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Date: July, 2004

Technical Paper

Application of Vicast for Optical Device Fabrication

Abstract

Optically transparent polymers have applications in fields ranging from telecommunications to biotechnology. In the Vahala Research Group at the California Institute of Technology, we explored the use of Vicast as an optically transparent polymer in the telecommunications wavelength band (near-IR) for the fabrication of toroidal microresonators. These devices are the optical analogue of an acoustic tuning fork, resonating at a pre-determined optical frequency.

The process fabricating Vicast microresonators follows traditional molding methods. Silicone open-molds were formed using silica toroidal microresonators with quality factors (Q) in excess of 108 as a master structure; these molds were then used to cast Vicast microresonators. The Q factors of the Vicast microresonators are close to material-loss limited, affirming the integrity of the replication process, and as high as 5x106 or nearly a factor of 40 greater than previous polymer-based devices. Because the molding process is non-destructive, both the master and molds can be reused. Additionally, Vicast was able to be stored in the mold which provides a method to preserve the whispering-gallery Q factor.

Historical Background on Microresonators

The acoustic whispering gallery effect was first observed by Lord Raleigh in the St. Paul Cathedral in London in 1910 when a whisper on one side of the perimeter of the gallery was able to travel around to the other side. Optical analogue to this effect is observed in optical resonators. The quality of the optical resonator is expressed in its quality factor (Q) which describes how long energy can be stored in the resonator. Alternatively, Q describes a single photon's lifetime in the resonator.

The whispering gallery mode in an optical resonator resides primarily in the periphery of the resonator, are also several methods used to minimize loss in the whispering gallery mode which have been developed in the past few years involving both novel material development and resonator fabrication methods.

The intrinsic Q (Qo) of an optical resonator can be described as the decay time for a single photon in a whispering gallery mode. More specifically, if w is the resonant frequency and t is the photon lifetime, then . There are several loss mechanisms which can impact Q and must be taken into account in order to determine a resonator's intrinsic Q. The general equation governing Q is:

$$Q_{tot}^{-1} = Q_{mat}^{-1} + Q_{scatt}^{-1} + Q_{surf}^{-1} + Q_{ext}^{-1} + Q_{WGM}^{-1}$$

where the loss mechanisms are: material absorption, surface scattering, surface absorption, and external coupling to an external mode in an alternative medium and whispering gallery loss.

One of the loss mechanisms in resonators is material absorption, a. The equation describing absorption limited Q is:

$$Q_o^{abs} = \frac{2\pi n_{eff}}{\lambda\alpha}$$

where neff is the effective refractive index, since the whispering gallery mode is not entirely confined inside the resonator, and l is the resonant wavelength. In silica resonators, material absorption is extremely low in the telecommunications wavelength band.

Another loss mechanism arises from surface scattering or surface roughness. In order to couple light into optical resonators, optical waveguides, such as planar waveguides, tapered optical fibers or prism couplers, must be used. During the transfer between the waveguide and the resonator, any surface roughness leads to surface scattering and loss.

Both of these loss mechanisms are reduced in silica microresonators. Silica has very low material absorption in the telecommunications wavelength band, significantly reducing the effect of Qmat. In addition, the surface roughness is reduced by exposing them to a CO2 laser and allowing surface-tension to form nearly atomically smooth surfaces. (Figure 2) It is these extremely smooth surfaces coupled with the low material loss of silica that enable the silica toroidal microresonators to achieve ultra high Q (Q>108).

In previous polymer resonator fabrication, both of these loss mechanisms have played a dominate role in limiting the Q (Q~105). The techniques used during the fabrication of polymer resonators include various combinations of photolithography and etching. This results in lithographic blemishes on the periphery of the microresonator and roughening of the periphery where the whispering gallery mode resides. In addition, the materials which are suitable for these fabrication techniques have high material absorption in the telecommunications wavelength band, making them non-ideal for such applications.

Experimental Procedure

The replica molding process consists of 3 major steps as shown in Figure 3. First an array of ultra-high-Q silica microtoroid masters is prepared by defining silica pads on a silicon wafer using a combination of photolithography and buffered oxide etchant. Next a XeF2 gas etch is performed which results in the silica disks becoming isolated on silicon pillars. Finally the surface-tension induced microcavities are formed by exposing the silica microdisks to a CO2 laser. Next, a polydimethylsiloxane (PDMS) mold is made of the silica microtoroid array. To prevent adhesion between the PDMS and the silica master toroids, the microtoroid master arrays are silanized with trichloromethylsilane (TCMS). After silanization, PDMS is poured onto the microtoroid master and de-aired at 200 mTorr for 30 minutes. Once the de-airing process is complete, the mold is cured for 60 minutes at 80º C. To remove residue water or HCl from the PDMS surface and to complete the curing process, the mold is baked for 12 hours after release from the microtoroid master.

Finally, the Vicast replicas are cast from the silicone mold (Figure 4). One unique feature of the molds is the relatively large overhang and the small dimensions (toroidal minor diameters of 5 microns). The silicone molds are able to replicate both of these features. Since Vicast has a gel time of less than 15 minutes, the de-airing process was only 5 minutes. To remove the remainder of the air, a glass coverslip was pressed on top of the mold. Vicast is cured for 12-hours at 75º C and allowed to remain in the mold for an additional 48 hours at room temperature before release.

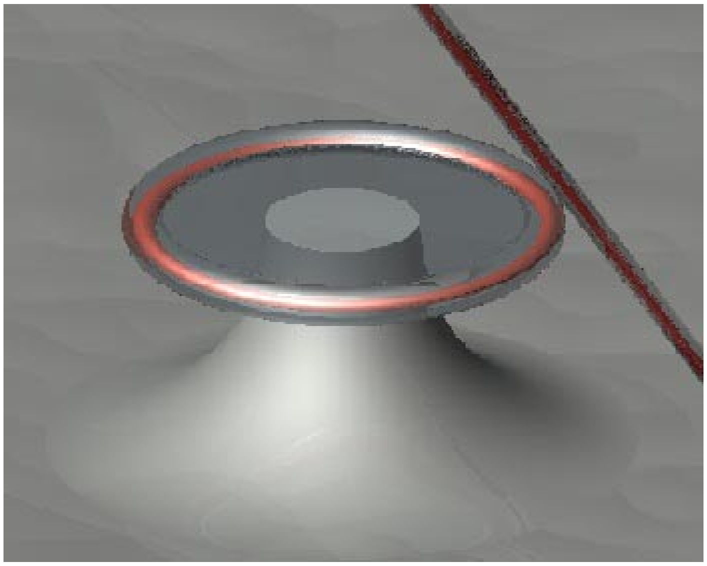
It should be noted that each step of the Vicast polymer replica fabrication process is non-destructive. Microtoroid masters and the PDMS negative molds were used repeatedly and no degradation in quality (as inferred by measurement of resonator Q factor) was observed in the final polymer replicas. In addition, Vicast microtoroids have been stored for several weeks in-the-mold without adhering to the mold and exhibit Q factors comparable to Vicast microtoroids immediately released from their molds. Since high-Q microresonators can be sensitive to long term environmental exposure, this feature is an important means by which the “shelf-life” of disposable microresonators can be increased.

Test Methods and Results

To determine resonator quality, measurement of the resonator quality factor and analysis of the modal structure was performed at three wavelength bands (980, 1300 and 1500 nm). For testing purposes, a single-frequency, tunable external-cavity laser was coupled to a single-mode optical fiber containing a short, tapered section. The tapered section acted as a waveguide, coupling power into the “whispering gallery modes” of the Vicast microtoroids. Tapered fibers are made by heating a standard, telecommunication, optical fiber with an oxyhydric torch while stretching the fiber. With the taper waveguide in close proximity to the polymer microtoroid, optical laser power was launched and transmission spectra monitored. Figure 5 is a typical transmission spectrum. Since the refractive index of Vicast is similar to that of silica (Vicast: 1.53 near 1300), both the modal structure and free-spectral-range of the polymer microtoroids are comparable to that of their silica master counterparts. Furthermore, the modal structure is dominated by principal transmission minima believed to be the fundamental transverse mode of the replica microtoroids.

The intrinsic Q factor for this mode was determined by scanning the laser (linewidth of 300 kHz) and measuring the transmission and the loaded linewidth (full-width-half-maximum) for several, waveguide-resonator, coupling conditions in the under-coupled regime. The intrinsic modal linewidth (and intrinsic Q) was then computed using a simple coupling model. The measured intrinsic Q factor (average of computed values described above) for Vicast in all wavelength bands tested is given in Figure 6. Points in the plot are located at wavelengths corresponding to specific modes measured while the lines provide a guide to the eye. The data is specific to one device, but is representative of measurements on many distinct polymer resonators. The maximum quality factor measured was 5×10^6 in the 980nm region. Comparing these results to all other chip-based, microresonator Q values, the maximum Q factor measured for the Vicast microtoroids is bettered only by the silica microtoroid master and is nearly a factor of 40 greater than all prior polymer-based devices.

The theoretical maximum Q factors for Vicast were also calculated. The Vicast material loss was measured at 1319nm and 1550nm using a Metricon system. These points gave a material-limited Q factor of 2.71×10^6 at 1319 nm and 3.11×10^6 at 1550 nm, which are consistent with the measured intrinsic Q factors. This indicates that the resonators main loss mechanism is material loss not surface scattering. To the researcher’s knowledge, this is the first time that polymer resonators have been fabricated where the surface roughness did not play a dominate role in Q degradation. Since the master microtoroids exhibit Q factors in excess of 100 million, the highest measured Q factor (5 million) provides a lower bound on the replication-process-induced Q degradation.



Conclusion

In summary, we have demonstrated replica-molded microresonators using ultra-high-Q microtoroid masters. Their Q factors are material-loss limited and typically in excess of 1 million. Q values in this regime make these devices well suited for application as biosensor transducers and also in photonic devices requiring low insertion loss. The micro-molding process lends itself to rapid, large-scale reproduction of dense arrays of devices and optically active dopants can be added directly to the host material. Additionally, by using Vicast as the replica polymer, we have shown that storage in-the-mold is possible and is a potential method to extend the shelf-life of the device. In applications requiring pristine optical interfaces such as biosensing this feature and the inherently "disposable" nature of devices produced by replica molding are attractive features. Patents have been filed on this work.

Andrea Martin is a fourth year PhD candidate at the California Institute of Technology, Pasadena, CA. She received her Masters degree in Applied Physics from the California Institute of Technology, Pasadena, CA and her Bachelors degree in physics from University of Chicago.

Figures

Figure 1: Rendering of a silica toroidal microresonator with the whispering gallery mode denoted in red coupled to a tapered optical fiber waveguide.

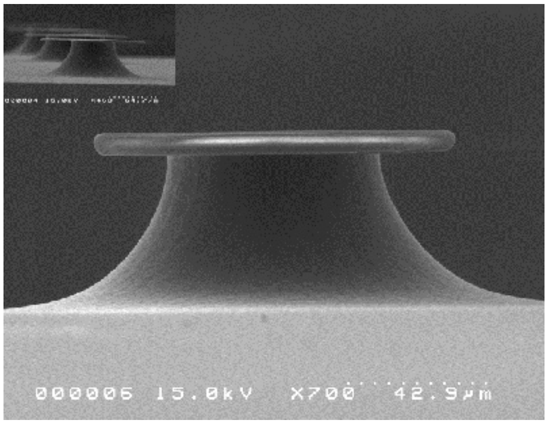


Figure 2: Silica toroidal microresonators after exposure to the CO2 laser. The inset shows microresonators before the lasing process.

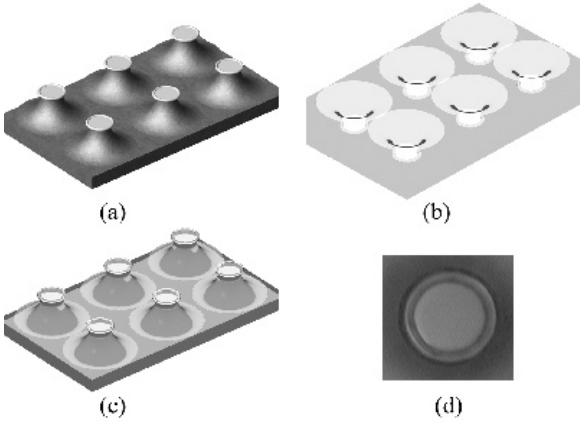


Figure 3: Fabrication process flow for Vicast microresonators: a) fabricate an array of ultra-high-Q silica toroidal microresonators, b) form a PDMS mold, c) cast Vicast disk, d) optical micrograph of a Vicast microresonator.

Figure 4: Optical microscope images of two different Vicast resonators demonstrating the ability to alter both the major and minor toroid diameter while maintaining a smooth surface.

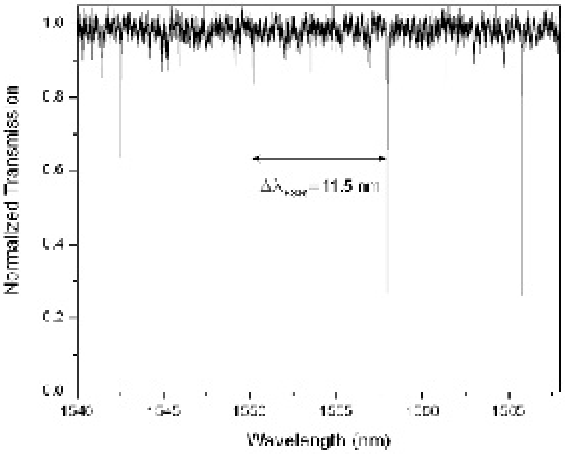


Figure 5: Broad band transmission spectra of a Vicast resonator. The free spectral range between fundamental resonances is noted on the figure.

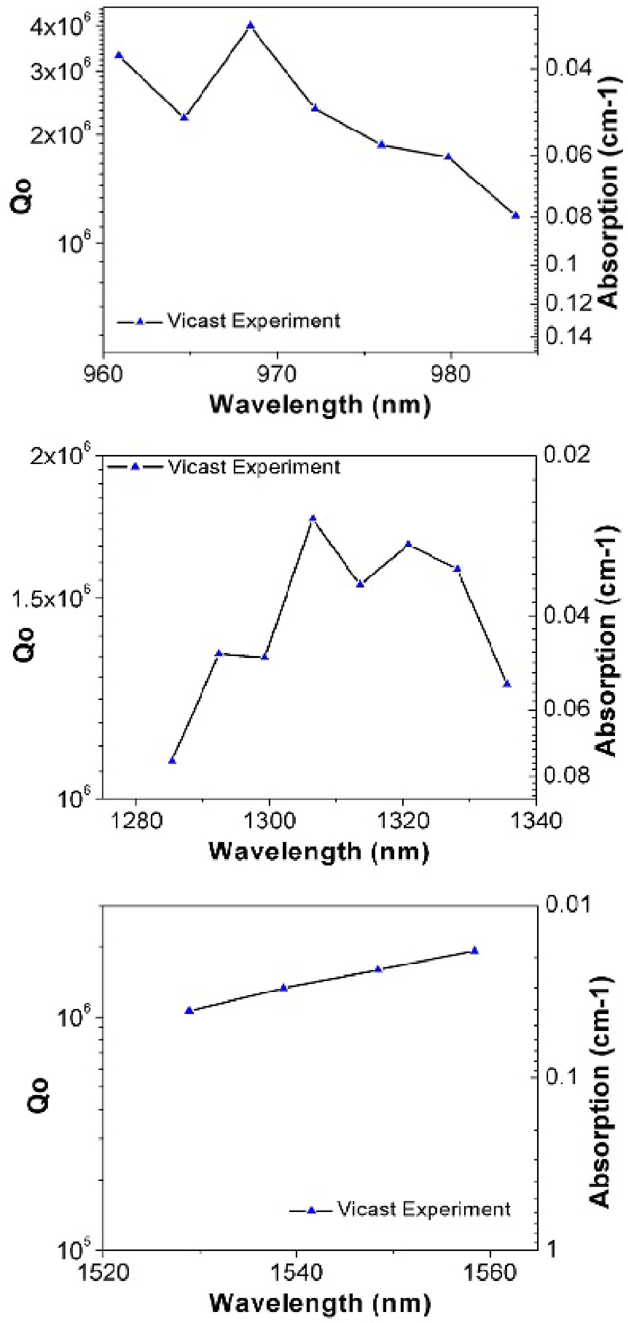


Figure 6: The intrinsic Q taken at resonant frequencies of Vicast microresonator is shown in blue. Each Q value represents at least 5 Q values taken at that wavelength. The free spectral range of the toroidal microresonator determines the spacing of these resonances and thus the number of data points in a given wavelength range. The black line is meant as a guide to the eye to show general trend.