Micro-Molded High Q Polymer Resonators for Optical Loss Determination

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ABSTRACT

Replica molding of ultra-high-Q toroidal microresonators can produce polymer microresonators with material-limited quality factors (Q). This was demonstrated previously using polymers which cure thermally. In this work, high Q polymer microresonators were fabricated using the replica molding technique from previously uncharacterized polymers which require either a thermal or UV cure. The quality factor and effective refractive index of whispering gallery modes was measured at wavelengths ranging from the visible (680nm) through the near-IR (1550nm). The optical absorption coefficient (material absorption) of these previously uncharacterized polymers was determined from the quality factor and effective refractive index of the polymer.

INTRODUCTION

Low optical loss polymers have recently demonstrated a wide range of applications in telecommunications, finding use in structures such as optical resonators and single mode waveguides [1,2]. An important property of an optical polymer is material or optical loss. A common method used to characterize optical loss is through waveguiding within thin films of the polymers. Alternatively, by fabricating the polymer into a microresonator, the optical loss can also be determined because the quality factor (Q) of the resonator is directly related to optical loss. This latter technique, however, requires resonators that have exceptionally low scattering loss so that Q factor is determined by material loss.

Recently, a micro-molding-based method of fabricating nearly absorption-limited polymer microresonators was demonstrated using thermally cured polymers [3]. Because the silicone molding material accurately replicates a silica ultra-high-Q microtoroid with an extremely smooth surface, the periphery of the polymer resonator is also extremely smooth endowing the resonator with very low scattering loss. While in the previous work, this method was applied only to polymers that cure thermally, it can also be applied to other classes of polymers, such as epoxy resins which cure upon exposure to UV light. This is because, in addition to the flexibility of silicone, it is also fairly transparent in the UV range, allowing the epoxy resin to cure.

In the present work, replica molding was applied to two polymers, Crystal Cast 9024 (Industrial Polymers) and Efiron WR-509 (Luvantix). These polymers represent two distinct classes of polymers that cure by either thermal (Crystal Cast) or ultra-violet (Efiron) exposure. Luvantix developed the Efiron WR line as a material for molding optical waveguides in the near-IR wavelength regime. However, WR-509 was never fully characterized by Luvantix. Crystal Cast is currently used to make artificial glass-looking vases and water. Since Crystal Cast appears clear to the naked eye, its material absorption was never characterized by Industrial Polymers. The material absorption of both polymers was determined by fabricating these
polymers into a resonant cavity and measuring the quality factor and effective refractive index at wavelengths ranging from the visible (680nm) to the near-IR (1550 nm).

EXPERIMENTAL DETAILS

The replica molding process consists of three major steps which are described in detail elsewhere [3], but will be briefly outlined here (Figure 1). First, an array of ultra-high Q silica masters is fabricated using standard photolithography, followed by a XeF2 isotropic etch and reflow using a CO2 laser [4]. Then, the silicone (RTV 184, Dow Corning 10:1) molds are formed by silanating the UHQ microtoroids and casting the inverse silicone mold [3]. Finally, the polymer microresonator is fabricated by filling the inverse silicone mold with either Crystal Cast or Efiron. A glass cover-slip is placed on top of the mold and acts as a substrate to facilitate removal of the replica from the mold after curing. Downward pressure applied to the cover-slip displaces air bubbles and allows the polymer to fill the mold completely. Crystal Cast requires an intermediate de-airing step at ~150 mTorr for 20 minutes before the glass cover-slip is placed over the mold to further reduce bubbles.

Figure 1: Replica molding process flow: a) ultra-high-Q microtoroid master array is fabricated and silanated with trichloromethylsilane; b) the master is coated with silicone to form the mold and subsequently filled with Efiron/Crystal Cast; after either ultra-violet or thermal exposure, c) the Efiron/Crystal Cast replica polymer microtoroid array is complete. d) Optical micrograph of a Crystal Cast microtoroid.

As stated previously, the two polymers cure by different mechanisms. To completely cure Efiron, both ultra-violet and thermal curing steps are necessary. After exposing Efiron to an ultra-violet lamp with an intensity of 20mW/cm² for 22 minutes in the silicone mold, the replicas are released from the mold and are post-cured at 80 degrees C for an additional 30 minutes in a gravity oven. The ability to mold and cure Efiron is only possible because of the transparency of
the silicone molds in the ultra-violet wavelength range. In contrast, Crystal Cast only requires a thermal cure at 80 degrees C for 1 hour in a gravity oven. This demonstrates that the silicone molds can be used to fabricate polymer resonators with ultra-smooth surfaces which cure by two distinctly different curing mechanisms. Although the smoothness of the resonator surface was not characterized by AFM, high quality factors could not be achieved without an ultra-smooth surface because surface roughness leads to scattering which degrades the Q. Additionally, no surface treatment was necessary to release either polymer from the mold.

Measurement of the resonator linewidth, free-spectral range and analysis of the modal structure was performed at 3 wavelength bands (680, 1300 and 1550 nm). An outline of the polymer microresonator testing set-up is shown in Figure 1. A single-frequency, tunable external-cavity laser was coupled to a single-mode optical fiber containing a short, tapered section. The tapered optical fiber waveguide coupled power into the “whispering gallery modes” of the Crystal Cast and Efiron microtoroids. Tapered fibers are made by heating a standard, optical fiber with an oxyhydric torch while stretching the fiber [5]. They function as high-efficiency probes of microresonators and are described in more detail elsewhere [6,7]. 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 the transmission spectra were monitored. The modal structure was dominated by principal transmission minima believed to be the fundamental transverse mode of the polymer microtoroids.

The intrinsic Q factor of the resonator modes was determined by scanning the laser (linewidth of 300 kHz) and measuring both the transmission and the loaded linewidth (full-width-half-maximum) for several waveguide-resonator coupling conditions in the under-coupled regime [8]. In order to minimize the effect of thermal distortion on the mode structure the optical input power was kept below 1-microwatt using an optical attenuator and the laser scan frequency was optimized so as to ensure that neither scan direction (increasing frequency vs. decreasing frequency) nor scan frequency had any observable impact on linewidth.

DISCUSSION

The effective refractive index (n_eff) of the microresonator was determined from the free-spectral range. Using the relation

\[ n_{\text{eff}} = \frac{\lambda^2}{\pi d \lambda_{\text{FSR}}} \]

where \( \lambda \) is the center wavelength of the free spectra range, \( d \) is the diameter of the resonator, and \( \lambda_{\text{FSR}} \) is the free-spectral-range, the effective refractive index was calculated at a series of discreet, resonant wavelengths.

In order to solve for the material absorption, the intrinsic Q (Q_o) must be determined. The intrinsic modal linewidth (and hence Q_o) was computed using a simple coupling model [8] to analyze the loaded transmission spectra. The material absorption was then calculated using the relation

\[ \alpha = 2 \pi n_{\text{eff}} / \lambda Q \]
where $\alpha$ is the material absorption, $n_{\text{eff}}$ is the effective refractive index of the material determined from the free-spectral-range, and $\lambda$ is the wavelength of the resonance.

Figure 2: Effective refractive index ($n_{\text{eff}}$) of both Crystal Cast (solid black squares) and Efiron (hollow red circles) decrease as wavelength increases.

The effective refractive index was observed to increase slightly as the wavelength decreases and the results are shown in Figure 2. For Crystal Cast and Efiron, the effective refractive index in the visible is very similar, $n_{\text{eff}}=1.48$; however, in the near-IR, the effective refractive indices of the two polymers changed to 1.33 and 1.38 respectively.

Figure 3: Intrinsinc Q ($Q_0$) of Crystal Cast (solid black squares) and Efiron (hollow red circles) in (a) the red visible wavelength band and (b,c) near-IR bands are shown. Data points are connected by curves as a guide to the eye.

The measured, intrinsic Q of Crystal Cast and Efiron were similar at all wavelengths tested and are plotted in figure 3. The maximum $Q_0$ achieved was $4.2 \times 10^5$, using Crystal Cast at 1300nm. Based on previous confirmation that $Q_0$ in these tests is material limited [5], the subtle changes in $Q_0$ around a given center wavelength are believed to be indicative of spectral structure in the material absorption (Figure 3).
Figure 4: Material Absorption in dB/cm of Crystal Cast (solid black squares) and Efiron (hollow red circles) in the visible wavelength range (a) and near-IR (b) and (c) are shown. Data points are connected by curves as a guide to the eye.

The material absorptions are determined by combining $Q_0$ and $n_{eff}$ data and are summarized in Figure 4. Crystal Cast has the lowest loss in the 1300nm wavelength region, which corresponds to the region where the intrinsic $Q$ was the highest. As the wavelength shifts to the 1550nm, the absorption of Crystal Cast increases to that of Efiron; however, the material absorption of Efiron is nearly constant throughout the near-IR region. Though never characterized, Efiron was originally designed by the manufacturers to be used as a polymer waveguide material, so it is not surprising that the material loss of Efiron is fairly constant throughout the near-IR. In the visible region, the material absorption of both polymers increases. However, the increase in the effective refractive index of the polymers at this wavelength maintains the $Q_0$ values of the resonators. However, one interesting point to note is that Crystal Cast has lower absorption at 1300nm than Efiron.

CONCLUSIONS

In summary, we have demonstrated the fabrication of high-$Q$ polymer resonators from polymers which cure both thermally and upon exposure to UV. Additionally, by using $Q_0$, we determined the material absorption for these previously uncharacterized polymers from the visible to the near-IR.

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