Novel Fabrication Method for a High-Q Capillary-Based Whispering-Gallery-Mode Biosensor

Michael Zakrewsky
Chemical Engineering, Rensselaer Polytechnic Institute

NNIN REU Site: Nano Research Facility, Washington University in St. Louis, St. Louis, MO
NNIN REU Principal Investigator(s): Dr. Lan Yang, Electrical & Systems Engr., Washington University in St. Louis
NNIN REU Mentor(s): Dr. Sahin Ozdemir, Electrical & Systems Engineering, Washington University in St. Louis
Contact: zakrem@rpi.edu, yang@ese.wustl.edu, ozdemir@ese.wustl.edu

Abstract:

We developed a novel fabrication method for a capillary-based Whispering-Gallery-Mode (WGM) resonator by employing pressurized inert gas to overcome the effects of surface tension during the capillary pulling process. Current fabrication protocols employing hydrofluoric acid (HF) etching of the capillary wall produce rough interior surfaces resulting in lower quality factors due to scattering losses. Using our protocol, we produced capillaries with less interior roughness and higher quality factors, showed a near-linear relationship between gas pressure and wall-thickness, and laid out a plan for further improvements.

Introduction:

Optical sensors rely on the light/molecule interaction, which is significantly enhanced by a resonant structure. A variety of optical resonators have been investigated for ultra-sensitive and label-free sensing [1-3]. Among them, WGM resonators, in which light is trapped in circulating orbits by total internal reflections, hold the highest quality. The quality (*Q*-factor) of a resonator is an important parameter reflecting the power dissipation rate of a resonant system, and is defined as $Q = \omega \cdot$Stored Energy/Power Loss $= \omega \cdot \tau$, where ω is the resonant frequency and τ denotes the photon lifetime in the resonator. Higher *Q*-factor implies stronger light-matter interactions [4], and *Q*-factors in excess of 100 million have been achieved in WGM resonators. Light can circulate around a WGM resonator millions of times allowing a single particle/molecule to cause a noticeable change in the transmission spectrum of outgoing light.

Over the past couple years, there has been a growing interest in the application of WGM resonators as biosensors, and they have been used for single molecule and label-free detection of a wide range of biomolecules; however, they also have the potential to quantify the behavior of amyloids and prions like never before. Unlike current analytical techniques, WGM biosensors are not limited to specific sample environments and large sample concentrations, which make them appealing for studying aggregate species. WGM biosensors provide real-time quantitative data on the change in refractive index and polarizability from which a particle's mass, conformation, and shape can be deduced, offering high-resolution kinetic data of amyloid nucleation and the conformation changes that occur during aggregation-all of which, to the best of the author's knowledge, have not been analyzed quantitatively, or at least not to the level of resolution possible with a WGM biosensor.

Before these experiments can be realized improvements need to be made to the resonators; in particular, higher *Q*-factors for water based samples and higher sensitivities to refractive index changes need to be achieved in a device that incorporates both the WGM resonator and fluidics to introduce our biological sample. For this reason, a capillary architecture was chosen as the sensor platform: the channel supports fluidics and the cross-sectional ring supports WGM.

Experimental Procedure:

Current fabrication methods call for tapering a glass capillary from an initial diameter of 1 mm down to 100 μm. Afterwards, the interior is etched with HF to reduce wall-thickness and achieve a desired sensitivity; however, doing so causes roughness to the interior surface, which increases scattering loss and subsequently diminishes the *Q*-factor.

To increase the *Q*-factor and sensitivity of capillary resonators, we developed a novel fabrication protocol by employing pressurized inert gas. By employing pressurized inert gas during fabrication, three improvements to the capillary resonator are achieved. First, we can fabricate thin-walled capillaries without the interior roughness attributed to acid etching. Second, we can fabricate capillaries with smaller mode volumes by decreasing the wall-thickness, thereby increasing the intensity and particle interaction of light within the resonator. Third, reflow of the resonator exterior, similar to procedures that made toroids with ultra-high *Q*-factors, can be performed to increase the *Q*-factors of capillary resonators.

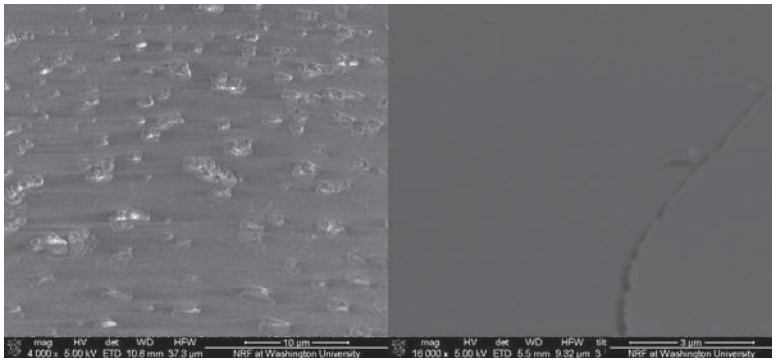

Figure 1: SEM images of capillary interior surfaces; acid etched (left), and pressurized with inert gas (right).

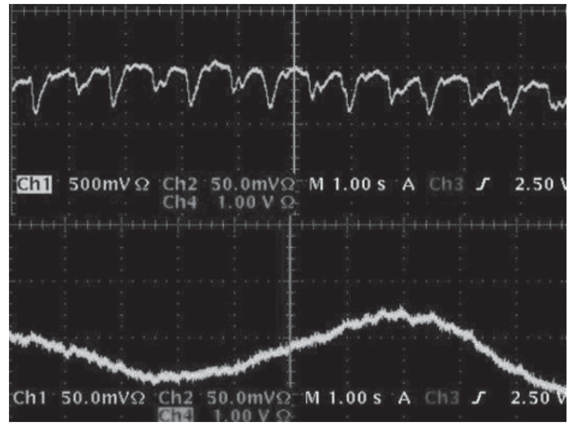

Figure 2: Transmission spectrum of a smooth capillary, before (top) and after acid etching (bottom).

Using our protocol, we produced capillaries with much less interior roughness than is possible with current HF etching methods (Figure 1). As expected, smooth capillaries showed a dramatic increase in *Q*-factor over acid etched capillaries.

The *Q*-factors of capillaries fabricated with pressurized inert gas were measured before and after etching with HF. Before etching, *Q*-factors around 10^4 were observed. After etching, resonance nearly disappears (Figure 2).

Next, capillaries were fabricated at various pressures to study the effect of gas pressure on wall-thickness, and showed a near-linear relationship (Figure 3). As gas pressure increased, the ratio of outer to inner diameter decreased.

Results and Conclusions:

Currently, fabrication of capillaries with sub-micron wall-thicknesses is being attempted, and the *Q*-factor and sensitivity of smooth capillaries supporting WGM are being tested. In the near future, reproducibility will be improved by using CO_2 lasers instead of a hydrogen flame to allow finer control of the glass temperature during pulling, and smooth capillaries will be fabricated using glass that is nearly exclusively preferred by others working with capillary WGM resonators due to its high quality, fused-quartz.

In conclusion, high-*Q* capillary-based WGM biosensors have the potential to further our understanding of both the light/molecule interaction in WGM resonators, and misfolding proteins and their diseases. We took the first step toward realizing this capability by developing a novel fabrication method that employs pressurized inert gas during the pulling process. Using our protocol we produced capillaries with smoother interior surfaces and higher *Q*-factors, showed a near-linear relationship between gas pressure and wall-thickness, and laid the groundwork for further improvements.

Acknowledgements:

National Science Foundation, National Nanotechnology Infrastructure Network Research Experience for Undergraduates (NNIN REU) Program, Amy Sears.

References:

[1] Armani, Kulkarni, Fraser, and Vahala. "Label-free, single-molecule detection with optical microcavities", Science, 317, pp.783-787, 2007.

[2] Vollmer and Arnold. "Whispering-Gallery-Mode Biosensing: Label-Free Detection Down to Single Molecules." Nature Methods 5 7 (2008): 591-96.

[3] Fan X.D. et al. "Opto-Fluidic Micro-Ring Resonator for Sensitive Label-Free Viral Detection." Analyst 133 3 (2008): 356-60.

[4] M.L. Gorodetsky, A.A. Savchenkov and V.S. Ilchenko, "Ultimate Q of optical microsphere resonators", Opt. Letters. Vol. 21, 453-455, 1996.

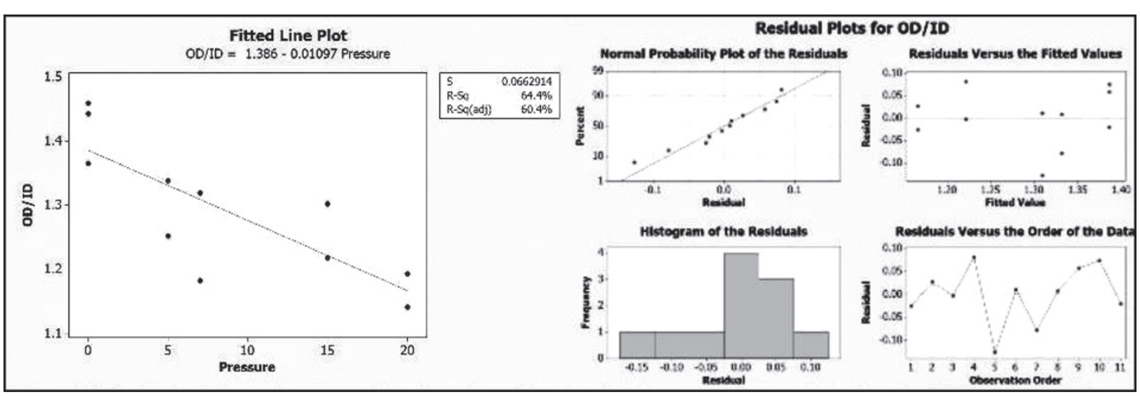

Figure 3: Near-linear relationship of gas pressure to wall-thickness.