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Ring laser oscillation using silicon (111) mirrors fabricated by MEMS technology

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Abstract: In this paper, we demonstrate for the first time ring laser oscillation using a set of silicon (111) mirrors fabricated by microelectromechanical systems (MEMS) technology with a semiconductor optical amplifier (SOA) as an optical amplifier medium. Four (111) mirrors were fabricated perpendicular to a (110) silicon wafer surface to form an optical loop. The (111) mirrors were fabricated by a combination of deep reactive-ion etching (DRIE) and anisotropic wet etching, followed by electroplating with a highly reflective Au film. Adjusting the mirror alignment for the oscillation was not required because the mirrors were already precisely positioned with the accuracy of the crystal orientation. In experiments, oscillation began at an injection current of more than 110 mA into the SOA. We confirmed that both forward and backward propagating lasers oscillated simultaneously in a single mode. Our results will especially be useful for realization of next-generation optical MEMS ring laser gyroscopes.

Keywords: ring laser gyroscope, optical loop, DRIE, anisotropic wet etching, semiconductor optical amplifier

Classification: Micro- or nano-electromechanical systems

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1 Introduction

Ring laser oscillation, in which an optical loop acts as a resonator and both forward and backward laser beams oscillate simultaneously in the loop, is an important topic in the field of optics. For example, ring laser gyroscopes (RLGs) directly use the Sagnac effect in ring laser oscillation. In conventional RLGs, He–Ne oscillation in a triangular glass block with three mirrors at the apexes of the block has been used. However, this device is large and difficult to machine and requires high voltage and power. Therefore, some attempts have been made to miniaturize the device and to reduce its operating power, for example, using a semiconductor optical amplifier (SOA) with a looped optical fiber or semiconductor waveguide [1, 2]. However, they have some disadvantages that degrade their properties. The fiber type requires complex alignment of the SOA and fiber coupling. The waveguide type exhibits high absorption of light in the looped waveguide. On the other hand, we have proposed a microelectromechanical systems (MEMS) RLG [3].

In this paper, we demonstrate for the first time ring oscillation using an optical loop with silicon (111) mirrors fabricated by MEMS technology. In the MEMS-RLG, complex alignment such as that required for the fiber type is not needed because the mirror is aligned along the crystal orientation when the optical loop is fabricated. Furthermore, the laser beams of the MEMS-RLG propagate in free air surrounded by four (111) vertical mirrors, so absorption does not occur. In addition, MEMS technology allows certain optical components to be inserted into the optical loop after mirror fabrication to improve the performance.

Figure 1 shows a conceptual diagram of the hourglass-shaped optical loop formed by the (111) silicon surfaces. Four (111) mirrors are fabricated with anisotropic wet etching perpendicular to a (110) silicon wafer. The pairs of diagonal surfaces are precisely parallel because the crystalline error is usually

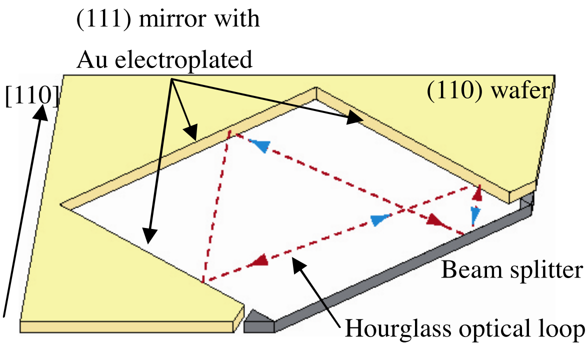

Fig. 1. Conceptual diagram of MEMS-RLG.

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$< 0.001°$ over the entire wafer. The roughness of the anisotropically wet-etched surface is reduced to several nanometers; therefore, it is suitable for optical mirrors. However, anisotropic wet etching has a slow etching rate ($\sim$1.2 μm/min), and it is difficult to form arbitrary shapes because of crystal anisotropy.

This paper reports the fabrication of a silicon optical loop made by combining deep reactive-ion etching (DRIE) with anisotropic wet etching, and the demonstration of external oscillation using an SOA in the fabricated optical loop. The combination of DRIE and anisotropic wet etching provides a high etching rate, allows an arbitrary shape to be formed, and produces extremely flat vertical (111) mirrors. Direct Au electroplating [4] was also employed to improve the reflectance of the vertical mirrors. The external oscillation was confirmed by the relationship between the light intensity and the injection current applied to the SOA, and by the oscillation spectrum.

2 Fabrication of optical loop

Figure 2 shows the fabricated silicon optical loop and the installed SOA with the optical loop.

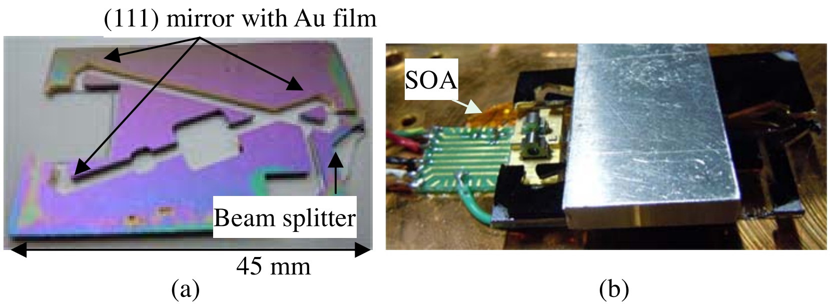

Fig. 2. (a) Fabricated silicon optical loop. (b) SOA installed with optical loop.

The optical loop was fabricated in an n-type silicon wafer with a thickness of 1000 μm, (110) surface orientation, and resistivity of $< 1\,\Omega\cdot$cm. The surface of the wafer was initially oxidized to a thickness of 500 nm. A 400 μm thick Pyrex wafer was anodically bonded with the silicon wafer. Before the optical loop was fabricated, a wagon-wheel pattern was anisotropically wet etched to find the (111) orientation. An optical loop pattern was formed with photoresist according to the (111) orientation. The pattern in Fig. 2 (a) has an hourglass shape because the optical loop was formed by four (111) mirrors with crystalline-defined angles. The SiO_2 film and the silicon wafer with a resist mask were etched by RIE and DRIE, respectively. The DRIE etching rate was 16 μm/min. The resist was removed by O_2 plasma. After RIE, the residual scallops and tapers after DRIE on the silicon (111) mirrors were removed by anisotropic wet etching with tetra-methyl ammonium hydroxide (TMAH) (22%, 80°C, 240 min) to obtain a smooth surface.

The mirrors appear at angles of 54.7° and 125.3° to the [110] direction,

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and the two pairs of diagonal mirrors were very precisely parallel to each other because of the small crystalline error. The measured arithmetic average roughness (Ra) of the (111) mirror was 53 nm in the area of ϕ0.8 mm. Because the reflectance of the bulk silicon surface was only 31% for 1550 nm wavelength light, Au, which has high reflectance at infrared wavelengths, was electroplated directly onto the three mirrors at a thickness of 150 nm. On the remaining mirror, which acts not only as a mirror but also as a beam splitter for obtaining laser rays outside the device, thinner Au (20 nm) was electroplated. The electroplating conditions were 40°C and 1 mA/cm^2. K-24EA10 (Kojundo Chemical Lab) was used as the solution. The calculated reflectance of a 150 nm thick Au mirror is 96%. The calculated reflectance and transmittance of the beam splitter are 83% and 13%, respectively. The roughness of the mirrors did not change after the electroplating process. The gold has a high diffusion coefficient for silicon, and the diffusion of the gold might make worse the reflectivity of the mirrors in long-term. Although we can not observe the deterioration of the mirrors in short-time at room temperature, we are now evaluating long-term stability of our Au coated Si mirrors. The total optical loop length was 101 mm. Part of the Pyrex wafer in Fig. 2 (a) was removed by sandblasting in order to install an SOA. The SOA (COVEGA 1004P, Thorlabs Inc. Gain band: 1530∼1570 nm), which was used as a gain medium, consisted of a laser chip, two collimation lenses, a thermistor and a Peltier device. The lens diameter was ϕ0.8 mm. The outer package of the SOA was mechanically removed. According to the RLG theory, the sensitivity (beat frequency to the applied angular velocity) can be calculated to be 38.4 Hz/(deg/sec) [3].

3 External oscillation with silicon optical loop

The SOA and optical loop were fixed to individual jigs as shown in Fig. 2 (b). In the ring oscillation experiment, the temperature of the SOA chip was maintained at 20 ± 0.1°C by the Peltier device. To confirm the ring oscillation, the laser rays emitted through the beam splitter were observed, and the relationship between the light intensity and the injection current was measured (Fig. 3 (a)). Aligning only the SOA produces ring oscillation in the hourglass-shaped optical loop because the diagonal mirrors were very precisely set to parallel, and alignment of the individual mirrors was not required. The light intensities from the optical loop were sensed by two detectors (MA9302A, Anritsu) for forward and backward laser rays, respectively. The threshold current was 110 mA, and ring oscillation was confirmed. We also observed an intensity difference between the two laser rays. This is because the SOA was not perfectly collimated, and part of the laser beam leaked from the optical loop outside the beam splitter. When the optical loop was interrupted, the oscillation stopped immediately, which clarified that the optical loop acted as the resonance cavity. Figures 3 (b–d) show the optical spectra at injection currents of 115 mA, 135 mA and 155 mA, respectively. The center oscillation wavelength was 1563.59 nm. We observed that the oscillation was single

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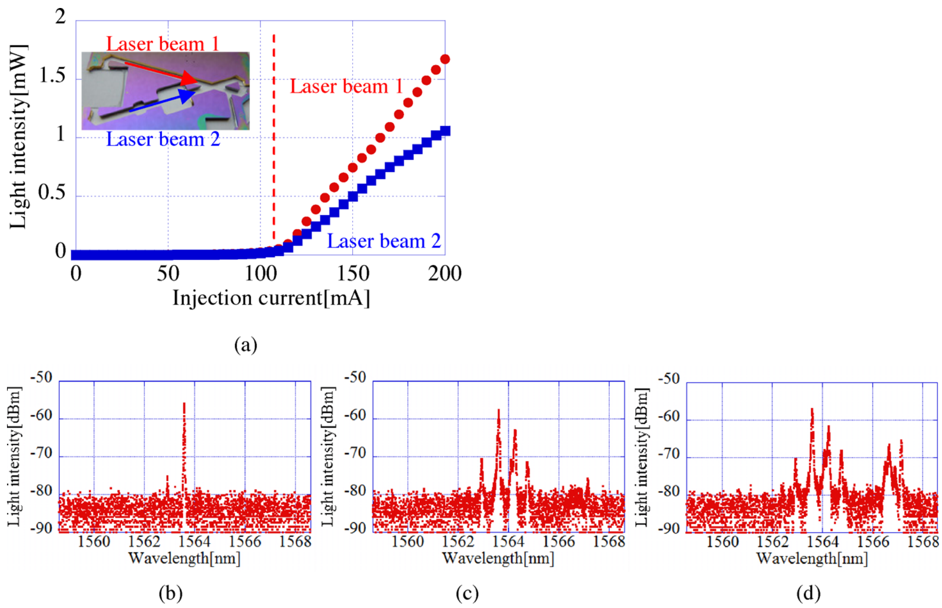

Fig. 3. (a) Light intensity–injection current characteristics. (b) Spectrum at 115 mA. (c) Spectrum at 135 mA. (d) Spectrum at 155 mA.

mode near the threshold current; however, when the injection current was increased, it became multi-mode and unstable.

4 Conclusion

To the best of our knowledge, this is the first study of ring oscillation using an SOA as the gain medium and a silicon optical loop fabricated by MEMS technology was realized. The optical loop was fabricated using a combination of DRIE and anisotropic wet etching of a thick silicon wafer. To improve the reflectance of the mirrors, direct Au electroplating was employed. Ring oscillation was observed in a set consisting of the SOA and the optical loop. The threshold current was 110 mA, and the oscillation wavelength was 1563.59 nm. Two counter-propagating laser beams were obtained simultaneously. In conclusion, it was confirmed that MEMS technology is effective for ring laser oscillation and miniaturized, low-power ring laser applications such as gyroscopes.

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