Improvement of the laser reflow system and demonstration of resonant wavelength tuning by additional laser reflow

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In this research, we improved the laser reflow system used to perform the laser reflow processes of silica toroid microcavities. Furthermore, we confirmed the feasibility of resonant wavelength tuning by additional laser reflow. The observed resonant wavelength shift was approximately 100 pm toward blue wavelengths.

**Key words:** silica toroid micro cavity, laser reflow, CO$_2$ laser, wavelength tuning

1. Introduction

An optical microcavity is a small container that can confine light. The performance of a cavity can be evaluated in terms of its Q factor. A high Q cavity can greatly enhance the inner light intensity even when the power of the input light is very small.

A silica toroid microcavity was proposed in 2003 by Vahala’s group [1]. The quality factor of this microcavity was $2.1 \times 10^8$ [1], which was much higher than that of a silicon micro-ring cavity ($Q = 1.43 \times 10^5$ [2]) or a photonic crystal cavity ($Q = 1.2 \times 10^6$ [3]).

Optical microcavities are expected to be used for cavity quantum electrodynamics (QED) or coupled resonator induced transparency (CRIT). Precise control of the resonant wavelength is very important if we are to employ microcavities for these applications; for example, the resonant wavelength of a cavity must be perfectly matched to the transition wavelength of a single atom in cavity QED experiments. However, since fabrication errors are inevitable, the resonant wavelength can differ from the designed wavelength. This makes cavity QED and CRIT difficult to achieve.

To solve this problem, a post-fabrication process has been commonly used that can tune the resonant wavelength. However, the post-fabrication wavelength tuning of an ultra-high Q cavity has not been reported. Therefore, in this research, we demonstrate the resonant wavelength tuning of a silica toroid microcavity by using an additional laser reflow process. Moreover, we also report an improvement of the laser reflow system that performs a preliminary procedure in wavelength tuning experiments.

2. Production process and post process

First, we describe the processes used to fabricate a silica toroid microcavity. A schematic diagram is shown in Fig. 1.

First, photolithography is employed on a silicon-on-insulator (SOI) substrate to create disk-shaped silica pads on silicon (top left in Fig. 1). Next, dry etching is carried out and the silica pads are undercut (top right in Fig. 1). Finally, the silica disk is irradiated with a CO$_2$ laser. Then, just the silica disk is melted and shrunk, and a mushroom-shaped structure (bottom of Fig. 1) is obtained because silica has a larger thermal conductivity and absorption coefficient than silicon. This process is called the "laser reflow process" and is essential if we are to achieve a silica toroid microcavity with an ultra-high Q.

![Fig. 1: Flow diagram illustrating the process used to fabricate silica toroid microcavities [1].](image)

Next, we describe our improvement of the laser reflow system. Fig. 2 shows a silica toroid microcavity fabricated with the conventional system. When we employed the conventional system, the shape of the silica toroid microcavity became an ellipse. As a result of this distorted shape, the maximum Q was only about $10^5$.

![Fig. 2: SEM picture of toroid microcavity fabricated with the conventional laser reflow system](image)

We considered the cause of the distortion to be the fact that the beam spot provided by the lens was much smaller than the diameter of the disk. To make the beam spot larger, we replaced the lens of the reflow system with one that had a longer focal length. A schematic image is shown in Fig. 3.
Moreover, we improved the camera observation system. In the conventional system, we used a ZnSe lens that was designed to be used for IR light for both laser reflow and the camera observation system. This design made the camera resolution low and laser light alignment very difficult. To solve this problem, we employed a new objective lens, which was designed for use with visible light, for the camera observation system. The resolution of the camera improved and the laser light alignment became very easy. The new laser reflow system is illustrated in Fig. 4.

The procedure for the resonant wavelength tuning experiment was as follows.

1. We prepared several silica toroid microcavities on the same chip.
2. Measurement was started after 30 minutes to minimize the influence of TO and the formation of a water layer on the cavity surface (discussed later).
3. After measurement, the microcavities were reinstalled in the reflow system, and irradiated with the laser.

The toroid cavities were fabricated with an irradiation power of 4 W (power density 53.2 MW/m²) and an irradiation duration of 50 ms. In the wavelength tuning experiments, the additional laser reflow power was gradually increased by 1 W, +2W, …, and 6 W. This is because the diameter of the toroid depends only on the laser reflow power [1], so we predicted that the diameter would not change if we performed an additional laser reflow with the same irradiation power.

Next, we report our experimental results. First, we show transmission spectra measured after the 1st and 2nd additional laser refloows (the irradiation powers were 1 and 2 W) in Fig. 7. The figure shows that the shape of the transmission spectra was greatly changed and the Q value was increased from $7.3 \times 10^5$ to $1.3 \times 10^6$ after the 2nd additional reflow.
The transmission spectra measured after the 2nd and 3rd additional laser reflows (the irradiation powers were 2 and 3 W) are shown in Fig. 8. The figure reveals a wavelength shift of 86 pm toward a shorter wavelength. After the 3rd additional reflow, the $Q$ value decreased from $1.3 \times 10^6$ to $1.0 \times 10^6$.

Finally, we discuss the results. In Fig. 7 the shape of the transmission spectra was changed after the 2nd laser reflow. This is because the surface became smooth after the 2nd additional reflow and then high-$Q$ resonance was generated. The increase in $Q$ after the 2nd additional laser reflow supports this hypothesis.

Next, we discuss whether or not the wavelength shift in Fig. 8 is caused by the additional laser reflow. The resonant wavelength can be shifted for several reasons other than an additional laser reflow. These include the formation of a water layer on the surface, which can increase the cavity diameter, a thermo-optic (TO) effect and a change in the distance between a cavity and a taper, which can change effective refractive index of the cavity. However, we confirmed experimentally that the influence of the water layer and taper-cavity distance was trivial. In addition a wavelength shift of 100 pm corresponds to a temperature change of approximately 10K and it is unrealistic to regard that wavelength shift as being induced purely by a TO effect. Therefore, we can conclude that the wavelength shift was caused by the additional laser reflow.

Finally, we discuss the result shown in Fig. 9. We consider that the change in the transmission spectra was caused by the large diameter change. According to Eq. (1), a radius change of 1 $\mu$m leads to a wavelength shift of a few tens of nanometers. So it is very difficult to trace the wavelength shift when a high power additional reflow is irradiated. Note that the decreased $Q$ was caused by the surface roughness induced by the high irradiation power.

5. Conclusion

In this study, we improved the laser reflow system and fabricated a silica toroid microcavity with a $Q$ factor of $1.6 \times 10^6$, which is ten times higher than that of the cavity fabricated by the conventional system. Note that this value is much smaller than that reported in ref. [1] due to cavity contamination, surface roughness and water layer formation. The elimination of these effects is an important task.

Moreover, we achieved a resonant wavelength shift of about 100 pm by additional irradiation. When the irradiation power is too high, it is difficult to observe the wavelength shift because the induced wavelength shift is very large. We have not determined the optimum power yet and so we must conduct further experiments to examine the additional laser reflow conditions.

Reference