Replica-molded high-Q polymer microresonators

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Ultrahigh-Q microtoroids on a chip are applied as replication masters to demonstrate replica-molded high-Q microresonator arrays. Replica Q factors are nearly material loss limited, affirming the integrity of the replication process, and are as high as 5×10^6, or nearly a factor of 40 greater than previous polymer-based devices. Because the molding process is nondestructive, both the master and the molds can be reused. Additionally, by using a novel optical polymer (Vicast), we demonstrate storage of high-Q microresonators in the mold for weeks, providing a method to preserve the whispering-gallery Q factor. © 2004 Optical Society of America

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Resonant microcavities have a variety of applications in fields such as nonlinear optics,[1,2] biosensing,[3] and telecommunications.[4] However, fabrication protocols for these devices, as is typical in all device microfabrication, are material specific. In this work, recently developed ultrahigh-Q whispering-gallery-type microresonators[5] are utilized as masters in a novel application of micromolding of polymeric resonators. In addition to being a fast and effective method of producing high-Q polymer microresonators, the process is capable of producing resonators that are material loss limited. As such, it has a secondary application for rapid evaluation of optical loss in previously untested polymers. To illustrate this application, both polydimethylsiloxane (PDMS) and Vicast (a polymer heretofore known only in household and consumer applications) are evaluated at several wavelength bands. In addition to producing record Q factors for polymer-based microresonators, Vicast is found to facilitate resonator storage in the mold until time of application.

The replica-molding process consists of three major steps as shown in Fig. 1. First, an array of ultrahigh-Q silica microtoroid masters is prepared according to the procedure described in Ref. 5. A PDMS mold is then made of the microtoroid array, and finally, PDMS or Vicast replicas are cast from the mold. The molding process is similar to that used in previous microfluidic[6–8] and photonic device work.[9,10] Because the present structures feature a relatively large overhang and contain both a silica and a silicon surface, the negative-mold polymer must be mechanically flexible and must not adhere to either the silica or the silicon. PDMS (RTV 184, Dow Corning 10:1), a silicone elastomer, was found to satisfy these requirements.

To prevent adhesion between the PDMS and the silica master toroids, the microtoroid master arrays are silanized with trichloromethylsilane. After silanization, PDMS is poured onto the microtoroid master and deaired at 200 mTorr for 30 min. When the deairing process is complete, the mold is cured for 60 min at 80 °C. To remove residual water or HCl from the PDMS surface and to complete the curing process, the mold is baked for 12 h after release from the microtoroid master.

Replica resonators were cast with two different polymers, PDMS and Vicast (AOC, 100:1). Optical devices, such as waveguides, have been molded from PDMS[9,10] previously. However, Vicast has never been used for optical device fabrication, nor have its optical properties been characterized. Whereas both polymers are optically transparent, the mechanical properties are significantly different. However, the flexibility of the PDMS mold allows for the rigid Vicast microtoroids to be cast.

In casting PDMS-based microtoroids, the mold is first treated with oxygen plasma for 20 min to facilitate removal of the polymer microtoroid replica from the PDMS mold. After deairing, the liquid PDMS is cured for 1 h at 80 °C and released from the mold. The casting procedure for Vicast microtoroids omits the oxygen plasma treatment. However, Vicast must be cured for 12 h at 75 °C and remain in the mold for an additional 48 h at room temperature before release.

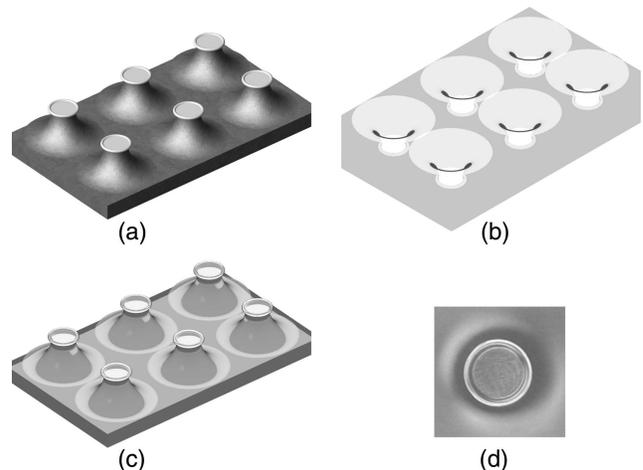It should be noted that each step of the PDMS and Vicast polymer replica fabrication process is

Fig. 1. Replica-molding process flow: (a) an ultrahigh-Q microtoroid master array is fabricated and silanated with trichloromethylsilane to aid in the release of the master from the mold; (b) the master is coated with PDMS to form a PDMS mold, which is subsequently exposed to an oxygen plasma and filled with PDMS or Vicast to form (c) a PDMS or Vicast replica polymer microtoroid array. (d) Optical micrograph of a PDMS microtoroid.
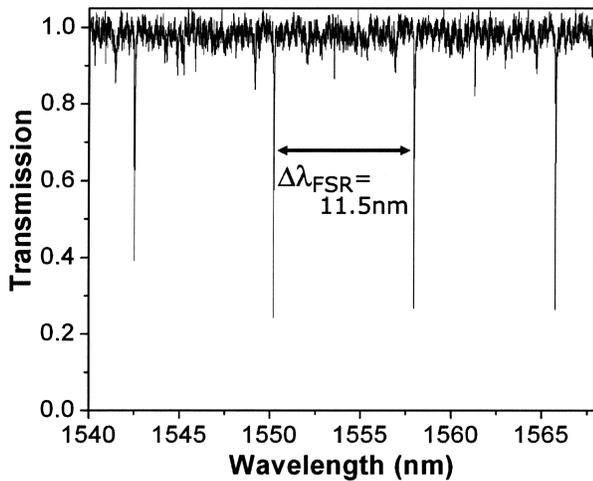
Fig. 2.   Transmission spectrum for a 45-μm-diameter Vicast polymer microtoroid.   The free spectral range (FSR) of the polymer high-Q microtoroid is in agreement with the theoretical prediction of 11.5 nm.

nondestructive. Microtoroid masters and the PDMS negative molds were used repeatedly, and no degradation in quality (as inferred by measurement of the 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 with 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.

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 was used to couple power into the whispering-gallery modes of the PDMS and Vicast microtoroids. Tapered fibers are made by heating a standard telecommunication optical fiber with an oxyhydric torch while stretching the fiber.[11] They function

as high-efficiency probes of microresonators and are described in more detail elsewhere.[12,13] During testing, the polymer microtoroids were placed on a high-resolution translation stage (100-nm step resolution) and were monitored by two cameras (top and side view) simultaneously. With the taper waveguide in close proximity to the polymer microtoroid, optical laser power was launched and transmission spectra were monitored. Figure 2 is a typical transmission spectrum. Since the refractive indices of both PDMS and Vicast are similar to that of silica (PDMS, 1.46; Vicast, 1.53 near 1300 nm), both the modal structure and free spectral range of the polymer microtoroids are comparable with that of their silica master counterparts.[5] 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 both the transmission and the loaded linewidth (full width at half-maximum) for several waveguide–resonator coupling conditions in the undercoupled regime.[13] The intrinsic modal linewidth (and intrinsic Q) was then computed with a simple coupling model.[12] To minimize the effect of thermal distortion on the mode structure, the optical input power was kept below 1 μW with an optical attenuator, and the laser scan frequency was optimized so as to ensure that neither the scan direction (increasing frequency versus decreasing frequency) nor the scan frequency had any observable effect on linewidth. The measured intrinsic Q factor (average of the computed values described above) for both Vicast and PDMS in all wavelength bands tested is given in Fig. 3. Points in the plot are located at wavelengths corresponding to the specific modes measured, and the curves provide a guide to the eye. The data are specific to one device but are representative of measurements on many distinct polymer resonators. Maximum quality factors of 5×10^6 were measured for Vicast and 2×10^6 for PDMS. Comparing these results with all other chip-based microresonator Q values reveals that the maximum Q factor measured for the Vicast microtoroids is surpassed by only the silica microtoroid
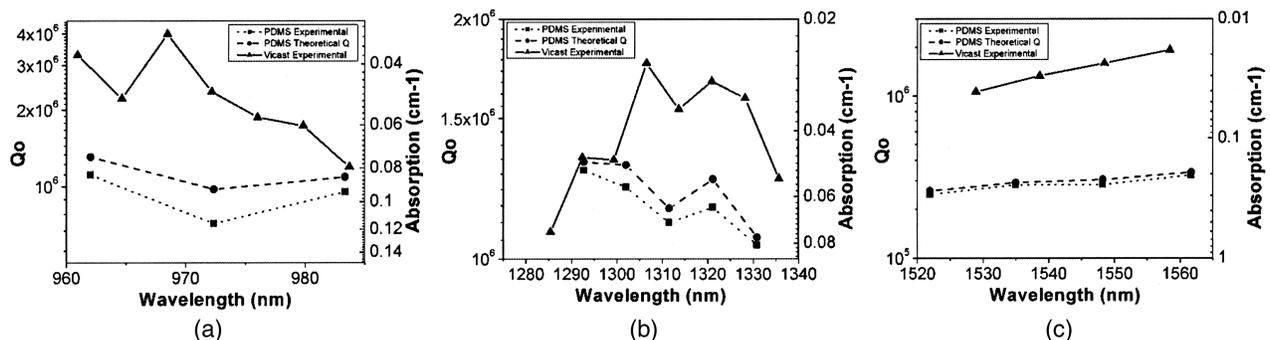

Fig. 3.   Intrinsic Q for PDMS (solid curve) and for Vicast (dotted curve) replicated microresonators measured in the following bands: (a) 980 nm, (b) 1300 nm, and (c) 1550 nm. Data points are connected by curves as a guide to the eye.   Intrinsic Q (dashed curve), inferred for PDMS from material absorption spectra, is also shown.   For reference, an equivalent loss (in cm^{-1}) is also given.

master and is nearly a factor of 40 greater than all prior polymer-based devices (highest Q reported in Ref. 14).

The material-limited maximum Q factors for PDMS are also presented in Fig. 3 and were inferred with the available absorption spectra.[15,16]   Both the magnitude and the spectral dependence of the measured, intrinsic Q factors are consistent with the inferred curves for PDMS, indicating that cavity Q is dominated by material loss and not surface scattering. The PDMS and Vicast material losses were also measured at 1319 and 1550 nm with a Metricon system, a prism coupling measurement using planar waveguides. The Metricon PDMS absorption values were compared with the published PDMS absorption spectra and indicate that the measured loss was limited by bulk absorption (not waveguide scattering). The Metricon-derived data point for Vicast yielded material-limited Q factors 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. 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.

In summary, we have demonstrated both rigid and flexible replica-molded microresonators with ultrahigh-Q microtoroid masters. Their Q factors are material loss limited and are typically in excess of 1 million. Q values in this regime and the ability to functionalize polymers[17,18] for analyte-specific detection makes these devices well suited for application as biosensor transducers[4] as well as in photonic devices that require low insertion loss.[19] The micromolding process lends itself to rapid, large-scale reproduction of dense arrays of devices,[8] and optically active dopants[20] 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 and the inherently disposable nature of devices produced by replica molding are attractive features. Certain polymers, such as poly(methyl methacrylate),[21] are known to exhibit even lower material losses at shorter wavelengths. By use of such polymers, replicated devices with Q factors in excess of 100 million, i.e., comparable with their masters, could be molded and used to probe nonlinear optical and thermo-optic tuning effects.[5]

Note added in proof: The authors would also like to call the readers' attention to work on micromolding of resonators by Yariv and co-workers.[22]

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