Fabrication and characterization of whispering-gallery-mode resonators made of polymers

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Abstract: High-quality whispering-gallery-mode resonators made of polymethylmethacrylate (PMMA) are fabricated by simple mechanical turning and polishing according to a technique used by Ilchenko et al. to produce crystalline whispering-gallery-mode resonators with high quality factors (Q-factors). The high-Q PMMA resonators are investigated in two wavelength regimes: in the near infrared between the wavelengths 1470 and 1580 nm and at the wavelength 635 nm. The Q-factor in the infrared regime is limited by material absorption to 3×10^5. At 635 nm the Q-factor is limited by surface scattering only and reaches 4×10^7, which is a new record for polymers.

OCIS codes: (160.5470) Polymers; (230.5750) Resonators; (300.1030) Absorption.

References and links

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1. Introduction

There is large interest in low-loss polymer resonators for optical applications: Chemical sensors and micro-lasers are realized based on such resonators [1, 2, 3, 4], taking advantage of the possibility that it is simple to dope polymers. Another area is, e.g., building very sensitive force sensors in which strain changes the optical properties of the polymer [5]. For this variety of applications whispering gallery mode (WGM) resonators made of such polymers enable to build very efficient integrated devices in which the light travels long distances and hence strongly interacts with the host material.

There exist several methods to fabricate polymer microring resonators and polymer WGM resonators, which in many cases are extensive and material specific. Polymer microring resonators were obtained either by molding from a master structure [6] or by direct lithographic patterning of the polymer [7]. The maximum quality factor (Q-factor) achieved so far has been 5×10^6 in the infrared wavelength regime [6]. Macroscopic resonators have been built by freezing molten droplets [5] yielding a Q-factor of 10^6.

In this article we apply a fast, cheap, and effective method to produce polymer WGM resonators with high quality factors. This method [8] has been developed by Ilchenko et al. and has been used so far to fabricate crystalline WGM resonators with record high finesse [9] and Q-factors. But the fabrication method can be applied to any polishable material.

2. Theoretical considerations

The Q-factor is a measure for losses in a WGM resonator. For macroscopic WGM resonators the most important loss terms are given by the bulk absorption [10] and the scattering at surface inhomogeneities [11],

$$Q_{\mathrm{abs}}=\frac{2\pi n}{\alpha\lambda}\quad\text{and}\quad Q_{\mathrm{ss}}=\frac{\lambda^3 r}{8n\pi^2B^2\sigma^2}\,, \tag{1}$$

where λ is the light wavelength in vacuum, α is the absorption coefficient, n is the refractive index, r is the radius of the resonator, σ is the surface roughness, and B is the correlation length [8]. Finally, there are coupling losses Q_{coupl} [10] and radiative losses [12]. However, for resonator diameters larger than 10 μm radiative losses are negligible [12]. The overall Q-factor is determined by the individual loss terms according to

$$Q^{-1}=Q_{\mathrm{abs}}^{-1}+Q_{\mathrm{ss}}^{-1}+Q_{\mathrm{coupl}}^{-1} \tag{2}$$

and from the experimental WGM spectra by [13]:

$$Q^{-1}=\frac{\lambda}{\Delta\lambda_{\mathrm{FWHM}}}\,, \tag{3}$$

where $\Delta\lambda_{\mathrm{FWHM}}$ is the full-width-at-half-maximum of a Lorentzian peak of one mode. The free spectral range $\Delta\lambda_{\mathrm{FSR}}$ between two modes and the finesse $\mathscr{F}$ are given by

$$\Delta\lambda_{\mathrm{FSR}}=\frac{\lambda^2}{2\pi nr}\quad\text{and}\quad\mathscr{F}=\frac{\Delta\lambda_{\mathrm{FSR}}}{\Delta\lambda_{\mathrm{FWHM}}}\,. \tag{4}$$

The free spectral range can also be determined directly from the mode spectra.

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3. Fabrication

As starting material we use PMMA of the type Plexiglas GS 233 from the Evonik Röhm GmbH. Resonators out of this material are turned and polished on a common turning lathe.

As the first step, a piece of PMMA is turned by a fine cutting tool to the approximate form of the resonator. We generally use a conically shaped form of the rim [14] to ensure that only a few modes can be excited. In such resonators the side wall is tapered such that modes are restricted to a small about 100 μm thick ring.

Afterwards, the equatorial region of the resonator is smoothed by polishing. Diamond pastes with successively diminishing grit sizes (3, 1, and 0.25 μm) are used to polish the resonator until no scratches are visible under a binocular microscope. The diamond paste is put on a paper tissue and held by hand onto the turning resonator.

After polishing, the resonator has to be cleaned very accurately. This can be done on the lathe using tissues wetted with ethanol. The whole process of machine turning and polishing can be done within one hour.

In a last step, the mechanical tension inside the polymer resonators, caused by the machining process, should be removed. This is done by heating the sample in an oven at 90 °C for 1 hour. Figure 1 shows a resonator fabricated with the method described above.

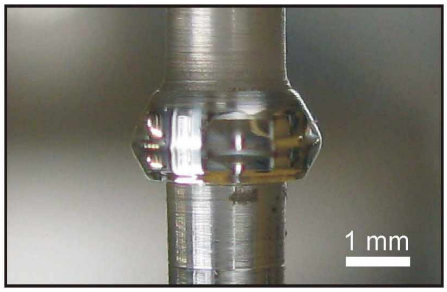

Fig. 1. WGM-resonator made of PMMA with a standard turning lathe.

4. Experimental methods

Measurements of the Q-factor in the infrared wavelength regime, reaching from 1470 to 1580 nm, are performed with a tunable diode laser (Tunics Plus). The laser linewidth is much smaller than the expected linewidth of the modes of the polymer resonators. Measurements of the Q-factor in the visible wavelength regime are performed with a tunable diode laser (New-Focus Stablewave 7004) with the center wavelength at 635 nm and a linewidth smaller than 500 kHz. Figure 2 shows a schematic sketch of the setup. Both lasers emit linearly polarized light and are coupled to single-mode fibers. In the infrared wavelength regime, a gradient index lens at the end of the fiber focusses the light onto the contact point between a prism and the resonator under the critical angle for evanescent coupling. At 635 nm a conventional lens with 8 mm focal length is used. To prevent the resonator from heating up, light is guided through a 20 dB fiber attenuator. A polarization controller enables changing the polarization direction. All measurements are performed in TE polarization, i.e. with the electrical field being perpendicular to the equatorial plane. The light coming out of the resonator is detected with a standard photodiode. Mode spectra are recorded by scanning the wavelength of the laser and measuring the intensity of the transmitted light. Then the Q-factor is determined according to Eq. (3). For all measurements a prism made of SF11 glass is used since the refractive index of the prism must be higher than that of the resonator to achieve evanescent coupling. It was ensured that

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neither the laser scan frequency nor the scan direction had any observable influence on the linewidth.

Absorption measurements of PMMA at infrared wavelengths are performed with a Varian Cary 500 spectrometer. To achieve an automatic reflection correction for the absorption measurement without precisely knowing the refractive index of PMMA, two plane PMMA pieces, one with the thickness $d_1 = 0.63$ cm and one with $d_2 = 0.965$ cm, are used. The transmissions T_1 and T_2 of theses samples are determined, and by considering one back reflection and assuming that both pieces show the same reflectivity, α can be determined according to

$$\alpha = \frac{\ln(T_2/T_1)}{d_1 - d_2} \, . \tag{5}$$

Higher-order back reflections do not contribute significantly, and therefore they are neglected. Since the absorption of PMMA in the visible is too low to be measured with a Varian Cary 500 spectrometer, absorption measurements of PMMA are conducted by measuring the transmission of 633-nm laser light for two pretty large different optical pathlengths, $d_1 = 0.998$ m and $d_2 = 0.495$ m. Here higher-order reflections appear spatially separated and do not affect our measurements.

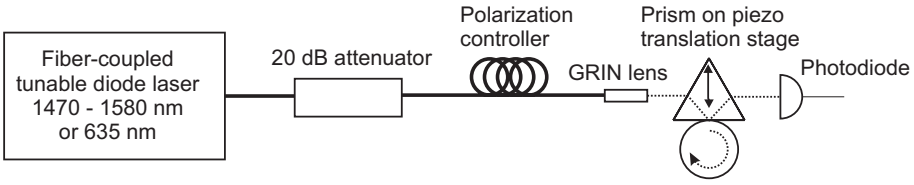

Fig. 2. Schematic sketch of the setup used for the determination of the Q-factors. At 635 nm a conventional lens is used instead of the GRIN lens employed in the infrared wavelength regime. The material of the prism is SF11 glass.

5. Experimental results

Mode spectra of the resonators are recorded at room temperature. The resonators used in this work have diameters of (4.21 ± 0.01) mm (P5), (2.50 ± 0.01) mm (P6), and (15 ± 0.01) mm (P8).

5.1. Infrared wavelength regime

Measurements in the infrared wavelength regime are performed with the prism in contact with the resonator. Although the prism is mounted onto a piezoelectrically-driven translation stage, it is not possible to achieve critical coupling, since even in contact Q_{coupl} [10] is much larger than the measured Q-factor, and increasing the gap between the resonator and the prism does not lead to a higher quality factor. Figure 3 shows a characteristic mode spectrum. Such mode spectra are stable over more than 14 hours, i.e., the mode drift is less than 20 pm, at constant room temperature. A Lorentzian fit at 1549.99 nm gives $\Delta\lambda_{\mathrm{FWHM}} = 0.0055$ nm. According to Eq. (3) this implies $Q = 2.9 \times 10^5$ at 1549.99 nm. By scanning the wavelength from 1450 to 1580 nm, the Q-factors of the resonators P5 and P6 are determined for several wavelengths (Fig. 4). For some mode spectra it is not possible to obtain the Q-factor because several modes coincide. The solid line in Fig. 4 shows the calculated absorption-limited Q-factor Q_{abs} (Eq. (1)) for the absorption coefficient measured by the absorption spectrometer.

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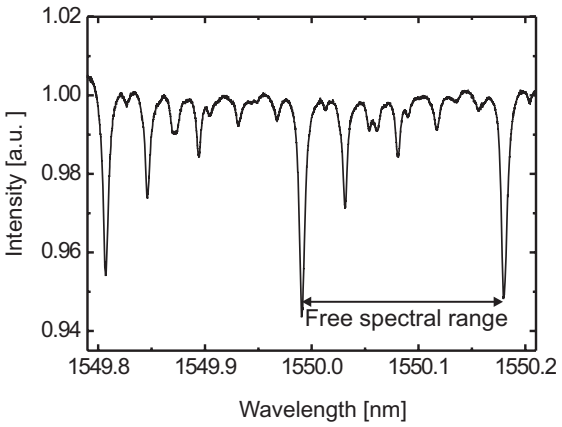

Fig. 3. Typical mode spectrum around 1550 nm.

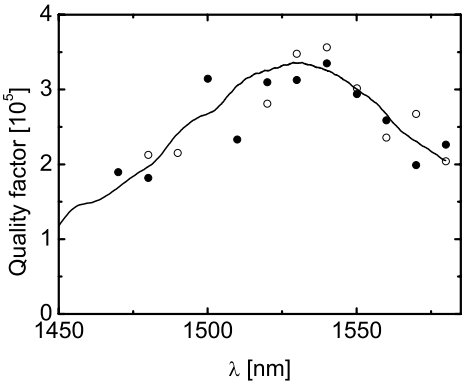

Fig. 4. Comparison of the calculated absorption-limited Q-factor Q_{abs} (solid line) with the measured Q-factor Q for PMMA resonators P5 and P6 (solid and open circles).

5.2. Red wavelength regime

Similar Q-factor measurements are conducted at 635 nm, but in this case they are performed in the undercoupled regime, so that Q_{coupl} can be neglected again. Since the tuning range of the laser is limited, the Q-factor can only be determined at this wavelength. The maximum Q-factor measured so far is $Q = 4 \times 10^7$ (P8) at 635 nm with a finesse of $\mathscr{F} = 360$. The absorption measurements at 633 nm give $\alpha_{633nm} = 0.0011$ cm^{-1}, yielding $Q_{\mathrm{abs}} \approx 1.2 \times 10^8$. As expected from Eq. (1), the Q-factors of resonators P5 and P6 are lower due to their smaller radii. The thermal annealing step described in Sect. 3 does not influence the maximum Q-factor reached. Instead, it is useful for eliminating the mode drift (of the order of a free spectral range per day) observed in untreated samples during the first days. The mode drift is about 40 pm/h directly after fabrication and less than 5 pm/h after annealing.

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6. Discussion

The measurements of the quality factor clearly demonstrate that the fabrication technique presented leads to high-quality polymer WGM resonators. It has been clearly shown (Fig. 4) that the Q-factor is absorption limited in the infrared spectral range around 1550 nm to values of about 4×10^5. Q-factors as high as 4×10^7 are reached for red light. Analyzing the results of the Q-factor measurements at 635 nm shows how smooth the surface of the resonators is. According to Eq. (1) we get a surface roughness of 30 nm only for resonator P8, considering that the measurements were done in the undercoupled regime, i.e., $Q = Q_{\mathrm{ss}}$, and assuming $B = \sigma$. There is still room to improve the polishing and to achieve smaller resonator sizes as presented by reference [8] so that Q-factors in the range of 10^7 should in principle be achievable for smaller resonators. Smaller resonator diameters lead to larger $\mathscr{F}$, hence the number of round trips $\mathscr{F}/(2\pi)$ of the light inside the resonator and the light intensity inside the resonator increases. This is essential for applications such as mentioned in [3]. The maximum finesse $\mathscr{F} = 360$ at 635 nm, corresponding to 57 round trips, might therefore be increased significantly. In order to increase the number of round trips in the infrared, a reduction of the radius r is essential since Q is already maximal. For applications such as absorption or refractive index change measurements the sensitivity depends only on the Q-factor. For these applications large resonators are the best choice, while for applications depending on the finesse small resonators [6] are better suited.

A key question is: What are the highest feasible Q-factors for polymer resonators? A threshold, that cannot be overcome, is set by the material absorption. For infrared light in the telecommunication regime, this limit is already reached experimentally in this work. For the best state-of-the-art low-loss polymers at this wavelength [15] one can expect Q values of $Q_{\mathrm{abs}} = 4 \times 10^6$ (see Eq. (1)). The absorption of red light is much less. There Q-factors of 10^8 can be expected. Thus moderate improvements of the polishing and annealing used in the present work would bring the resonators to this threshold.

7. Conclusion

In this contribution an efficient fabrication technique [8] is used to produce high-quality polymer WGM resonators. The resonators are absorption limited around 1550 nm. At 635 nm the measured Q-factor of 4×10^7 sets a new record in polymer WGM resonators to the best of our knowledge. Since the fabrication technique used in this paper is not specific for PMMA, any transparent low-loss polymer can be used that allows mechanical machining and polishing.

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