Ultra-small Optical Fiber Fabry-Pérot Cavities Fabricated by Laser-Induced Photothermal Effect

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Abstract: We proposed the HF etching method using laser-induced photothermal effect and found that curvatures of cavities can affect its Q-factor. We also show the potential for the novel metal (Ag) coating process for the cavity surface.

1. Introduction

Optical fiber-based Fabry-Pérot cavities (FPC) have been intensively investigated for not only optical communication systems but also quantum electrodynamics (QED) and sensing systems [1] as they can provide a promising small size for close proximity to molecules and they can achieve high light-matter interactions with inherent ultra-small loss (attenuation coefficient of 0.2dB/km). The fiber-based optical resonator is a powerful platform and offers a number of advantages, such as low cost, small mode volume, lightweight, and low insertion loss due to direct coupling to light sources [2].

Fundamental figures of merits for the FPC are its Finesse and Q-factor. Finesse essentially quantifies the average number of round trips between mirrors, prior to several loss steps, such as being absorbed, dispersed, or scattered out of the cavity [3]. Q-factor has a similar concept with finesse, except that it depends on the cavity length. Because of the advantages of high finesse and Q-factor, there has historically been a great deal of effort to increase the values by changing the reflectance and cavity length. In addition to reflectance and cavity length, the radius of curvature (ROC) is also an important factor of FPC with cavity stability and coupling efficiency, and its relationship with Q-factor is not reported directly.

In this study, we report how ROC can enhance Q-factor as well as Finesse. To create concave surfaces at the end facets of optical fibers, in recent decades, a well-known method using hydrofluoric acid (HF) was introduced by researchers at the University of Birmingham, in 2007 [4]. The concave shapes were formed by different etch rates between the core and the cladding layers due to the refractive index contrast of the layers [5]. However, the concave shapes and their ROCs by the classical etching methods are intrinsically determined by the index contrast. In addition, their values are also non-controllable. To overcome this limitation, we proposed a new fiber facet etching method based on a laser-induced photothermal effect in [6], and we changed laser power, etching time, and HF concentration in this work. Furthermore, to enhance finesse and Q-factor of the cavities from the effect of improved reflectivity, we coated low loss novel metals, such as Ag and Au, onto the etched fiber facets. The authors believe that the proposed method and processes will allow us to achieve a controllable ROC of the end facets of optical fibers and improve the performances of the cavities.

2. Controllable ROC using Laser-Induced Photothermal Effect

Laser-induced photothermal effect can be a solution for the existing HF etching method, which has the disadvantage that ROC cannot be controlled. Fig.1 (a) and (b) schematically shows the proposed fabrication procedures for concave facets of optical fibers. The laser with a wavelength of 1.55 μm was applied to the optical fiber. Then the etchant (HF aqueous solution) absorbed the laser and heated up by laser-induced photothermal effect as shown in Fig 1(a). The absorption coefficient of the HF aqueous solution is estimated to be 10.0/cm when the wavelength of 1.55μm laser is applied, which is higher than those of UV, visible, and NIR ranges [7]. As a result of these fabrication processes, the cleaved flat fiber facet becomes concave as shown in Fig 1(b).

Fabrication of concave fiber facet based on the laser-induced photothermal effect can be affected by several variables. Among them, three variables had selected, which are laser power, etching time, the concentration of HF aqueous solution. Then, we manipulated and controlled those variables, and looked at how the ROC of concave facet changed. In order to identify the ROC changes according to the applied laser power, the laser of 1.55 μm wavelength, which is widely used in optical communication and SMF-28 optical fiber.

The applied laser power was changed to 0, 10, 20, 30, 40, and 48 mW. After etching for 5minutes in 49% HF aqueous solution with the laser applied, etched fiber tips had been soaked in a beaker containing DI water for 1 minute to prevent additional etching by the residual HF aqueous solution on the fiber tips even after the desired etching time. These samples were photographed through an optical microscope and then the ROC of the etched fiber tips were analyzed. Fig.1 (c) shows the ROC of the etched fiber facet with respect to the power of laser applied during etching for about 5 minutes on a 49% HF aqueous solution. The results showed that as the laser power increased, the ROC of the concave fiber facet increased until the laser power was 20mW, and for the laser power greater than 20mW, the ROC gradually decreased.

Next, we looked at how the variation of ROC over etching time depends on the power of the laser applied. To this end, the ROCs of the concave fiber facet, which were etched with laser power of 0, 10, and 20 mW in 49% HF aqueous solution for 5, 7.5, 10, 12.5, 15, and 17.5 minutes, were measured. As shown in Fig. 1 (d), when the lasers of different power are applied, the behavior of the ROC according to the etching time was all similar. The smallest ROC was obtained when etched for 7.5 minutes without an applied laser process and when etched for 10 minutes with a laser.

The concentration of the HF aqueous solution can be another factor influencing the ROC of the concave fiber facet fabricated by HF aqueous solution. To see how the concentration of the HF aqueous solution affected the change in ROC according to the applied laser power, the concave fiber facet was fabricated in different conditions, where the concentration of the HF aqueous solution was changed to 31.8, 40.7, 49%, respectively, and the power of the laser was 0, 10, 20 mW. As shown in Fig.1 (e), the greater the ROC of the concave fiber facet can be obtained by the higher the concentration of the HF aqueous solution.

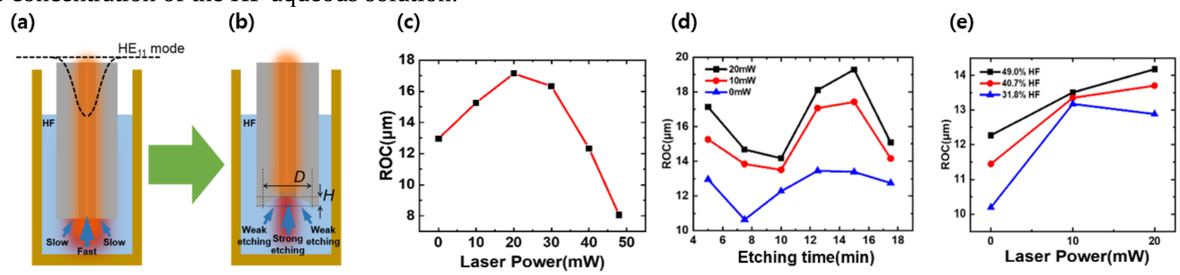

Fig. 1. (a), (b) Fabrication procedures of a concave fiber facet using laser-induced photothermal effects.
(c) ROC of the concave fiber facet due to laser power. (d) ROC of the concave fiber facet due to etching time.
(e) ROC of the concave fiber facet due to concentration of the HF aqueous solution.

We measured the Q-factor and Finesse of the concave fiber-based cavity from the transmission spectrum obtained by optical spectrum analyzer (OSA) and compared it with the case of a flat fiber-based cavity. As shown in Fig. 2, two types of cavities were fabricated. Fig.2 (a) and (b) shows combinations of the flat facets and curved facets, respectively. When a free spectral range (FSR) is 0.561 THz, which is dependent on the cavity length, the cavity with flat facets presents 270.37 of Q-factor and 0.78 of finesse values. Regarding the effective index of SMF-28 and 1.55 μm wavelength, the values are reasonable and quite well agree with the theoretical values (0.65 of finesse and 4% of reflectivity between air and silica interfaces). However, the cavity consisted of two curved facets, which are fabricated by a chemical etching method using 49% HF aqueous solution with 5 minutes, shows 503.54 of Q-factor and 1.28 of finesse values when an FSR is 0.489 THz. From this result, we can believe that the ROC can affect Q-factor. Curved facets can reduce the optical loss with higher coupling efficiency, rather than that of the case of Fig.2 (a), at the end facets during round trips and build-up process inside the cavity space. However, the longer cavity length generally shows an improved Q-factor value, therefore, in this comparison between samples (a) and (b) in Fig. 2, FSR should be regarded. Even though the length of the cavity of the case (b) is 1.15 times longer than (a), Q-factor is improved 1.86 times. We can believe that the improved Q-factor can be obtained from the curved facets, and the light inside the cavity can stay longer inside the cavity with curved facets.

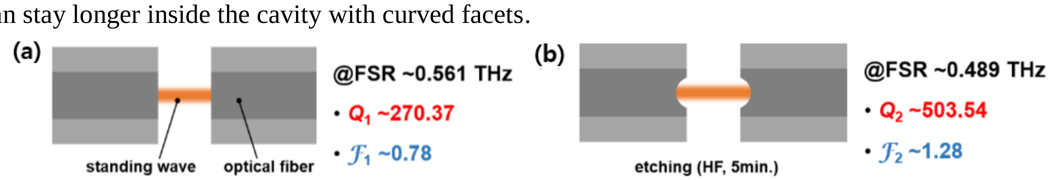

Fig. 2. (a) Calculated Q-factor and Finesse of the flat surface cavity. (b) Calculated Q-factor and Finesse of the concave surface cavity.

3. Metal Coated Fiber Facets

The surface conditions, especially reflectivity were considered to improve the performance of the cavity. To enhance reflectivity inside a cavity, novel metals, such as Ag and Au has been adopted. Because of low loss at a wavelength of 1.55 μm, Ag and Au are very welcome to be used as mirrors at the end facets of the fiber-type cavities. Even though the loss is much higher than that of Bragg mirrors with dielectric layers, the metal deposition is easy to be formed at the end facets and shows a cost-effective method. Figure 3(a) and (b) shows scanning electron microscope (SEM) images of the thickness of about 60 nm Ag (a) and Au (b) coated surfaces. Ag-coated surfaces show better results in terms of surface roughness and flatness rather than Au surfaces. Au-coated surfaces show worse roughness, and adhesion condition seems not good between metal and silica facets. Therefore, it seems that adhesion layers, such as Ti, should be used between Au and silica fiber substrate. As a result, in this study, we used Ag coating for improved reflectance with good roughness quality of metal surfaces.

As shown in Fig 3(c) and (d), due to the metal deposition, visibility has increased compared to the uncoated fiber cavity. Figure 3(e) schematically shows a cavity with Ag-coated flat type surfaces compared to an uncoated fiber end facets based cavity, which is shown in Figure 3(f). When an FSR is 0.338 THz, the metal-coated cavity shows 1784.48 of Q-factor and 3.12 of finesse values. Although there are many points that need to be further developed in the metal deposition process, there is also some crucial point that we should note. As shown in Figure 27, there is a preceding case that shows 875 of Q-factor and 3 of Finesse by using a dielectric coating. Considering that our experimental result (Figure 3(e)) shows 1784.8 of Q-factor and 3.12 of Finesse, our results can be meaningful in that they show somewhat higher performance than when the dielectric coating was performed using low-cost metal-coated [8].

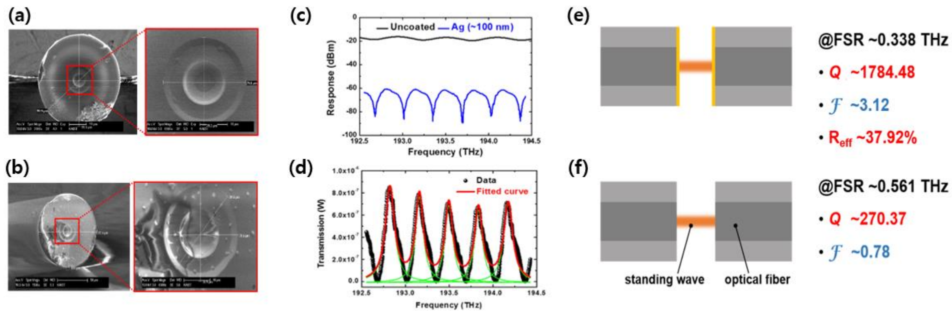

Fig. 3. (a) SEM images of the curved Ag-coated facet. (b) SEM images of the curved Au-coated facet. (c) The difference of visibility between Ag-coated and uncoated facet. (d) The Lorentzian fitted curve at the measured data of Ag-coated facet. (e) Q-factor and Finesse of the flat Ag-coated cavity. (f) Q-factor and Finesse of the flat uncoated cavity.

4. Conclusion

Improvement of the cavity performance is an important topic in cavity quantum electrodynamics (CQED) [8]. In that view, ROC is an important factor because it can affect the stability and coupling efficiency of cavities. However, the existing HF etching method has a disadvantage that it cannot control the ROC. As a solution for this, we proposed the HF etching method using laser-induced photothermal effect. We found out how the ROC differs according to each of the variables, such as laser power, etching time, and the concentration of HF aqueous solution, and as a result, we were able to achieve controllable ROC of fiber facets. Additionally, we found that the ROC of the cavity surface can affect to Q-factor, not only stability and coupling efficiency by experiment. We have also made efforts to increase the reflectivity of the cavity, which is already known to affect Q-factor and Finesse. Here, we used novel metal, Ag, which shows a low loss at a wavelength of $1.55\mu m$. Even though the loss is much higher than that of Bragg mirrors with dielectric layers, which is commonly used in fiber coating, it could be a cost-effective method. For further research, we are going to try to splice the Ag coated concave fiber facets fabricated by our proposed etching method. We expect that the above method can be used to fabricate ultra-small fiber-based Fabry-Pérot cavities with a high Q-factor.

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