Compact On-Chip crystalline Resonator Integration with Etching Tapered Fiber Waveguide

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Abstract: Whispering-gallery mode crystalline resonators currently maintain the best quality factor (Q) record, however, compact on-chip packaging is still a challenge although various coupling architectures have been developed. Here, a chemical etching method is proposed to fabricate a miniaturized tapered fiber waveguide on silicon substrate. The Marangoni effect is implemented to reduce the surface roughness of the cone region. The optical loss of 0.1 dB/mm is obtained, and the Q of on-chip crystalline resonator exceeds 108. Additionally, TEC is implanted in the package to actively customize the temperature, and the temperature response of 18 pm°C is consistent with the theoretical calculation.

1. Introduction

Crystalline resonators with ultra-high quality factors (Q) have become a versatile platform for fundamental studies and technological applications of light. The surface roughness of the crystalline resonators fabricated by mechanical cutting and polishing has reached the order of sub-nanometer[1], crystalline has the advantage of high purity and low material losses, with higher Q compared to resonators of other materials. More importantly, crystalline resonators that support whispering-gallery modes (WGMs) can preserve ultra-high-Q factors for longer time because they do not absorb water vapor from the surroundings, which have been widely studied in nonlinear optics[2, 3], microwave photonic applications[4, 5], and especially high-sensitivity sensors[6, 7].

WGMs[8, 9] have rotational symmetry, which are confined inside the crystalline resonators[10]. Due to the isotropic emission property resulting from the rotational symmetry, the resonators have to rely on evanescent field couplers to excite the modes and collect their emission[11]. Various evanescent field couplers for crystalline resonators have been implemented so far[12], including prism[13, 14], waveguide[15], grating-based fiber[16], and tapered fiber[17]. In comparison, tapered fiber fabricated by the heat-and-pull method has the highest coupling efficiency and fewer transmission losses[18], which is widely used for research in the lab but not for on-chip integrated applications[19]. The reason for this is that it does not provide sufficient stability and compactness due to its own length and fragility. Therefore, it is still a challenge to realize the on-chip compact high-efficiency coupling package of crystalline resonators while making full advantage of the ultra-high-Q.

In this paper, we propose a chemical etching method to fabricate an on-chip tapered fiber by multi-step etching with different concentrations. Mostly, the Marangoni effect drives the flow of hydrofluoric (HF) acid microdroplets to reduce post-etch pitting, and resulting smooth tapered fiber cone. On this basis, we have achieved a compact package of the on-chip etched fiber coupled with the crystalline resonator and added temperature control function. The experimental results show that this package keeps the Q factor at the order of 108, which is
more compact and stable, in addition to good temperature response. This packaging method provides an efficient way for the application of crystalline resonators.

2. Fabrication and experimental setup

As a preparation before the etching process, we mechanically stripped a standard single-mode fiber (SMF-28) 15 mm of the coating and ultrasonically cleaned it with isopropanol to remove surface impurities. The optical fiber is fixed on a special HF-resistant U-shaped bracket. The acid droplet is placed on the 3D printed Polytetrafluoroethylene (PTFE) circular concave surface with a diameter of 5 mm, which placed in the middle of the optical fiber holder. The acid droplet will form a spherical shape due to surface tension.

In the first step, the optical fiber is etched by a droplet of 48 % HF acid for 30 min. When the droplet contacts the fiber, it is stretched along the fiber due to surface tension, which creates a gradient of concentration. At the same time, a surface tension gradient is created along the fiber as a result of lower acid concentrations correspond to higher surface tensions. Thus, the Marangoni effect ensues, i.e. the flow of liquid from low to high surface tension, which causes the fiber to taper and removes surface corrugations, as shown in Fig. 1(a). In the second step, the concentration is changed to 24 % in order to precisely control the diameter of the fiber waist and reduce the etching rate. The laser and power meter are connected on both sides of the fiber, which determines the termination etching time by the change of transmission power, as shown in Fig. 1(b). As the concentration decreases, the etch rate becomes lower and the HF acid microdroplets flow slowly. We obtained a smoother surface by placing a movable platform to physically accelerate the flow of droplets, while eliminating the corrugations on the fiber surface. Finally, the tapered fiber is etched with 5% HF acid, which transferred from the fiber holder to a 10 mm × 20 mm silicon substrate for fixation with UV glue (NOA63). Then we observe the diameter of the fiber waist through a microscope until the desired, to prepare for the subsequent coupling, as shown in Fig. 1(c).

![Fig. 1. (a) Schematic diagram of HF etching principle (b) Etching device with movable platform and monitoring power change (c) Etching on a silicon substrate, the diameter of fiber is observed through microscope.](image)

Compared with previous method[20], our devices are more secure and controllable to fix the acid droplet in the container, which can determine the required fiber length by adjusting the droplet size through the container. Our approach is primarily based on safety, time required, and optical power loss, and the entire process is carried out in a fume hood to prevent harmful gases from entering the environment.
3. Results and Discussion

3.1 Etching rate and Fiber characteristic

Etching rate is uncontrollable because of changes in environment (mainly temperature). We have found that there is low loss at the beginning of etching, but when the diameter of the fiber waist drops to 9-11 μm, the optical power will drop suddenly, as shown in Fig. 2(b). The reason for this phenomenon is that the core part starts to be etched after the cladding part of the single mode fiber is completely etched. This will destroy the total reflection of light along the fiber, resulting in a large optical loss.

High-concentration HF acid has strong etch ability, but the etching process is difficult to terminate in time in the thin fiber area, we choose low-concentration HF as the termination etchant. The lower the concentration, the slower the reaction rate and the smoother the fiber surface. However, performing the entire etching process with a diluted HF acid solution takes too much time. To reduce reaction time, a movable platform was placed under the acid container with the direction of motion parallel to the fiber. By controlling the speed of the moving platform, etching rate of the fiber is accelerated and the defects on the surface of the fiber are repaired.

![Fig. 2](image)

We transferred the etched 9-11 μm fiber from the fiber holder to the treated silicon substrate to complete the final step of etching. Considering that the fragility of the optical fiber and subsequent packaging, silicon substrates can serve as not only packaging bases to better protect optical fibers, but also reaction vessels. Dilute HF acid(concentrated HF acid has poor hydrophobicity) can form Si-H bonds on the silicon surface resulting in hydrophobicity[21]. We etched the on-chip optical fiber to 1-3 μm with 5% HF acid under the microscope, and its insertion loss was measured to be 0.1 dB/mm at 1550 nm wavelength. In addition, we study the rate of etching SMF-28 single-mode fiber with 48% HF in the range of 23-29 °C by the water bath method. The fiber etching rate increases with temperature as shown in Fig. 2(d), the growth rate is growing slow. Since HF acid is extremely volatile, the concentrations will gradually decrease as the ambient temperature increases, which evolves the main factor to restrict etching rate.
3.2 Coupling and Testing

We fabricated the calcium fluoride (CaF$_2$) crystalline resonators by single-point diamond cutting and mechanical polishing. The device for measuring resonant transmission spectroscopy is shown in Fig. 3(a), which includes a tunable laser, a polarization controller, a coupling system, a photodetector (PD), and a digital oscilloscope. The wavelength of the laser is scanned to obtain the transmission spectrum for characterization of the resonator, the polarization controller is used in the polarization state of the laser beam, and the light output from the fiber cone is output from the PD to the oscilloscope through the adjustable attenuator for data acquisition. The disk resonators and tapered fibers are monitored simultaneously from the side and the top by two CCD cameras. For increasing the robustness of the system, the tapered fiber is tightly attached to the resonator surface to prevent changes in the coupling gap from affecting the resonant spectrum.

![Diagram](attachment:image.png)

**Fig. 3.** (a) Schematic of the experimental setup used to measure the resonance of the CaF$_2$ disk resonators (b) Transmission spectra of disk-taper coupling system (c) Coupling of disk resonators with tapered fibers prepared by the heat-and-pull method (d) The disk resonator is transferred to the silicon substrate and coupled with the tapered fiber prepared by the etching method.

After the CaF$_2$ disk resonator is fabricated it is fixed with wax on the designed copper column. The resonator is controlled to move by a high-accuracy 6-axis positioning system in an upside-down state. Subsequently the resonator gradually approaches the on-chip etched tapered fiber while the optical transmission of the fiber is monitored. The optimal coupling position is found by controlling the coupling spacing and observing the WGMs in the transmission spectrum. Next the resonator is slowly moved away from the fiber and a trace of UV curable adhesive is placed at that position on the silicon substrate. Then the resonator is moved back to the previous coupling position and the adhesive is cured by UV light in order to fix the resonator on the chip. Finally, the disk resonator and the copper column are separated by heating to melt the wax, and the coupling of the on-chip fiber to the CaF$_2$ disk resonator is completed. The whole process is implemented in an ultra-clean room to avoid pollution of the external environment. The Q factor reflects the ability of the resonators to confine and store photons. Through the two measured transmission spectra in Fig. 3(b), it is found that the Q and coupling efficiency do not change much after the disk resonator is transferred, which is maintained at an order of magnitude. This shows that the method of coupling the on-chip fiber with the CaF$_2$ disk resonator is feasible. The optical fiber is fabricated on a silicon chip as a monolithic structure, coupled with the disk resonator and in physical contact, the structure remains very robust.
We measure $Q \approx 1.2 \times 10^8$ by the linewidth method in the spectrogram, and many modes can be observed. This means that it cannot only be applied to the study of nonlinear optics, but also the high-Q characteristics can enable the WGM-based optical resonator sensors to obtain higher resolution. The most important thing is that the effective volume of the entire on-chip structure is $5 \times 15 \times 0.5$ mm$^3$. The small size can make it easier to use in other optical systems and microwave photonic systems, and can also work with other optoelectronic integrated devices on-chip systems.

### 3.3 Packaging and Temperature sensing

The crystalline resonators are extremely sensitive to the external environment, especially temperature, so we add a temperature control system. To reduce temperature fluctuation and improve measurement stability, a 20 mm$\times$20 mm TEC is placed under the silicon substrate, and thermal grease is added in the middle to ensure efficient heat transfer. For silicon-based sensors, the high thermal conductivity of silicon can provide larger temperature detection signals while reducing background noise, thereby improving the overall signal-to-noise ratio. A sensor with resolution of 0.002 °C was placed on the silicon substrate for more accurate feedback of the resonator temperature. Then the whole device is sealed and packaged with a designed aluminum casing through a sealant to prevent external environmental influences, as shown in Fig. 4(a). TEC and the thermocouple sensor are externally connected to the controller to control and read the temperature.

![Fig. 4. (a) The physical image and internal structure diagram after packaging and the size is 25 mm$\times$25 mm$\times$5 mm (b) The transmission spectrum of the on-chip tapered optical fiber and the CaF$_2$ disk resonator coupling packaging system at two different temperatures.](image)

To demonstrate the practicality of the device, the experiments for temperature sensing tests were carried out. The location of the resonance wavelength is determined by the geometry of the resonator and the material properties of the device, which can be expressed by the following expression:

$$\frac{\Delta \lambda}{\lambda} = \frac{\Delta n}{n} + \frac{\Delta R}{R},$$  \hspace{1cm} (1)

Where $\lambda$ is the resonant wavelength, $n$ is the refractive index, $R$ is the radius of the resonator, and $\Delta$ is the change. The change in refractive index and the deformation of the resonator are affected by the thermo-optic effect and the thermal expansion effect. The temperature sensitivity and thermo-optic and thermal expansion effects can be described by the following equations[22]:
\[ S = \frac{\Delta \lambda}{\Delta T} = \lambda \left( \theta + \frac{1}{n} \frac{dn}{dT} \right), \]  

(2)

Which \( S \) is the temperature sensitivity, \( \lambda = 1550 \) nm is the resonant wavelength of the resonator, \( \theta = 18.85 \times 10^{-6} \) K\(^{-1} \) is the thermal expansion coefficient, \( n = 1.426 \) is the refractive index of CaF\(_2\) crystalline, \( dn/dT = -10.6 \times 10^{-6} \) K\(^{-1} \). The theoretical value of temperature sensitivity is 17.7 pm/K.

The transmission spectrum was obtained by scanning with a tunable laser source in the wavelength range around 1550 nm, which was read by a PD. Setting the packaged device at two temperatures of 21.85 °C and 27.12 °C, one can see that the wavelength of WGMs shifts to longer wavelengths, as shown in Fig. 4(b). The thermal displacement of WGMs is 95.15 pm, and the temperature sensitivity measured by calculation is 18.06 pm/°C, which is consistent with the calculated theoretical value.

To obtain the sensitivity more precisely, we measure the wavelength shift of the resonance at both elevated and reduced temperatures in units of 0.1 °C at 23-24 °C. For ensuring the reliability and difference of the data, two different resonance peaks in the transmission spectrum are selected, as shown in Fig. 5(a). It is determined that the sensitivity is 18.53 pm/°C when the temperature rises, and the sensitivity is 18.14 pm/°C when the temperature decreases through linear fitting, as shown in Fig. 5(b). The resulting error may be related to the hysteresis of the TEC and the accuracy of the thermocouple, but the temperature response is very close to the theoretical value.

![Graph](image)

**Fig. 5.** (a) Shifts of WGM resonances at different temperatures in the range of 23 °C to 24 °C (b) Linear fitting of wavelength shifts with respect to temperature.

4. **Conclusions and Outlook**

In conclusion, we propose a kinematic etching method to fabricate on-chip tapered optical fibers coupled with CaF\(_2\) crystalline resonators to achieve a compact package structure, which successfully has ultra-high Q factor and isolates the interference of external environmental factors. The temperature sensing test is done while adding the temperature control to the coupling system. Meanwhile, the resonant wavelength shifts are obtained by adjusting the temperature in the range of 23-24 °C, and the linear fitting shows that the temperature response is 18 pm/°C, which is very close to the theoretical value. This work facilitates the development of WGM-based applications and portable, tunable and robust devices such as optical filters, optical frequency combs and optical gyroscopes.
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