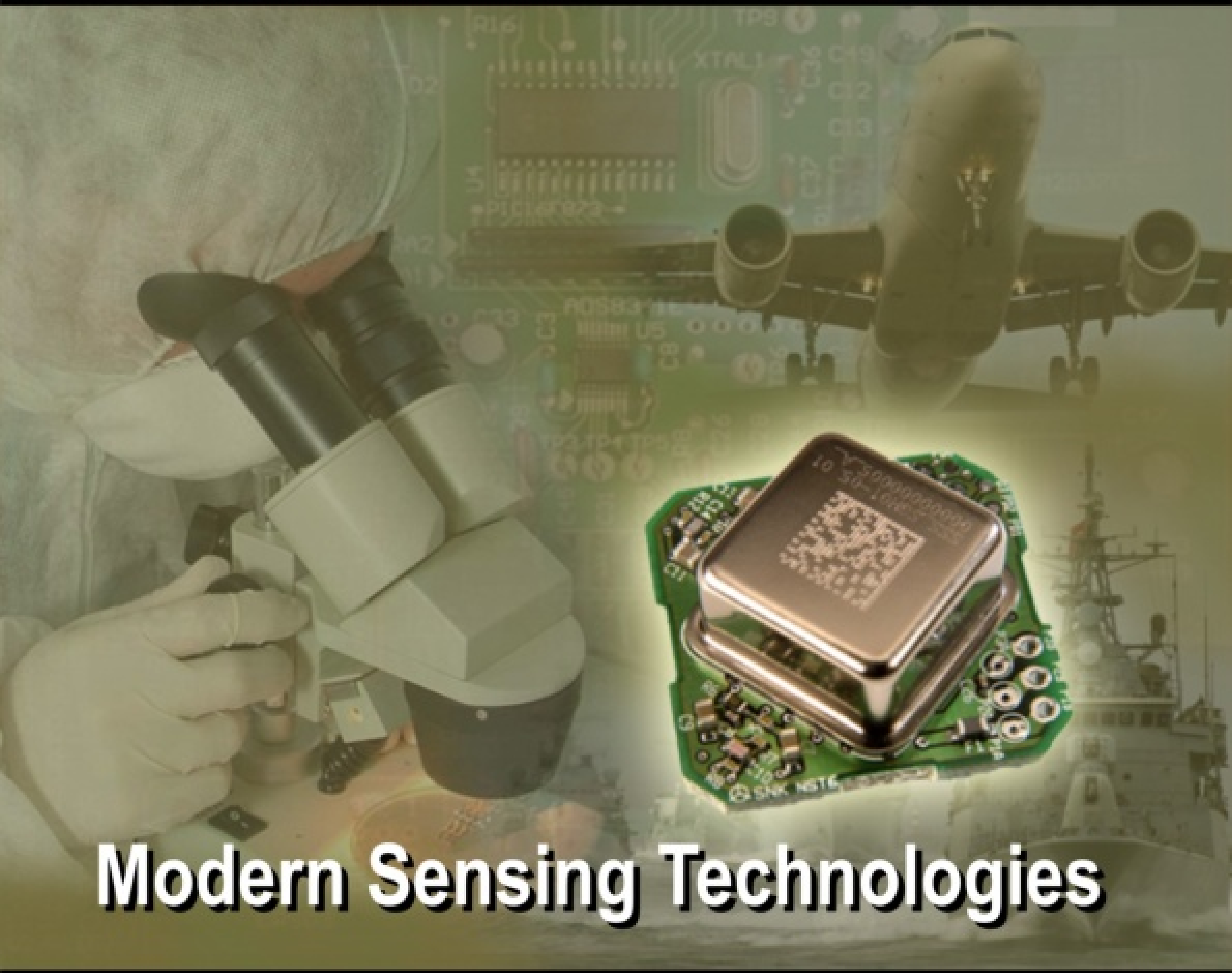

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A Special Vibration Gyroscope

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Abstract: A novel silicon micro-machined gyroscope which is driven by the rotating carrier's angular velocity is introduced. The principle of structure is analyzed. The mathematic module is also established. Process of making the vibration silicon modules is given and the manufacturing of "Sandwiches" sensor is showed. The gyroscope has been tested, the result have certificated that the principle of the gyroscope is correct. *Copyright © 2008 IFSA.*

Keywords: Vibration, Gyroscope

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1 . Introduction

In 1990's, all kinds of micro-machined gyroscope appeared along with the development of microelectronic technology. There is two parts in those gyroscope' sensor, one part is driving (including driving circuit), the other part is sensing (including sensing circuit). Those gyroscopes can sense Coriolis force when vibrating mass is driven by the carrier. Designing and manufacturing this kind of gyroscope is very difficult because of the micro-machined gyroscope must be driven first [1-2]. The high frequency vibrating micro-structure is the driving part. In order to avert the difficulty of the design and manufacture silicon micro-machined gyroscope's driven part, the authors are propose to utilize rotating of the carrier itself as the driven force [3], thus the driving part needless to be used in the gyroscope. So while the carrier spin, the carrier's yaw angular velocity or pitching angular velocity uprightness to the carrier's spin angular velocity orientation can be detected. This structure of the gyroscope is simple, and it is easy to process.

2. Principle of the Structure

Fig. 1 shows the structure of the micro-machined silicon gyroscope derived by carrier's angular velocity. In Fig. 1, 1 - stand for silicon proof mass (sensing mass, mass), 2 - stand for silicon elasticity torsion girder, 3 - stand for electrode. Four electrode and silicon proof mass consist of four capacitors.

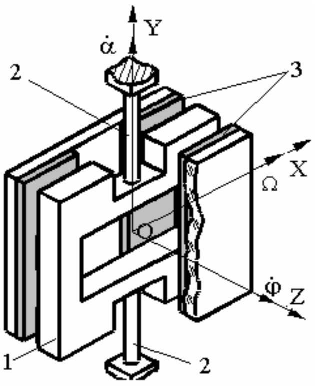

Fig. 1. The principle structure of sensor.

The coordinates OXYZ is fixed on the mass of sensor, $\dot{\alpha}$ is angular velocity about mass vibrating around the OY axes, $\dot{\varphi}$ is carrier's spin angular velocity, Ω is carrier's yaw or pitching angular velocity. The gyroscope is fixed on the carrier and rotates with the carrier at the speed of $\dot{\varphi}$, yawing or pitching at the speed of Ω at the same time. The mass is affected by Coriolis force which changed frequently (the frequent of the Coriolis force equals to the frequent of carrier rotating), and then the mass oscillates around the OY axes. The four capacitors (C1, C2, C3, C4) which are consist of mass and four electrodes are varied as the mass is oscillating. It is shown in Fig 2, variety of capacitance is converted into the variety of voltage signal and then the voltage signal is amplified, so we can obtain the voltage signal in proportion to the angular velocity Ω that we want to detect.

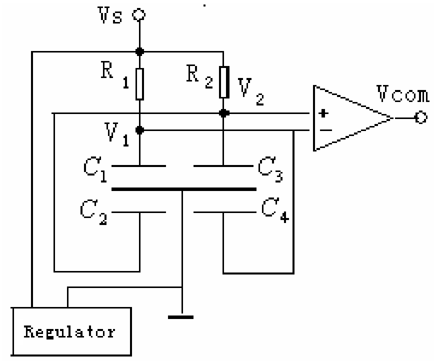

Fig. 2. The principle of signal detecting circuit.

3. Dynamic Model

The dynamic equation in OY axis can be obtained

$$J_Y\ddot{\alpha} + D\dot{\alpha} + \left[\left(J_Z - J_X\right)\dot{\varphi}^2 + K_T\right]\alpha = (J_Z + J_Y - J_X)\Omega\dot{\varphi}\cos(\dot{\varphi}t), \qquad (1)$$

where J_X, J_Y, J_Z are the moments of inertia for the gyroscope mass in X, Y, Z axises; K_T is the coefficient of torsion rigidity; D is the damping coefficient.

Stable solution for equation (1) is

$$\alpha = \frac{(J_Z + J_Y - J_X)\Omega\dot{\varphi}}{\sqrt{\left[(J_Z - J_X - J_Y)\dot{\varphi}^2 + K_T\right]^2 + (D\dot{\varphi})^2}}\cos(\dot{\varphi}t - \beta) \tag{2}$$

Amplitude of angular vibration is

$$\alpha_m = \frac{(J_Z + J_Y - J_X)\dot{\varphi}}{\sqrt{\left[(J_Z - J_X - J_Y)\dot{\varphi}^2 + K_T\right]^2 + (D\dot{\varphi})^2}}\Omega \tag{3}$$

4. Dynamic Parameter Analysis and Calculation

4.1. Rigidity Coefficient of Elastic Girder

The structure of elastic girder is shown in Fig. 3, length, width and thickness of girder are L, W, and t. In order to be convenient for get the torsion rigidity coefficient of elastic girder, it can be supposed as follow:

(1) Turning angular is direct proportion to girder length;
(2) Warp of all brace girder ‘s cross-section are equal;
(3) Twist moments of girder’s ends are equate and their orientation are contrary.

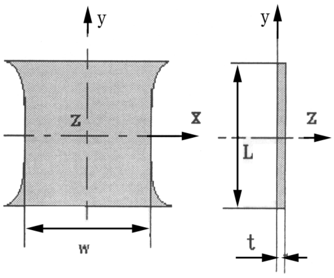

Fig. 3. Structure of supporting girder.

According these assumptions, from elasticity mechanics, the total rigidity of two girders is got

$$\begin{aligned} K_T &= 0.657 \times \frac{Gt^3 w}{L} \sum_{n=1,3,5,\ldots\ldots}^{\infty} \frac{1}{n^4}\left(1 - \frac{2t}{n\pi w}\tanh\frac{n\pi w}{2t}\right) \\ &\approx \frac{2}{3}\cdot\frac{Gt^3 w}{L} \end{aligned} \tag{4}$$

Put w=0.8 mm, L=0.8 mm, t=0.025 mm, G=5.1×1010 (N/m^2) into the formulation (4), get: K_T=5.313×10^{-4}N·m.

4.2. Angular Vibration Damping Coefficient of Vibration Devices

When a rectangle plane with length A and width B moves towards underside whose gap breadth is H, the press membrane damping coefficient is

$$
\begin{aligned}
f &= \frac{F_{damp}}{dh/dt} = \frac{AB^3\mu}{h^3}\left[1-\frac{192B}{A\pi^5}\sum_{n=1.3.5...}\frac{1}{n^5}\tanh\frac{n\pi A}{2B}\right] \\
&\approx \frac{96\times\mu}{h^3.\pi^4}B^3A\left[1-\frac{2}{\pi}\cdot\frac{B}{A}\tanh\left(\frac{\pi}{2}\cdot\frac{A}{B}\right)\right]
\end{aligned}
\qquad (5)
$$

As the structure of the vibrating mass is complex, it is difficult to calculate the damping coefficient. For reducing the calculation difficulty, the gyroscope mass is divided into three areas with distinct colors, shown in Fig 4. then add damping of three district as the gyroscope vibration global damping approximately.

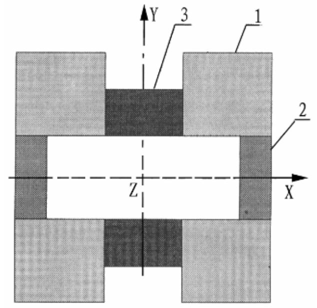

Fig. 4. Damping partition.

Angular vibration damping factor of three distinct are got. Three relationship curves about damping coefficient and vibration angular are shown in Fig. 5.

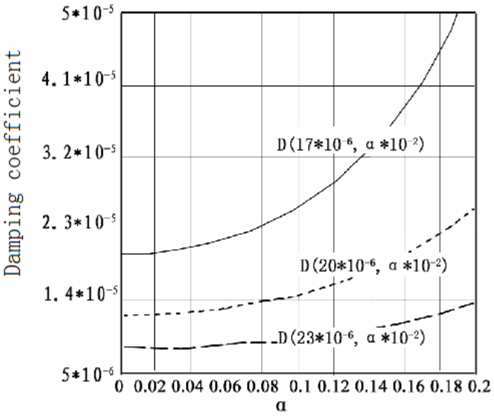

Fig. 5. Relationship of damping coefficient.

From Fig. 5, When d=0.020 mm, we get damping coefficient

$$D(2\times10^{-5},0)=1.231\times10^{-5}(N\cdot m\cdot s)$$

4.3. Relationship Curve about Gyroscope Mass Angular Vibration Inherent Frequent, Angular Vibration Amplitude and Detecting Angular Velocity

The gyroscope mass angular vibration inherent frequent calculated using dynamic parameter is

$$\omega_s = \sqrt{\frac{K_T}{J_Y}} = 917\,(\text{rad/s}) = 146\text{ Hz} \tag{6}$$

Put the dynamic parameter into formulation (3), get relationship curve about a_m vs. detecting angular velocity Ω. It is shown in Fig. 6.

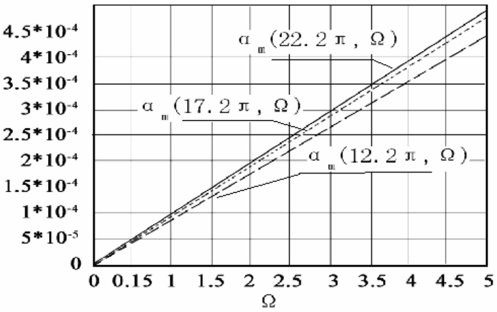

Fig. 6. Curve of relationship about angle vibration range α_m and angle velocity Ω.

When $\dot{\varphi}$ =17 Hz , Ω =0.01 (rad/s), $\alpha_m = 9.505\times10^{-7}$ (rad) and vibration amplitude of gyroscope vibration mass' outer fringe is

$$A_m = \alpha_m \cdot \frac{a_3}{2} = 5.03756\times10^{-9}\,(m)$$

5. Signal Detection

The signal detection circuit of micro-machined gyroscope is shown in Fig. 3. When gyroscope spin with angular rate $\dot{\varphi}$, deflection angular α variation leads to four capacitors C1, C2, C3, C4 changing. The capacitance variety convert into voltage signal and the signal is amplified; get the signal whose amplitude correspond to detected angular velocity Ω.

The capacitance variety of micro-machined gyroscope is very small and be affected by distribution capacitance easily. Signal processing use alternating current bridge, sense capacitance device is used as operation arms of the bridge. The bridge supply is equivalency amplitude high frequent alternating voltage. When operation capacitors are changed, the amplitude modulation wave signal modulated by operation capacitors variety at the output of the bridge and signal is amplified and demodulated, then get low frequent output signal.

It is known in Fig. 2, as silicon pendulum without turning (α = 0), C1 = C2 = C3 = C4 = C0 and then

$$C_0 = \varepsilon \left\{ \begin{array}{l} \left(b_1 - b_2\right)\left(\dfrac{a_1 - a_0}{2d}\right) \\ + \left(b_3 - b_2\right)\left(\dfrac{a_2 - a_1}{2d}\right) + b_3\left(\dfrac{a_3 - a_2}{2d}\right) \end{array} \right\} \tag{7}$$

When silicon pendulum turning ($\alpha \neq 0$), C1 = C2, C3 = C4, capacitance variety can be expressed by following formulation:

$$dC = \frac{\varepsilon}{d + \alpha r} dS = \frac{\varepsilon \Delta b}{d + \alpha r} dr$$

In the formulation, d is the clearance between mass and electrode, α is turning angular of mass angular vibration, ε is the dielectric constant.

Setting $R_1 = R_2 = R$, thus

$$V_1 - V_2 = 2\omega_e R(C_2 - C_1)V_S \, , \tag{8}$$

where ω_e is the AC frequent; Vs is the AC voltage on bridge; ω_e is the AC angular frequent, R is the bridge resister.

Putting $\varepsilon = 8.85 \times 10^{-12}$ (C/m), $\omega_e = 3.7 \times 10^5$ (rad/s), R =75kΩ, V_S =5 V.

The relationship curve about output voltage and swing angular shown in Fig. 7 is obtained. It is known that when d=0.020 mm and α at 0 ~ 0.002, amplitude of output voltage is

$$U_{out} = 7.875 - 6.75 = 1.125(mV)$$

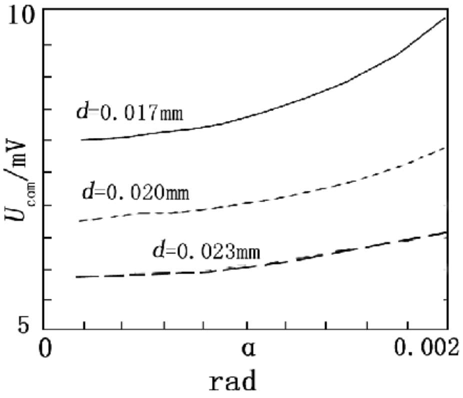

Fig. 7. Characteristic curve about export voltage and swing angle.

6. "Sandwich" Sensor

Gyroscope sensor is formed by the electrode on the top and the bottom and the vibration silicon modules in the middle, they form the "sandwiches" structure. As is shown in Fig. 8, the temperature expansion coefficient of silicon is 2.6×10^{-6}/□.To ensure the stability of the "sandwich" structure, the temperature coefficient of expansion of the electrode has been closed with the temperature coefficient of expansion of the silicon. We choose the No.75 ceramic Substrate.

Vibration silicon modules is shown in Fig. 9, the silicon quality is in the middle, outside are the frames, two flexible beams put the quality and the frames together. So that the quality can rotate around the axis consisted of two beams, the thickness of the frames are 30 um thicker than the thickness of the quality, so the two facets of the frame are 15 um higher than the two facets of the quality. The thickness of the beam is 48 um. There is prescribe hole in the center of mass of silicon, and 7 grooves outside, they are used to reduce the damping, the whole vibration modules is one structure through the micro-machined processing used the silicon as the material, Fig. 10 is the chart of the plates, blotted out regional in the map is copper electrode, electrode substrate are made by ceramics, the electrode on the top and the bottom and the vibration silicon modules in the middle formed the “sandwiches” sensor, Fig. 11 is the plate with copper electrode.

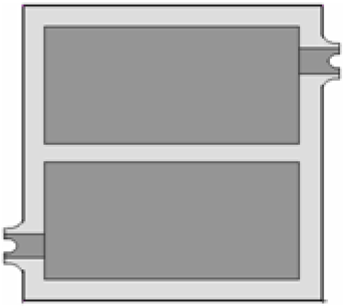

Fig. 8. “Sandwiches” sensor.

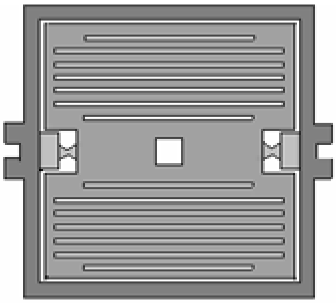

Fig. 9. Vibration silicon modules.

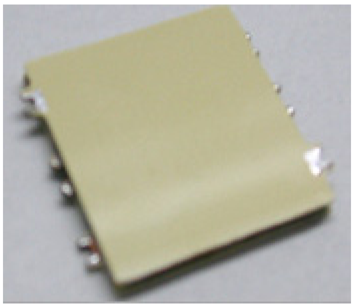

Fig. 10. Chart of the plates.

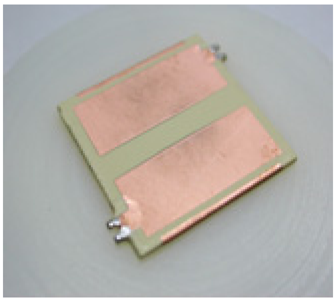

Fig. 11. Plate with copper electrode.

7. Process of the Vibration Silicon Modules

Using the 4-inch silicon, type N, double Polishing, (100) crystal face. In the experiment, we use 30 % of the concentration of KOH solution for corrosion, temperature is 104 °C, corrosion rate is approximately 4.3. The process is shown in Fig. 12.

a. 2000 Å silicon dioxide layer double growth;
b. Double lithography, get rid of the oxide layer;
c. 15um silicon surface of the deep corrosion each plane;
d. 1.5um silicon dioxide layer double growth;
e. Second double-lithography, 24 um silicon surface of the deep corrosion each plane;
f. Third double-lithography, 80 um silicon surface ;

g. of the deep corrosion each plane;
h. Forth double-lithography, 64 um silicon surfaces of the deep corrosion each plane, Link up.

After seven steps above, we got the vibration silicon modules, But then the silicon beam vibration unit has not been processed out, next, the process is to make the elastic beam of the silicon modules vibration. We put single silicon modules in solution for lithography silicon corrosion, then we got the vibration silicon modules, as is shown in Fig. 13.

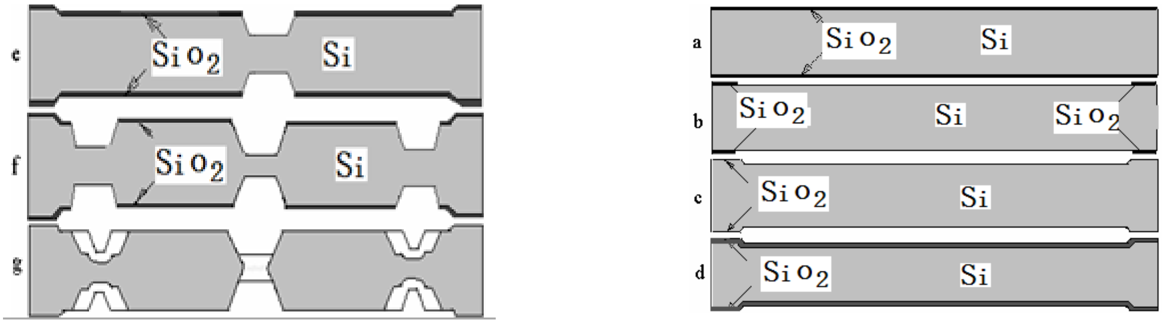

Fig. 12. Process of silicon modules.

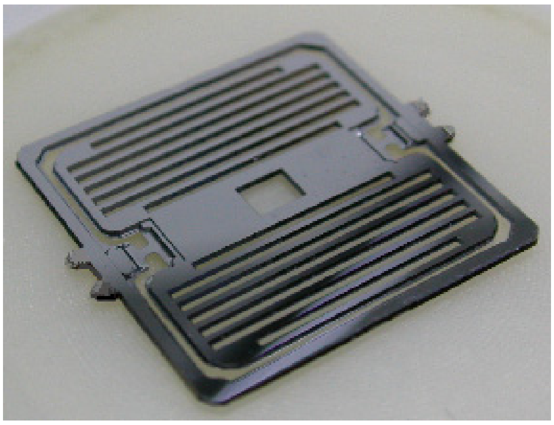

Fig. 13. Silicon modules.

8. Silicon Micro-machined Gyroscope Tests

Gyroscope has been tested. The tests were held on dynamic stand controlled by personal computer. The Gyroscope was set in the range 5 ~ 25 Hz by a rotation simulator. The tested sensors proved the total efficiency on all the conditions of the carried tests.

Dependence of the sensor output signal on the measured angular rate at different rotation frequencies of simulator is shown in Table 1 and Fig. 14.

Table 1. Gyroscope Dependence of the sensor output signal on the measured angular rate at different rotation frequencies of simulator.

Ω/°/s	50		100		150		200		250		300	
$\dot{\varphi}$ /Hz	CW	CCW	CW	CCW	CW	CCW	CW	CCW	CW	CCW	CW	CCW
5	726.8	698.4	1440	1412	2157.6	2139.4	2875.2	2845.2	3600	3568.6	4327.2	4294.2
11	1481.2	1449.4	2957.6	2928.8	4440.8	4417.6	5872.8	5849.8	7263	7254	8652.8	8662.4
17	1835.8	1803.6	3633.6	3582.2	5429.8	5324.8	7193.4	7038.8	8982.4	8772.2	10833.8	10601.2
25	2019	1870.6	3823.6	3677.8	5569.6	5482	7371.4	7248.8	9217.2	9139.6	11264.4	11170.2
Stability/%	±32.65	±31.98	±31.61	±31.25	±31.04	±30.74	±30.89	±30.59	±30.92	±30.67	±31.35	±31.08

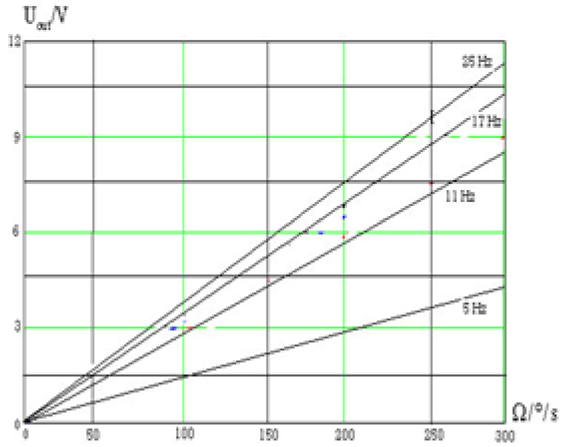

Fig. 14. Dependence sensor output signal from input rate.

9. Conclusion

Depend on carrier's rotating angular velocity as driving force without driving circuit and driving girder, the principle of this micro-machined gyroscope is correct. Because of the instability of the angular velocity of the rotating carrier itself, the output voltage error reached to 30 %.under low damp situation output signals of silicon micro-machined gyroscope is proportional to the rotate speed of the carrier.

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