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学位論文題目　Degenerated MEMS Resonators for 3-Axis Frequency Modulated and Rate Integrating Gyroscopes
（3 軸周波数変調・積分ジャイロスコープのための縮退 MEMS 振動子）

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論文内容要約

With rapid development of some application fields such as autonomous cars, drones, robots, etc., high performance Micro-Electro-Mechanical Systems (MEMS) gyroscopes are extremely required in modern society, because of their various advantages, including small volume, outstanding stability, relatively low costs, and so on. Some kinds of developed MEMS gyroscopes have achieved good working performance and are already applied in many fields.

MEMS gyroscopes usually contain a micro-resonator together with two resonance modes, the primary mode, and the secondary mode. The resonator can vibrate at its primary resonance mode with a constant frequency and amplitude by electrostatic, electromagnetic, piezoelectric, or other force. In this mode, the drive oscillation or primary oscillation will maintain the gyroscope vibrating along the driving direction. And in the secondary mode, the angular rate or angle in the secondary mode direction can be detected because of the Coriolis force coupling between the two modes. Therefore, one way to categorize MEMS gyroscopes, depending on the model shape, application, and design parameters of the resonator that used in the MEMS gyroscopes. At present there have been a varies of resonators developed for application in MEMS gyroscopes. The concentrated mass resonator is under rapid development and attracting more and more interest as good candidate for high performance gyroscopes, because of its various advantages especially the relatively simple structure for design and fabrication. Other good candidates for high-performance CVGs are ring and disk resonator. This kind of resonators has advantages in terms of the structural simplicity and highly symmetrical structure, which means that they have low immunity towards acceleration, low anchor loss, and less sensitivity to environment vibrations. Ring and disk gyroscopes also have unique advantages in the fabrication complicity for the two-dimensional structures, inherent mode matching, and high Q-factors.

Another way to categorize MEMS gyroscopes is based on the control system of them. For past several decades, the amplitude information is widely used in conventional MEMS gyroscopes, including amplitude modulated (AM) and force to rebalance (FTR) Types. The AM technology has been applied in gyroscopes for a long time, and showed excellent working performance in real application. However, this kind of gyroscopes have a trade-off problem between the sensitivity and bandwidth. Therefore, FTR gyroscopes were developed to solve this trade-off problem, in which a typically closed loop control is used to suppress the vibration of the sensing mode and the rate of rotation. FTR type extends the bandwidth of the gyroscope beyond the limitation of the open loop sensing mode, achieving high sensitivity and large bandwidth at the same time. To further improve the performance of MEMS gyroscopes and solve the relatively high temperature coefficient of sensitivity problem in conventional gyroscopes, frequency modulated (FM) and rate integrating (RI) gyroscopes have been proposed. These kinds of gyroscopes can obtain better temperature stability and larger operation bandwidth by modulating inertial rotation with resonance frequency and utilizing the differential sensing signal.

For FM/RI gyroscopes, highly symmetric degenerated resonators are necessary, which means that the stiffness and damping ratio should be matched in both driving and sensing axis for the resonator, which is difficult especially for realizing high performance 3-axis FM/RI gyroscopes. There is severe frequency split problem for the resonator made on (100) single crystal silicon (SCS), which is widely used for fabrication and integration of resonators. And there is also quality factor problem for roll/pitch axis degenerated resonators. These problems make it difficult to further improve the performance for 3-axis FM/RI gyroscopes.

As introduced, FM and RI gyroscopes have been integrated in many researches for their high stability, low energy consumption, robustness against long-time accumulated errors, and immunity to temperature fluctuation. For FM and RI gyroscopes, highly symmetric degenerated resonators are necessary, which means it is extremely important to keep the same resonant frequencies and Q-factors between two modes for the resonators applied in FM and RI gyroscopes. However, there are still problems for realizing high performance 3-axis FM/RI gyroscopes at present. For symmetric yaw axis degenerated resonators, there is severe frequency mismatch problem due to the material anisotropic properties like (100) single crystal silicon (SCS), which is widely used for fabrication and integration of resonators. There is also Q-factor mismatch problem, which is contributed by several factors, for roll/pitch axis degenerated resonators, for that degeneration between IP and OOP modes is challenging, and the fabrication is also difficult.

Therefore, in this thesis, two novel degenerated resonators are proposed to solve these problems and for application in 3-axis FM/RI gyroscopes. To realize symmetric degenerated yaw axis resonator on (100) SCS, a new structure was adapted in disk resonators for anisotropic problem, which could be integrated with roll/pitch resonators. And another new roll/pitch resonator was developed towards the degeneration challenging. These resonators' concepts are firstly proposed in this work and are validated by experimental results. Through tentative experiments in real gyroscopes, the proposed structure has been demonstrated to have large potential for application as FM and RI gyroscopes.

In Chapter 2, a novel mode-matched multi-ring disk resonator is proposed for solving the stiffness anisotropy problem, which comes from material property of (100) SCS, in fabrication of disk resonators. Based on analysis of structure design, elliptic spokes for compensating the effective stiffness of whole disk resonator are applied in interconnection structures. This shape has outstanding stability and smooth edges compared with other shapes, and this characteristic can also reduce the effect brought by fabrication imperfections commonly appeared in devices, which is very important for increasing the robustness of MEMS gyroscopes. Then the proposed working principle is demonstrated by numerical study, and design parameters are optimized using FEM simulation. Afterwards, the fabrication process for proposed disk resonators and comparison group of conventional disk resonators are presented in detail. Finally, the evaluation set and obtained results of fabricated disk resonators are introduced. Both comparison group of one conventional disk resonator with linear beams, and experiment group of several proposed disk resonators with elliptic spokes, were evaluated in the experiments, and these experiments were normally conducted under a vacuum condition of less than 5 Pa. The evaluation results show that a frequency mismatch as small as 1300 ± 900 ppm could be obtained by proposed multi-ring disk resonators with elliptic spokes. As comparison, the frequency mismatch for conventional resonator with linear beams is as large as 30,000 ppm. These results well demonstrated that the (100) SCS stiffness anisotropy could be successfully compensated by the proposed novel disk resonator structure, which also has good robustness against fabrication imperfections and stability in working performance. Thus, this proposed disk resonator is applicable for high-performance FM/RI Z-axis gyroscopes.

In Chapter 3, the dynamically balanced structure is introduced at the beginning, together with the theoretical analysis on the structure design and development for cancelling mechanical anchor on the substrate, which should be the main reason for Q-factor mismatch between IP and OOP modes. In section 3.2 and 3.3, the resonant frequencies for IP and OOP modes were matched with each other by careful design with optimization on many structure parameters, while the mismatch reached only 0.26 % in the analysis. The dynamically balanced structure was mainly for minimizing the anchor loss damping in OOP mode, which was demonstrated by FEM simulation. For further matching the Q-factors between two modes, other factors of TED and viscous damping were analyzed in this case study. And the appropriate ambient pressure for Q-factor matching was discovered in the analysis. Then the optimized designed resonator was fabricated by developed novel fabrication technology, which using thermos-compression bonding for OOP resonance structure manufacture. In section 3.5, the fabricated resonator was applied in evaluation with LDV instruments. And the resonant frequency mismatch and Q-factor mismatch between IP and OOP modes were evaluate as 1.3% and 32%, respectively, which were as small as the value for usual IP mode Z-axis resonators. Therefore, compared with previous research works, this study successfully demonstrates the effect of proposed working principle, and shows a suitable IP/OOP mode-matched resonator towards the challenge in implementing 3-axis FM/RI gyroscopes.

In Chapter 4, the electrostatic tuning was firstly applied to realize the mode-matching in proposed novel disk resonator with elliptic spokes. The advantages and structure effect of proposed novel multi-ring disk resonator with elliptic spokes was proved by electrostatic sensing in this study at the beginning, which is the fundamental work for gyroscope characteristics. In the experiments, the as-fabricated frequency mismatch between two n = 2 wineglass modes as small as 53 Hz was detected by synchronous differential signal processing technique without any tuning method. This result combined with the analysis in Chapter 2 well demonstrate that proposed structure could effectively compensate the anisotropy stiffness problem brought by SCS. Then the remaining frequency mismatch was eliminated by electrostatic tuning method. The frequency mismatch as small as 2 ppm could be observed for the mode-matched disk resonator, which means that the resonator was well mode-matched. After mode-matching, the stability of this device was evaluated under AM and FTR operation modes. Based on the obtained experimental results, the BI of proposed mode-matched resonator under two control systems could be calculated as 2.7°/h and 0.68°/h, respectively, which well demonstrated the working performance as a MEMS gyroscope of proposed mode-matched resonator, and it is applicable for high-performance gyroscopes including FM/RI gyroscopes.

Finally, a conclusion of this research work is made in Chapter 5. As a general conclusion, this research proposed novel degenerated resonators for application in FM/RI gyroscopes, and these techniques should be beneficial for solving present challenges. Chapter 2 and Chapter 3 introduce the concept of a disk resonator towards stiffness problem from material property, and a dual mass resonator towards Q-factor mismatching in 3-axis gyroscopes, respectively. These proposed degenerated resonators were demonstrated by both numerical study and evaluation experiments, to be effective for solving mentioned problems. In Chapter 4, the mode-matched disk resonator was applied as gyroscope and recorded improved working characteristics. These proposed technique and results provide well degenerated resonators required for high performance 3-axis FM/RI gyroscopes.