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Influence of micro-cracks using optical micro-resonator processing of single-crystal calcium flouride, manufactured by ultra-precision cylindrical turning

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Abstract
Optical signal circuits can realize ultimately efficient signal processing. Optical micro-resonators, which can localize light at certain spots, are important parts in terms of achieving the circuits. From the perspective of absorption rates, single-crystal calcium fluoride (CaF_2) is the most suitable material for highly efficient optical micro-resonators, and ultra-precision cylindrical turning (UPCT) is a feasible fabrication process for CaF_2 optical-micro resonators. However, CaF_2 is characterized by brittleness and crystal anisotropy; therefore, it is necessary to prevent micro-cracks in UPCT because such cracks would lead to light scattering and resonator performance deteriorations. In this study, rectangular optical micro-resonators are manufactured by UPCT, and the influence that micro-cracks have on resonator performance is experimentally investigated.

Single crystal calcium fluoride, optical micro-resonator, ultra-precision cylindrical turning

1. Introduction

To reduce the energy loss caused by Joule heating in electric signal circuits, the circuits should be replaced with optical ones. Optical micro-resonators, which can localize light at certain spots, are essential parts in optical signal processing. Although Silica or $SiNb_3$ are conventionally used for optical micro-resonators [1], single-crystal calcium fluoride (CaF_2) is the most suitable material for high Q-factor optical micro-resonators [2]. In terms of the manufacturing of high Q-factor optical micro-resonators, they must be satisfactory with regard to form accuracy, surface roughness and single crystal. Etching is an inadequate approach for obtaining bulge-shaped resonators because of crystal anisotropy; therefore, ultra-precision cylindrical turning (UPCT) is the most feasible fabrication process. However, CaF_2 is characterized by brittleness and crystal anisotropy. Hence, it is necessary to conduct ductile-mode cutting to make a surface without any cracks, taking into account the crystal anisotropy. In a previous study, the UPCT performance of CaF_2 had been investigated to determine the most appropriate cutting condition in terms of crystallography [3]. In this paper, optical micro-resonators were manufactured by UPCT, and the influence that micro-cracks have on resonator performance was experimentally evaluated.

2. Experimental procedure

2.1. Experimental set-up

The UPCT of CaF_2 was carried out by the ultra-precision 5-axes machine tool (ROBONANO α-OiB, FANUC Co., Ltd). A CaF_2 workpiece (6 mm diameter, 35 mm length) with an end face orientation of (100) plane was prepared. Figure 1 shows the experimental set-up of UPCT. A workpiece, fixed on a brass jig with wax, was mounted onto a collet chuck. For the production of optical micro-resonators, two single point diamond tools were used, as well as a nose straight diamond tool. The specifications are listed in Table 1, and Figure 2 shows the appearance of tool #3.

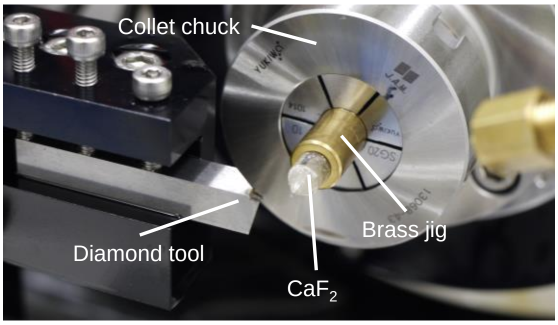

Figure 1. Experimental set-up

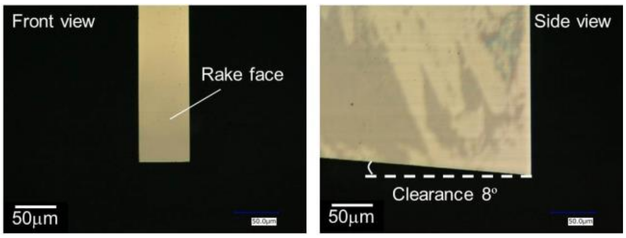

Figure 2. Nose straight diamond tool

Table 1 Specification of cutting tool

Diamond tool geometry	Tool #1	Tool #2	Tool #3
Nose radius/mm	0.2	0.05	-
Rake angle /°	-20	0	0
Cutting edge angle on rake face /°	40	40	90

2.2. Fabrication process of resonators

Figure 3 shows an electromagnetic field analysis of the rectangle resonator, which can store light in a rectangular area. Figure 4 illustrates a fabrication flow of a micro rectangle-shaped resonator:

1) First, brittle-mode rough cutting was carried out with tool #1 to achieve the pen-shape as in Figure 4 (b) with around a 0.54 mm diameter under the following cutting conditions: 1000 min^{-1} rotational speed, 20 μm/rev feed per revolution, and 2 μm depth of cut.

2) Secondly, finish cutting was carried out with tool #2 to make a crack-less surface until around a 0.52 mm diameter was achieved. The cutting conditions are: 1000 min^{-1} rotational speed, 0.1 μm/rev feed per revolution, and 50 nm depth of cut.

3) As shown in Figure 4 (c), the CaF_2 was removed with tool #2 by applying the diagonal tool path under the same condition. Then, a bulged-shape as in Figure 4 (d) was manufactured.

4) As shown in Figure 4 (e), the CaF_2 was removed with tool #3 by moving the tool path under the same condition, except for the feed per revolution. The tool was fed manually by 1 nm at the feed rate of less than 0.01 mm/min.

5) Finally, the rectangular-shaped resonator as in Figure 4(f) was obtained.

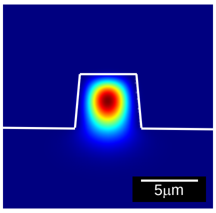

Figure 3. Electromagnetic field analysis of rectangle resonator

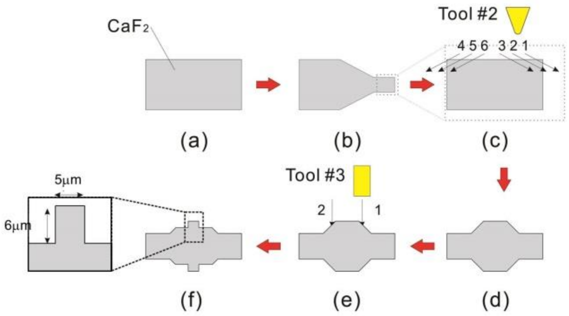

Figure 4. Fabrication flow of resonators

After the UPCT, the optical micro-resonator was cleaned by alkaline agents and ultrapure water to remove the cutting fluid and cutting chip. After drying the resonator with a heater, the resonator performance was evaluated.

3. Results and discussion

Figure 5 shows the appearance of the resonator manufactured by UPCT and the magnified image of the rectangular-shaped portion based on optical microscopy. The diameter of the resonator was around 530 μm, no crack existed throughout the whole cylindrical surface on the resonant part, and its surface roughness Sa was around 2 nm. Figure 6 (a) shows the picture of the resonant part that resulted from scanning white light interferometry microscopy, and the rectangle resonator (Width 5 μm × Height 6 μm) was obtained. The resonator performance was measured by using a wavelength-variable laser (Santec TLS-510, 1pm wavelength resolution). Figure 6 (b) shows the transmission spectrum corresponding to the wavelength. The peak indicates a resonance point where the transmission spectrum temporarily becomes low as a result of the resonator absorbing its resonant wavelength at 1542.803 nm. The quality of an optical micro-resonator is generally characterized by Q-factor, which is given by Eq. (1).

$$Q = \lambda/\Delta\lambda \tag{1}$$

Where λ is a resonant wavelength, Δλ is a full width at half maximum. Light localization time τ is calculated by Eq. (2).

$$\tau = Q/2\pi f \tag{2}$$

Where f is a resonant frequency. A 1.2×10^6 Q-factor and the time of localizing light 0.98 ns were obtained. This result means that light moved through the resonator around 87 times. Figure 7 shows the resonator with a micro-crack. A 4.0×10^4 Q-factor and a 0.04 ns light localization time were obtained. This result shows that light moved through the resonator around 2 times; therefore, it indicates that light scattered from the micro-crack on the resonator, and the influence of the micro-crack was a crucial factor on the resonator performance.

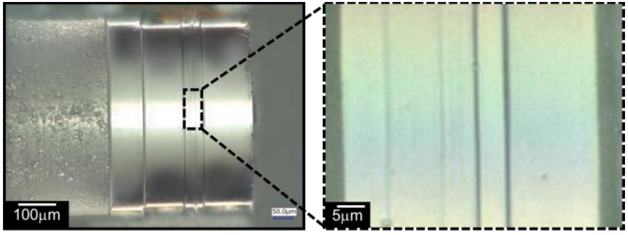

Figure 5. (a) Appearance of resonator (b) Expanded resonant part

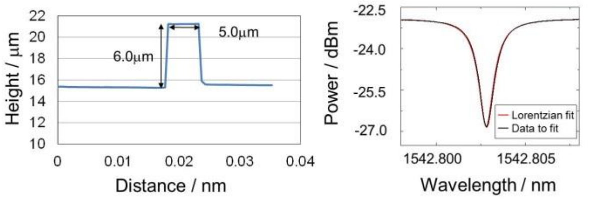

Figure 6. (a) Shape of rectangle resonator (b) Transmission spectrum of the CaF_2 resonator

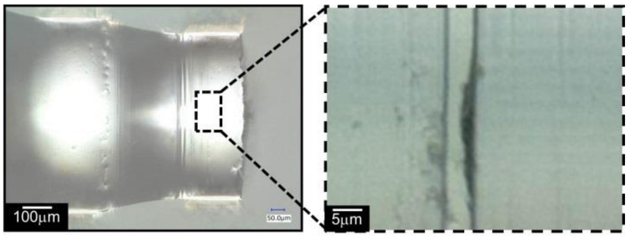

Figure 7. Optical micro-resonator with micro-crack

4. Conclusion

The present paper shows the manufacturing of a CaF_2 rectangle optical micro-resonator with a Q-factor of 1.2×10^6 and without any significant crack. In addition, the influence of a micro-crack on resonator performance is investigated, and this leads to the finding that a micro-crack greatly deteriorates resonator performance. Future work will investigate the influence that resonator shapes have on resonator.

Acknowledgement

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