Investigation of the loss mechanism in a silica toroid microcavity

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We must obtain a silica toroid microcavity with a high $Q$ factor if we are to generate various nonlinear optical effects. Factors limiting the quality factor of a silica toroid microcavity have been studied theoretically, and the effects of, for example, the impurity of a Si wafer, Rayleigh scattering loss, and the adhesion of water molecules have been analyzed. However, when it comes to an actual measurement, none of these are dominant because the $Q$ limited by these factors becomes dominant when its value exceeds $10^8$ but the measured value is usually $Q < 10^7$. Therefore, we investigated other effects limiting the current $Q$ factor of a silica toroid microcavity. We studied the effects of cavity fabrication methods, the external environment, optical measurement, and the cavity structure. As a result of our investigation, we succeeded in achieving $Q = 6.5 \times 10^7$, which is an improvement on the highest $Q$ factor of $Q = 2.0 \times 10^6$ that we reported last year.

**Key words**: Air cleanliness class, surface roughness, fundamental mode

1. Abstract

The silica toroid microcavity was first described as an attractive platform for studying various optical nonlinear phenomena in 2003 because of its ultra-high $Q$ and because it could be fabricated on a chip [1]. The cavity is fabricated with the following procedure. First, a Si wafer is thermally oxidized and a silica layer is formed. Then a circular pattern is formed photolithographically (details omitted). Next, the Si wafer is etched with reactive gas XeF₂. Finally, a CO₂ laser is irradiated from above (this process is called “reflow”). The procedure is outlined in Fig. 1.

![Fig. 1: Fabrication of a silica toroid microcavity.](image)

The performance of the cavity is not limited by the use of photolithography. Therefore, in this study, we investigated to the way in which the $Q$ factor was affected by the reflow process, changes in air cleanliness, the profile of the CO₂ laser, the optical measurement method and the cavity structure.

2. Reflow

After XeF₂ etching, a silica disk supported by a Si pillar is irradiated from above by a CO₂ laser and the silica disk forms a toroidal shape. This phenomenon occurs as a result of the difference between the heat absorption coefficients of Si and silica. Since Si has a much higher heat absorption coefficient, when a CO₂ laser is irradiated from above, the heat around the center of the silica disk flows into the Si pillar whereas heat at the edge of the silica disk is concentrated and the silica disk melts. We can expect that one way of obtaining a high $Q$ is to reduce surface roughness. We considered the reflow process to be crucial as regards surface roughness. Therefore, in this study we changed the CO₂ laser irradiation profile in two ways. One involved using pulse irradiation, which is the conventional approach, and the other involved using lamp irradiation.

![Fig. 2: Reflow process](image)

We found that by changing from pulse to lamp irradiation, the $Q$ factor and the surface roughness both improved from $Q = 3.9 \times 10^6$ to $Q = 1.7 \times 10^7$ and from 181 nm to 4 nm, respectively, as shown in Fig. 3.
3. Optical measurement

In addition to the improvement achieved by fabricating a better cavity, we found that the $Q$ factor can be greatly influenced by optical measurement. The optical model for a toroidal cavity can be expressed as shown in Fig. 4 [2]. When the fundamental mode is excited, the propagation constants in tapered optical fiber and in the cavity have the relationship expressed by eq. (1) below.

$$\beta_{\text{taper}}(a_f) \equiv \left[1 - \left(\frac{a - r_e + a_f}{2R_e}\right)^2\right] \beta_c \quad (1)$$

$\beta_{\text{taper}}$: The propagation constant in tapered optical fiber
$\beta_c$: The propagation constant in the cavity

Eq. (1) and Fig. 4 show that $a, r_e, R_e$ and $\beta_c(a)$ are determined by the cavity. Therefore, when the diameter of the tapered fiber is changed, a different mode is excited. The experimental results are shown in Fig. 5.

![Fig. 3: Surface roughness and $Q$ factor for pulse and lamp irradiation.](image)

![Fig. 5. Transmittance spectrum with different tapered fiber diameters. ($\Delta \beta$ is the value which is briefly calculated difference between the left side and the right side of eq. (1).)](image)

As seen in Fig. 5, we found that by changing the diameter of the tapered fiber, a different mode was excited and the $Q$ factor was greatly improved. The reason for the improvement in the $Q$ factor caused by the different mode is explained in Fig. 6. When the fundamental mode is excited, the light is confined in plane. On the other hand, in a higher order mode, the light is confined in plane and also vertically. Therefore, when light is confined in a higher order mode, it is influenced more by the surface effects than when the fundamental mode is excited.

4. External environment

As part this year’s improvements, our laboratory was renovated and we created a semi-clean room where the air cleanliness class was improved from 50000 to 5000. This renovation improved the preservation of cavities and we can expect impurity adhesion to be reduced. In this study, we exposed a cavity with a $Q$ factor of $Q < 10^7$ outside the laboratory (air cleanliness class 50000) for about 48 hours and compared the transmittance spectra (shown in Fig. 7) obtained before and after exposure.

![Fig. 6(a): Electrical field of FEM simulation for fundamental mode. (b): Electrical field of FEM simulation for second order mode.](image)
As shown in Fig. 7, the $Q$ factor decreased almost by half from $Q = 1.4 \times 10^7$ to $Q = 7.0 \times 10^6$. This was because the adhesion of impurities to the cavity caused the surface scattering of light, which is considered loss. Also, the transmittance spectrum had two dips. The origin of this phenomenon is back-scattering light. When light is reflected at a point where impurities adhere, a portion of the light scatters at the surface and constitutes a loss and another portion of the light scatters back and couples back to the cavity. Therefore, we revealed that a conventional environment limited the $Q$ factor to $Q < 10^7$.

5. Cavity structure

We have shown the effects of changes in the reflow method, optical measurement and external environment in terms of maximizing the $Q$ factor of a cavity. Next, we changed the diameter of the Si pillar and the minor diameter of the cavity (minor diameter corresponds to $a$ in Fig. 4.) Fig. 8(a) and (b): SEM images of two cavities with different minor diameters and their transmittance spectra.

Fig. 8 (a) and (b) reveal that the $Q$ factor was greatly changed by changing the cavity structure. To investigate the reason for this, we performed an FEM simulation for Fig. 8(a) and Fig. 8(b) as shown in Fig. 9(a) and (b).

In Fig. 9 (a) and (b), the intensity at the surface divided by the maximum intensity for each cavity was 0.25 and 0.32, respectively. Therefore, in Fig. 8(b), the light was more likely to be influenced by the surface than in Fig. 8(a) and thus exhibited a lower $Q$ factor.

6. Conclusion

In this study, we investigated the effects of changes in reflow, optical measurement, external environment and cavity structure. As a result, we revealed that the conventional reflow method limited the $Q$ factor to $Q < 10^7$, optical measurement limited the $Q$ factor to $Q < 10^7$, a conventional environment limited the $Q$ factor to $Q < 10^7$ and the cavity structure limited the $Q$ factor to $Q < 10^6$. Ultimately, as shown in Fig. 8(a), we achieved a $Q$ factor of $Q = 6.5 \times 10^7$.

Table. 1 Factors limiting $Q$ factor and $Q$ factor limits

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