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Fabrication of 120° silicon double mirrors robust against misalignment for use in micro optical gyroscopes

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ABSTRACT

This paper presents the fabrication of silicon double mirrors which are indispensable to realize an innovative concept for the miniaturization of an optical ring laser gyroscope (RLG). The 120° double mirrors provide a reduction of misalignment errors. Starting with the device layout, all major processing and manufacturing steps of the mirror elements are discussed. For the fabrication of these mirrors (100) silicon wafers are used, which are tilted by 5.3° towards the (110) plane, thereby ensuring that an etch flank of 60° is achieved by KOH wet chemical etching. A 36% KOH solution with addition of isopropanol is used to obtain uniform and smooth etched sidewalls for good reflectivity. For generating double mirror elements two structured wafers are connected by silicon direct bonding and then cut into small mirror elements to be mounted onto the RLGs micro optic platform. Roughness measurements on the mirror facets yielded values in the range of 20 nm for R_a and 60 nm for R_z. These roughness values are below what is considered as critical for the mirrors when used with laser radiation at a wavelength of $\lambda = 630$ nm. Optionally, the mirrors can be coated with a metal film to further improve the reflection properties. This novel micro mirror technology is extremely useful for the miniaturized optical gyroscope but may find other MOEMS applications where alignment inaccuracies can hardly be tolerated.

1. Introduction

For many positioning tasks inertial navigation is an essential component because it is reliable, robust against interference and able to deliver the full motion state vector. It is used in determining the position of aircrafts, vehicles and ships, but also of satellites, autonomous robots, as well as in personal navigation and many other applications. An inertial navigation system usually consists of three gyroscopes and three accelerometers. The gyroscopes measure the rotational speed in order to determine the position angle by integration. This leads to a linear accumulation of measurement errors in rotation rates over time when determining the orientation angles.

For several years different research groups, e.g. [1], have been trying to develop a MOEMS ring laser gyroscope (RLG) to attain a higher precision in comparison to the well-known MEMS vibration gyroscope (Coriolis gyroscope). In the case of conventional optical gyroscopes adjustable planar large-scale mirrors are used allowing the correction of angle errors, while miniature adjustable planar mirrors can in principle be used in the case of microscopic devices. In both cases, however, initial mirror misalignments have to be reduced or corrected by a subsequent alignment of mirrors. A systematic avoidance of errors is not possible when only planar mirrors are used.

The need for the introduction of movable or electrostatically sensitive components in the correction elements is a disadvantage of conventional optical gyroscopes concepts when miniaturization is considered. It leads to a decrease of robustness to external noise sources. For this reason a new concept for the realization of a MOEMS-gyroscope has been developed and will be described in the following.

2. Gyroscope types

There are different kinds of gyroscopes which are based on various operating principles. Depending on the particular application they typically have specific advantages or disadvantages. The laser gyroscopes are utilizing the Sagnac effect. Due to the constant speed of light time differences between the two beams propagating in opposing directions occur upon rotation of the ring interferometer, which also change interferences of the two beams. In laser gyroscopes mirrors or prisms are used to form a ring resonator, the laser light source can also be integrated directly into the beam path. The fiber optic gyroscope is also based on the Sagnac effect but uses a fiber optic coil as optical path. The optical fiber can be

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several kilometers long. With longer fibers the resolution increases, but the scattering in the fiber results in more drift and noise.

A (mechanical) vibration gyroscope is modeled after the sensors of insects. The sensor mass is excited to oscillate and is influenced by the coriolis force upon rotation. Various structures such as pistons, tuning forks or combs are possible and can be realized as micro mechanical structures (MEMS).

3. Concept of the novel MOEMS-gyroscope

A variety of concepts for the miniaturization of ring laser gyroscopes has been developed in the last few years. Most of them require elements for the adjustment of mirrors to reduce alignment errors which are generated during fabrication or assembly. The novel concept of a ring laser gyroscope with the use of silicon double mirrors allows abandoning subsequent controls of the mirrors.

Honeywell International Inc. commercializes a conventional He–Ne-laser gyroscope for military avionics [2]. The sensor has an edge length of only 2 cm in a triangular construction but the whole unit has a dimension of 7.0″ × 6.0″ × 2.9″ and weighs nearly 3 kg. However, many applications require gyroscopes with much smaller dimensions and less weight. The theoretical feasibility of a RLG in MEMS technology has already been shown by Lawrence in [3]. The essential constituents of his approach were patented in 1991 [4]. Lawrence used an annular resonator, but as a consequence of diffraction and reflection effects the diameter cannot be less than 50 mm. A miniaturized design with three or four micromechanical mirrors has not yet been described in the literature. One of the reasons for this lies in the lack of suitable fabrication technologies. For the miniaturized gyroscope sensor described here a classic triangular structure is chosen in which the laser beams can rotate in opposite directions until they are brought to superposition. The reflections at the corners of the triangular area will be effected by the double mirrors that will be described in the following. The choice of the triangular structure specifies the required angle within the double mirrors. Fig. 1 shows a micro optical testing platform micro fabricated from silicon for the 120° double mirror elements. This is also a possible arrangement of the double mirrors in the final optical sensor.

This new concept would close the gap between the very precise but heavy conventional optical gyroscopes and the small and lightweight but less accurate vibration gyroscopes that are already being produced in MEMS technology. The use of such a sensor is particularly interesting for aerospace applications because a very high angular accuracy and minimum weight are required in this case.

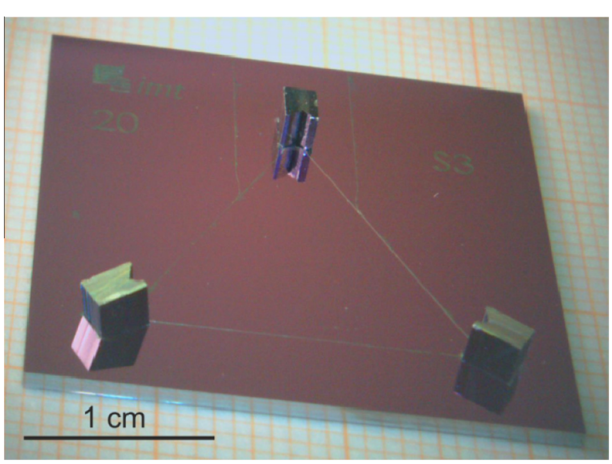

Fig. 1. Arrangement of the 120° double mirrors on the micro optical platform.

3.1. Double mirrors with tolerating alignment errors

The reduction of the angle errors can be achieved via precision mechanical mirror alignment elements in macroscopic optical gyroscopes or via controllable mirror actuators in microscopic optical devices. In both cases, however, errors can be either minimized or corrected by individual alignments subsequent to fabrication. A disadvantage is caused by the introduction of movable or electrostatically sensitive components in the alignment elements whereby the robustness to external noise decreases. A systematic suppression of errors is not possible using only planar mirrors.

The idea being pursued to improve the error tolerance is the use of double mirrors with a systematically unsusceptible total reflection angle. The principle of the double mirror is insensitive to small vertical axis errors (defined by rotation about the line of contact of the two mirror axes), resulting from installation or occurring in operation. If this alignment error lies within a defined acceptance range the reflection angle is not affected. The only requirement is that the beam still strikes both double mirror surfaces. In exemplary calculation based on realistic dimensions a mirror rotation of up to 15° can be compensated. Another case of displacement which can be compensated is the displacement of the elements in direction of the bisecting line of each 60° angle. In this case a dislocation of ±400 μm is compensated according to calculations based on realistic dimensions. Combinations of these two misalignment cases must be considered individually.

Fig. 2 shows the principle of the misalignment tolerant double mirror in which the two mirrors are oriented at an angle of 120° with respect to each other. At a total reflection around an angle γ of 120° the beam impacts twice on the double mirror. The sum of the individual reflections $\gamma 1$ and $\gamma 2$ gives the desired total angle γ ($\gamma = \gamma 1 + \gamma 2$) of 120°. Assuming an angular error ε caused by misalignment or distortion during operation (shown in Fig. 2 with 10°), the light wave is also reflected twice. The input and output of the first reflection angle (α') is reduced to the error ε, the single reflection angle $\gamma 1'$ increases by 2ε. The second angle of reflection increases depending on ε and thus the second reflection angle decreases by $\gamma 2'$ to 2ε.

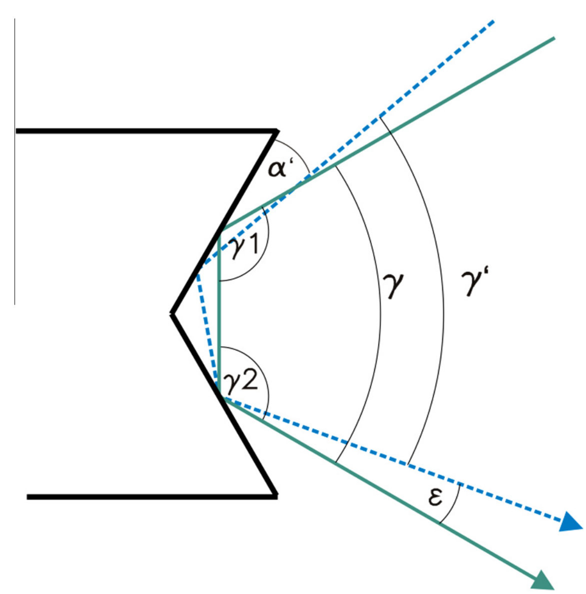

Fig. 2. Principle of the misalignment tolerant double mirror for reflections with small deviations from 120°.